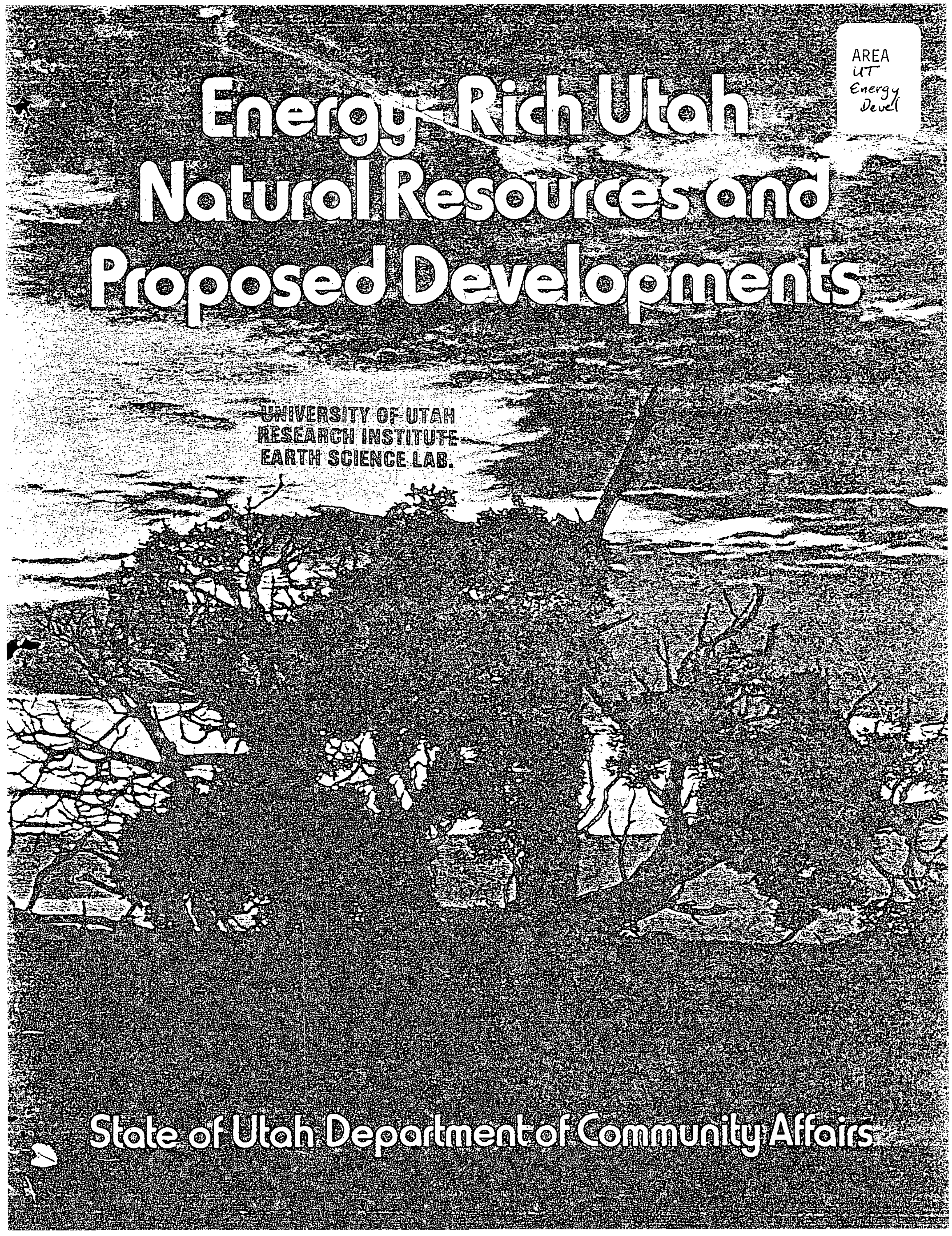
Energy-Rich Utah Natural Resources and Proposed Developments



State of Utah Department of Community Affairs

UNIVERSITY OF UTAH
RESEARCH INSTITUTE
EARTH SCIENCE LAB.

ENERGY - RICH UTAH:
NATURAL RESOURCES AND PROPOSED DEVELOPMENTS

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CALVIN L. RAMPTON
GOVERNOR

PREFACE

Because of an ever-increasing need for energy in our nation, Utah, along with other Rocky Montain states, is being called upon, due to its energy-richness to accelerate mining, developing and processing its fossil fuel resources. Crude oil and natural gas production is increasing; wild cat drilling is occurring; and oil shale extraction is being considered as are test wells for tapping our state's 25-billion barrels of tar sand deposits; geothermal leases are being offered; five electric power generating plants are under consideration, of which only one is currently in operation; and alunite magnitude will obviously impact the economic, social and physical character of the entire state.

Recognizing a need for current information regarding energy resources projects and potential development throughout the state, the Department of Community Affairs has published this report. Although many in-depth studies and publications have been conducted and published on the various projects currently being considered in Utah, no single document offers a profile of projects, by region, such as this report contains.

This report is not intended to be an in-depth analysis of energy resource development or of the impacts these projects will have on the state; however, it does give a broad overview of some potential policy implications should all these proposed developments occur.

FOREWARD

Prior to embarking on this project, the authors of this report set forth an overall objective: to provide energy resources information related to energy development, specific project data, and federal and state rules and regulations pertaining to energy resource development in the form of a comprehensive report and make it available to local and state officials, legislators, private enterprise, and citizens.

The authors would like to offer special thanks to Glen Merrill, artist for the Utah Department of Highways, for generously giving his time to provide us with several sketches. Thanks also to the Highway Department for the photograph on the cover of this document.

The data included herein is not original research, but is the most current information available to date. Thus, we owe a debt of gratitude to all those persons without whose studies this manual would not be possible. Our hope is that this compilation of data will serve as a ready reference in the hands of decision makers at all levels of government.

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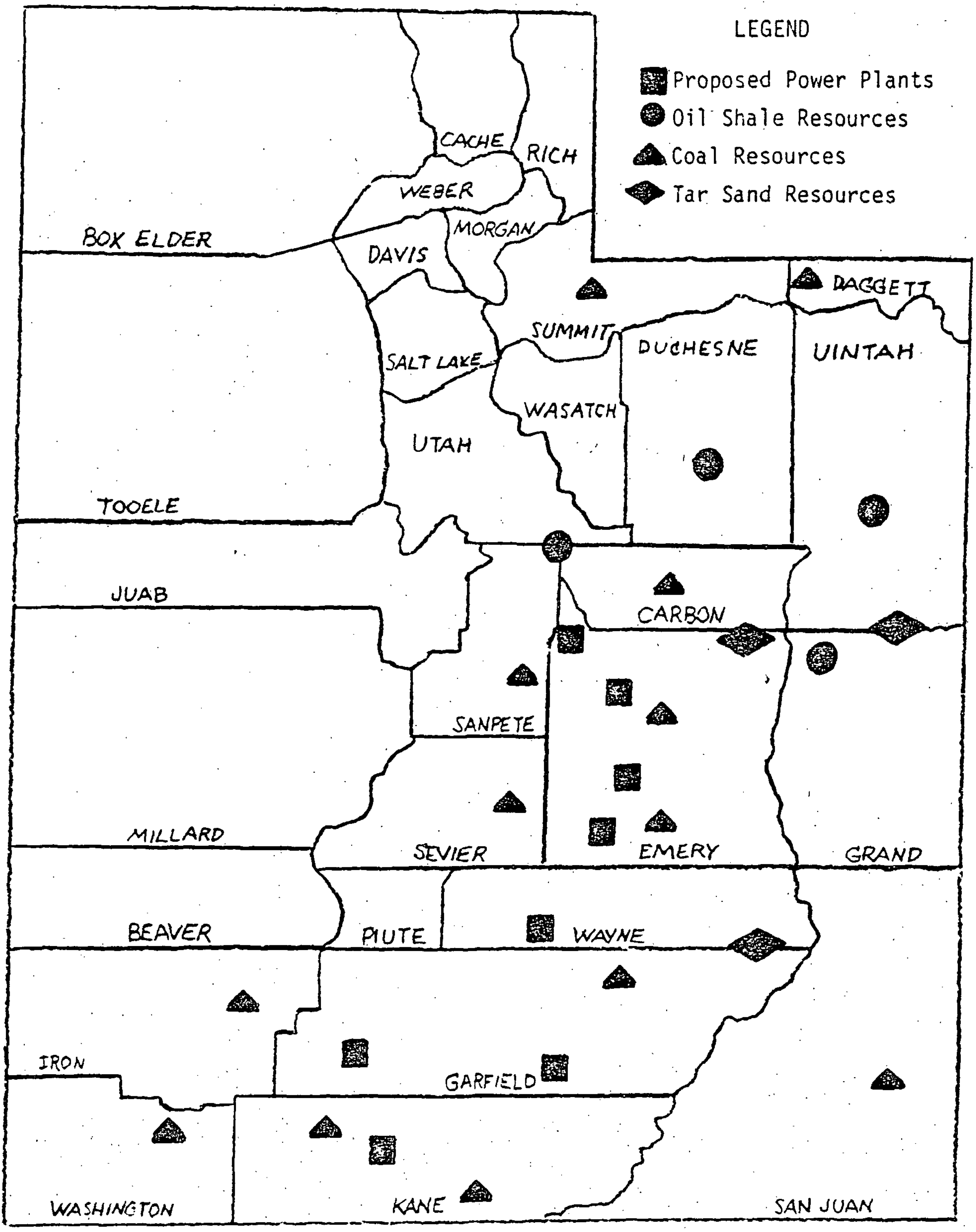
LEGEND
■ Proposed Power Plants
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CACHE
RICH
WEBER
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GARFIELD
WASHINGTON
KANE
SAN JUAN

A STATEWIDE OVERVIEW OF POTENTIAL ENERGY RESOURCE DEVELOPMENT

Introduction

One of this nation's primary concerns today and in the future is energy. It is estimated that the United States' current energy demands could triple by the year 2000. In order to meet the goal of energy self-sufficiency and reduce the nation's dependence upon imported resources, we are faced with the long-term effects of this policy. Along with other western states, Utah is experiencing a traumatic demand for its long dormant energy-related resources responding to the nation's impending energy crisis.

Strictly defined, energy resources refer to natural occurring minerals in either solid, liquid, or gaseous state which, when extracted from the earth, are suitable in their natural form or are capable of conversion into usable energy sources. These include coal, oil, oil shale, tar sands, geothermal, natural gas, and uranium. Because of Utah's richness in these resources (See Table I) along with alunite and potential solar energy, Utah will be heavily impacted. But how and when will that impact occur and what will be the effects of national energy policies on our state? This report is intended to accentuate the importance of these issues on the state's future growth and development.

Energy resource development can be defined as large scale public or private development which, because of its magnitude, will likely present social, political, economic, or environmental issues of more than local jurisdiction or capability.

TABLE I

INVENTORY OF UTAH'S ENERGY RESOURCES
January 1, 1975

Resource	Year first produced	Year first major production	Estimate of original reserve	Estimate of total production to end of 1974	Total remaining of original reserve (percent)	Possible remaining resource (indicated/inferred category)
Coal	1850 (1) 1870 (2)	1900 (3)	24.00 billion short tons	0.35 billion short tons (350 million s.t.)	23.65 billion short tons (98.5%) (6)	15.00 billion short tons (4)
Gilsonite	1888	about 1900	45.0 million short tons	4.5 million short tons to end of 1964 (no data for 1965-74)	41.5 million short tons to end of 1964 (90%) (5)	not known
Oil and natural gas liquids	1907	1948	775,512,000 barrels	511,000,000 barrels	264,512,000 barrels (34%)	200-300 million barrels
Natural gas	1895	1935	1.389 trillion cubic feet	0.364 trillion cubic feet (364 billion cu. ft.)	1.025 trillion cubic feet (74%)	0.250 to 0.400 trillion cubic feet (250 to 400 billion cu. ft.)
Oil-impregnated sandstone	1975?	1975?	26.0 billion barrels of oil in place	none	26.0 billion barrels of oil in place (100%) (6)	not known
Uranium	1912	1950	30.0 million short tons	12.1 million short tons	17.9 million short tons (60%) (7)	no estimate
Oil Shale	No production until 1980-1985. 100% of 90-115 billion barrels remains unexploited. (6)					

(1) Approximate first production.
(2) First records kept.
(3) First year of million ton production.
(4) Under less than 3,000 of cover.
(5) Indicate 65-70% remaining at end 1973.
(6) No estimate of % recoverable
(7) 0.26% grade.

Source: Utah Geological and Mineral Survey

Energy resource development will most likely impact existing communities, generating new towns, and the building of new recreation subdivisions, creating a corresponding demand for more tourist facilities in this region, and encouraging the extraction of other major mineral resources.

Utah has grown rapidly. Projections indicate a dramatic increase in the near future. In three years the population of the state increased nine percent from 1,059,273 in 1970 to 1,157,000 in 1973. Eighty percent of the population currently resides along the Wasatch Front on less than five percent of the land. The population of the state is expected to increase considerably during the next two to three decades. In the eight or nine counties where energy resources are most plentiful and the population is now sparse, development is anticipated to be the greatest.

Of the major projects now being planned in Utah, two of the largest are the Kaiparowits Power Plant and the Intermountain Power Project. The immensity of the Kaiparowits and the IPP projects is demonstrated by the fact that 9.0 million tons of coal, which is the estimated annual production of both plants, will generate 3,000 megawatts of electric power, which is sufficient for a population of 2,500,000--over twice the 1974 population of the entire state of Utah. 9.0 million tons of coal will also save 33 million barrels of oil. This is more than the total amount of petroleum products used in Utah each year. At present market prices, 33 million barrels of oil would cost approximately $400 million.

Other projects are the Allen-Warner Energy System (Warner Valley Project) in Garfield and Washington Counties and the alunite project in Beaver County in Southern Utah; Utah Power and Light plants (Huntington, Emery, and Garfield plants) in Southeastern and Central Utah, and coal mining in the Southeast; and oil and oil shale development in the Northeastern portion of the state. (See Tables II & III) Table V indicates direct employment resulting from coal mining throughout the state; whereas, Table IV shows projected coal development.

Communities in Garfield and Kane Counties will undoubtedly expand in population. Other areas include the Uintah Basin area, particularly Vernal. Bonanza could increase to 17,000, doubling in size, due to the prototype oil shale development. Roosevelt, located in the center of the oil rich Uintah Basin, is one example of a town which has already boomed as a result of oil development. The increased population led to increased demands for facilities and services outstripping funds and resources of the city to provide them. The Uintah Basin area has already changed significantly as a result of the oil in the Bluebell, Cedar Rim, and Altamont fields. Milford has grown as a result of the development of aluminum in the Wah Wah Mountains. St. George is expected to expand because of the Warner Valley Project and related facilities around the Dixie Project. Significant growth can be expected along the Wasatch Front since recreational developments, such as Park City, continue. Copper and mineral interests further have the potential for causing growth.

A recent development to be watched closely is the discovery of oil in Summit County, approximately fourteen miles east of Coalville. American Quasar made the oil discovery. Although precise information on the drilling will not be available until the fall of 1975, some information is known. Three wells have been drilled. One well is producing now, one well is expected to be producing within a short period of time, and the outcome of the third well is unknown. The oil well which is now producing is expected to continue for fifteen to twenty years. It will yield 1,522,000 barrels of oil and 1,217,600 M.C.F. of natural gas. Although it is not known how extensive this new oil field is, it is generally felt that it is significant.

Constraints

An important problem facing new towns or increasing growth of existing towns revolves around obtaining funds to cover "front end" costs of providing public services. Before tax revenues become available to the local governments from increased production costs such as fire, police, new schools, water, sewage disposal, roads and transportation facilities, communications facilities, housing and support businesses and other services must be planned for and provided for the additional population. Local governments, largely rural, have part-time public officials and lack the funds and often the planning staffs to prepare for the social costs of the problems which emerge.

Because Utah's population and economy are small, the state is vulnerable to demands arising elsewhere. In short, our growth problems will become increasingly complex with a corresponding need for more information and coordination. Problems of equity, accountability, fair access to use and development of resources and others need to be considered as they relate to the constraints, guidelines, and control mechanisms of planning for energy resource development. What are the social costs of crime, health, and other social problems which come with growth? What are the amenities of growth that is planned?

Some of the constraints surrounding potential energy projects will make comprehensive planning difficult to maintain, for example: Can energy production be consistent with adequate environmental safeguards? Manpower and service demands will increase with increased population. The economic structure of many communities and possibly the state will be altered. How can Utah maximize these changes to improve the quality of life for Utahns?

In the event that energy development comes into conflict with other kinds of values or interests in land use, i.e., environmental, agricultural, recreational, natural or scenically beautiful areas, how can these conflicts be resolved? These are a few of the questions which are presently being pondered by public officials at all levels of government.

The fact that Utah may not have enough water to support all the energy-related developments which its resources may attract is evidenced in the July, 1974 publication of the Department of Interior's study, Water for Energy in the Upper Colorado River Basin. Focusing only on oil shale, coal conversion, and coal-fired electric generating facilities, the study concludes that the demand for water from these sources could reach 243,450 acre-feet per year in the near future, which is more water than remains in Utah's Colorado Basin portion, the area where most energy related development would be located. The State Engineer now has applications for water presently on file in an amount which exceeds Utah's remaining share of Colorado River water. As a result of the demand for water and its insufficient quantity, difficult choices, based on potential costs and benefits associated with alternative potential water uses, will have to be made. What is the most desirable mix of uses which the state can attain? Other competing interests for the use of water will need to be considered, i.e., agriculture, municipal and industrial, recreation, fish and wildlife, and so forth.

What about water potential ways of creating energy? Because of its vast desert areas, Utah has the possibility of developing geothermal resources and generating solar energy. In Brigham City, Utah Power and Light Company has the necessary approval from the Division of Water Rights to begin drilling. However, operations have been suspended pending evaluation and further research. Phillips Petroleum Company is currently drilling at Roosevelt Hot Springs in Beaver County. A cooperative project involving Utah Power and Light, Geothermal Genetics, Inc. and McCulloch Oil Company includes plans to drill wells this year. Geophysical work is currently in progress. In addition to Utah Power and Light, other solar energy projects in the state are being considered. The University of Utah, Brigham Young University, Utah State University, and the State Solar Advisory Committee are all conducting research projects.

National Policy

The law of the land as stated in the National Environmental Policy Act (NEPA) checks energy developers and federal government agencies which approve energy projects. This may help balance out the either-or, development vs. environment syndrome, since it stresses placing environmental considerations along side other considerations. The 1969 Act claims that "Man is his environment." Such a claim has far-reaching implications for all of us as we relate to nature and the way in which it is being planned now and in the future.

In order to understand the federal framework within which any energy development must operate, a brief review of the NEPA Law is necessar at this time. For a further elaboration of the law's requirements, a copy of the act has been included in the Appendix (See Figure 2) of this report. The law requires two things: (1) that federal agencies, in conjunction with developers, explain what they are going to do, how they are going to do it, and what effect it will have on the environment; and (2) discuss the possible alternatives to the initial proposal.

The crux of the law is the Environmental Impact Statement (EIS) which is a system of reporting procedures on all major projects which "significantly" affect "the quality of the human environment." There are five important elements in an EIS: (See Figure 1 of Appendix for EIS Flow Chart)

1. <u>The environmental impact of the proposed action</u> - the negative and positive effects of the project.
2. <u>Any adverse environmental effects which cannot be avoided should the proposal be implemented</u> - the harmful effects of the project are noted.
3. <u>Alternatives to the proposed action</u> - other plans for accomplishing the same objective including the alternative of not doing the project at all.
4. <u>The relationship between local short-term uses of man's environment and the maintenance and enhancement of long term productivity</u> - how the values of the land may be preserved over time.
5. <u>Any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented</u> -

the change or removal from the environment situations or materials which can never be replaced.

This comprehensive statement includes preliminary inventory information such as: vegetation, soils, water bodies, circulation systems, land ownership, scenic areas, cultural areas, scientific areas, mineral resources, geologic features, and areas of potential industrial or community development.

Although a project cannot be stopped under NEPA, suits can be filed to determine the accuracy of the EIS under the law. It further allows for public participation and state and local agency review and comments on projects. Federal agencies are required to make their regulations consistent with federal environmental law under this Act.

A Council on Environmental Quality (CEQ) is established in the Executive Office of the President through this Act also. For information concerning other federal agencies such as the Environmental Protection Agency (EPA), set up by the CEQ, the acts they administer, and other pieces of pertinent federal and state legislation, we refer the reader to Handbook of Federal and Utah State Laws on Energy/Mineral Resource Development (See Bibliography).

It is the intent of this report to provide an overview of potential energy resource development facing the state. Hopefully it will illustrate the complexity of problems, pointing out social, political, economic and environmental implications surrounding possible energy development in Utah. No attempt has been made to provide answers to these critical issues; however, the following alternatives are inherent: How do we want to develop? What do we want to preserve or protect? And, how best can these goals be achieved?

Format of Report

In addition to the introduction, this publication contains two major sections. An analysis of the projects currently being proposed in each region throughout the state is discussed. Some of the major socio-economic problems that could accompany the affected communities are presented; however, this section is primarily a statement of the phase of each project at the current time.

Each major region of the state corresponds to a multi-county planning district system, utilized in the state for a more effective delivery of services to local government. This concept is discussed in the third section of the book. Additionally, how state and local governments are or might be interacting to resolve energy resource development problems is discussed in this section. What contributions to date, both financially and in terms of legislation, have occurred to support local government and to help alleviate the total burden resulting from this development is also reviewed.

Two additional sections of this report consist of an appendix and a bibliography. The appendix contains the NEPA law, a flow chart describing the EIS process, and a model executive order establishing an energy planning development council.

A list of references is attached at the end. It refers the reader to more in-depth studies from which this information has been extracted.

TABLE II

PROPOSED ENERGY RESOURCE DEVELOPMENT IN UTAH

County	Proposed Energy Resource Development
Beaver	alunite, geothermal, tar sands
Carbon	coal, Utah Power and Light
Daggett	natural gas
Duchesne	oil shale, mining
Emery	Utah Power and Light - Emery Plant, Utah Power and Light - Straight Canyon (No. Emery) Utah Power and Light - Huntington Plant, Intermountain Power Project
Garfield	oil, coal fields, Kaiparowits, tar sands, Utah Power and Light
Iron	geothermal, alunite
Kane	coal, Kaiparowits
Sevier	Utah Power and Light, Intermountain Power Project
Uintah	oil, oil shale, gilsonite mining, strip mining
Washington	Warner Valley, Dixie Project
Wayne	Utah Power and Light, Intermountain Power Project, tar sands (oil - impregnated sandstone

TABLE III

PROJECTED UTAH POWER GENERATING PLANTS

Company or Project	Location	Capacity	Fuel Type	Water Requirement and Source	Completion Date	Remarks
Utah Power and Light Company	Huntington Canyon Huntington, Utah Emery County	845 MW	Coal	14,000 AF/Y Electric Lake	1974 - 430 MW 1977 - 415 MW	Water Rights Reserved
*Utah Power and Light Company	Emery Emery County, Utah	830 MW	Coal	14,000 AF/Y Canal	1978 - 415 MW 1980 - 415 MW	7,000 AF/Y purchased from irrigators
Southern California Edison San Diego Gas Salt Lake River Project Arizona Public Service	Kaiparowits Plateau Kane County	3000 MW	Coal	50,000 AF/Y Lake Powell	1980 - 750 MW 1981 - 750 MW 1982 -1500 MW	
Nevada Power	Warner Valley St. George, Utah Washington County	500 MW	Coal	10,000 AF/Y for both Virgin River	1979 - 250 MW 1980 - 250 MW	Coal - from slurry line
Los Angeles Water & Power Board, et al.	Wayne County, Utah (Intermountain Power Project)	3000 MW	Coal	50,000 AF/Y	1980	Initial planning stage
Uintah Water Conservancy District	Uintah County White River	3 MW	Hydro		1978	
Bureau of Reclamation	SYAR Utah County	8 MW	Hydro		1981	
Bureau of Reclamation	DYNE Utah County	33 MW	Hydro		1981	
Bureau of Reclamation	Sixth Water Utah County	90 MW	Hydro		1981	
*Utah Power and Light Company	Garfield (Alternate site is Utah County)	830 MW	Coal	14,000 AF/Y Unknown	? - 415 MW ? - 415 MW	Tentatively planned for 1984

*If Utah Power goes to wet dry-cooling in 1978, water requirements will be cut in half.

TABLE IV

PROJECTED UTAH COAL DEVELOPMENT
January 1, 1975

Company or Project	Geographic Location of Production	Status of Proposal	Approximate Development	Projected Use	Point of Consumption	Type of Transportation	Production Annual Tons	Remarks
California Portland Cement	Central Carbon County, Utah	Firm	1975	Cement Plant	California	Truck & Rail	500,000*	Will reopen Premium Coal Co. Mine
McCulloch Oil Co. (Braztah Corp.)	Castle Gate, Carbon County, Utah	Firm	1974 to 1980	Power Generation	Midwestern United States	Rail	6,500,000*	Contract with American Electric Power Co.
Peabody Coal Co.	Huntington Canyon, Emery County, Utah	Firm	1977	Power Generation	Mine Mouth	Conveyor	1,200,000	Second Unit, UP&L Power Plant (Huntington Plant)
Utah Power & Light Company	Straight Canyon Emery County, Utah	Firm	1978 to 1980	Power	Mine Mouth	Truck or Conveyor	2,500,000	UP&L N. Emery Power Plant
Inspiration Development Company	Ferron Canyon Ferron, Emery County	Tentative	1975 to 1980	Unknown	Unknown	Truck & Rail	500,000 to 1,000,000	To be developed on private land
Consolidated Coal Company	Emery, Emery County, Utah	Tentative	1975 to 1980	Commercial & Power Generation	West Coast and Midwest	Truck & Rail	1,000,000* to 4,000,000	To be opened on Fee Land initially - Trucked to rail at Salina or Price, Utah
Kaiparowits Project	Central Kane County, Utah	Tentative	1978 to 1982	Power Generation	Mine Mouth	Conveyor	10,000,000	Impact Statement in Progress
Nevada Electric Power Company	Western Kane County, Utah	Tentative	1978 to 1982	Power Generation	St. George, UT Las Vegas, NV	Slurry Pipeline	11,500,000	Impact Statement Required In Progress
Intermountain Power Plant	Emery, Wayne, and Sevier Counties, UT	Tentative	1980 to 1985	Power Generation	Cainville, Wayne County, Utah	Conveyor and/or rail	10,000,000	Developed by Utah and Calif. Pvt. Utility Coal Acquisition & Env. Above data being acquired
Utah Power and Light Company	Escalante, Utah	Proposed	1980 to 1985	Power Generation	Mine Mouth	Conveyor	6,000,000	May be Dependent on Water Supplies and Environment Issues
Valley Camp and Routte County Dev.	Clear Creek	Tentative	1977 to 1980	Commercial	West & Midwest	Rail	1,300,000	Preliminary Mine Planning in Progress
Atlas Minerals	Wayne County	Firm	1975	Power Generation	California	Truck & Rail	600,000 to 1,000,000	
Buck Canyon Mining Co.	Grand County	Proposed	1976	Commercial		Truck	25,000	

*Also included on list of coal mines - operational
Source: Utah Department of Natural Resources

TABLE V

PROJECTED NEW DIRECT EMPLOYMENT RESULTING FROM COAL MINING

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Garfield County											
Utah Power & Light	0	0	12	84	180	456	760	973	1211	1387	1528
Kane County											
Kaiparowits	0	18	126	268	681	1135	1453	1808	2070	2280	2393
Warner Valley	0	0	0	200	300	400	400	400	400	400	400
Carbon County											
McCullough-Braztah	200	600	800	950	1000	1100	1150	1150	1150	1150	1150
Var. Other Operators	1524	1714	1969	2153	2184	2214	2216	2222	2227	2229	2280
Emery County											
Various Operators	1163	1223	1358	1683	1808	2158	2208	2258	2283	2308	2308
Grand County											
Western America Energy Company	0	100	120	120	120	120	120	120	120	120	120
Wayne County											
Intermountain Power	0	0	18	126	268	681	1135	1453	1808	2070	2080
TOTAL	2887	3655	4403	5584	6541	8264	9442	10384	11269	11944	12459

NOTE: Does not include secondary or service jobs created as a result of new jobs in basic industry. Projections are as of May, 1975. Administrative delays, technological or environmental problems, market conditions, or new projects could alter this schedule.

Source: Reports & Analysis, Utah Department of Employment Security

A REGIONAL PERSPECTIVE OF PROPOSED ENERGY PROJECTS

SOUTHEASTERN AND CENTRAL UTAH

INTRODUCTION

Southeastern and Central Utah encompass two multi-county planning districts which together include ten counties. The Southeastern Utah District comprises Carbon, Emery, Grand and San Juan Counties. The Central Utah District covers Juab, Millard, Sanpete, Sevier, Piute, and Wayne Counties. Both regional are herein treated together, since the majority of the energy activity will occur in four of the ten counties--Carbon and Emery in the Southeastern region, and Sevier and Wayne Counties in the Central region.

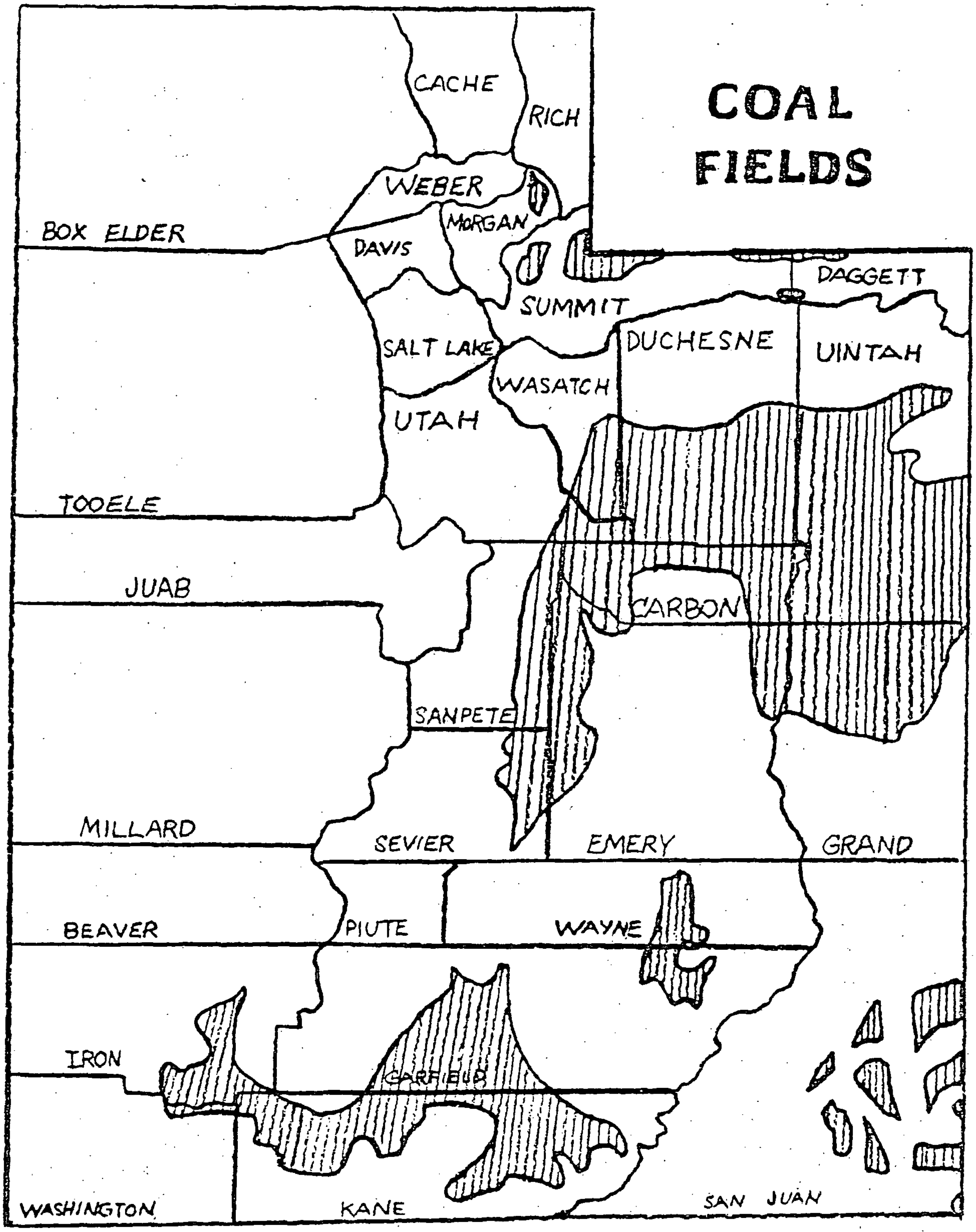
DISTRICT PROFILE

Coal

Emphasizing the future importance of coal on Utah's economy, Dr. Hellmut Doelling, Chief of Economic Geology for the Utah Geological and Mineral Survey, recently stated: "By 1985 there could be 8,000 megawatts of new generating capacity in Utah to serve both Utah and the entire southwest market. This would involve mining of some 36 million tons of coal annually, providing employment for 10,000 miners, 4,000 power plant workers, and nearly 20,000 employees for indirect facilities and service industries." These estimates compare with the total tonnage produced in 1974 of approximately 6.0 million tons requiring a work force of about 1,800 miners.

During previous decades, Utah coal was used almost exclusively for

COAL FIELDS


CACHE
RICH
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BOX ELDER
MORGAN
DAVIS
SUMMIT
DAGGETT
SALT LAKE
DUCHESNE
UINTAH
WASATCH
UTAH
TOOELE
JUAB
CARBON
SANPETE
MILLARD
SEVIER
EMERY
GRAND
BEAVER
PIUTE
WAYNE
IRON
GARFIELD
WASHINGTON
KANE
SAN JUAN

space heating, for firing railroad locomotives, for small in-state electric power plants, for manufacture of steel, and some export.

In future years it appears that coal for large in-state power generations plants will be the largest demand. There will also be large tonnages shipped to other states. Utah's coal is in demand due to its low sulphur content which minimizes pollution and its high BTU rating. Use in the steel industry will likely continue. Such new users as coal gasification and coal liquification could utilize large quantities as soon as production technology is perfected.

Coal and Other Mining Activities

Mining is the number one industry in Southeastern Utah, which includes: uranium, potash, petroleum, and natural gas. These activities are situated near the eastern edge of the Wasatch plateau, where geologic uplifting has exposed coal seams. The forested plateau is used for grazing and is also a source of water for agriculture and urban development in Castel Valley.

The Emery Company mining and processing of bituminous coal has been the largest industry, then uranium, sand and gravel, and natural gas.

Deposits of coal in beds over 30 inches thick amount to 3,477,000 tons. Much of the coal contains coal resin which has many possibilities for future development.

In 1969, seven companies were actively operating in Emery County. Although mining has been the primary industry, it has undergone the largest decline in terms of number of jobs over the last few years. Since 1955, the number of jobs associated with agriculture has declined by more than one-half.

At the present time, there are two types of coal being mined in the area. Kaiser Steel Corporation and U.S. Steel are operating mines to produce coking coal, which is used in the steel industry. U.S. Steel's production goes to its operation in Provo. Kaiser Steel produces coal for its Fontana, California steel operation and sells coking coal to other users. In 1973 this coking coal amounted to roughly half of the production and half of the work force in the industry.

The other coal mined in the area is primarily used for power plant operation. The growth projected is almost entirely related to production for power plants.

Valley Camp Coal is beginning operations in the Clear Creek-Schofield area and could employ 200 persons by 1976.

According to the Department of Employment Security, for every job initially in the coal mining industry, 3/10 of a job would be created in allied industry, which means that for every 100 jobs in the coal industry, 30 jobs would be created in the community. In seven or eight years, allied jobs would be parallel or equal to every job in the mines.

The following companies are known to be interested in Utah coal properties and major uses could develop:

Company	Location	Use
Consolidation Coal Co.	Emery & Kane Counties	Electric Power or Gasification
Peabody Coal Co.	Emery & Kane Counties	Electric Power or Gasification
El Paso Natrual Gas Co.	Kane County	Electric Power or Gasification
Sun Oil Company	Garfield	Electric Power or Gasification
Pacific Gas and Electric	Carbon & Emery Counties	Electric Power

Source: Claude P. Heiner, President, Claude P. Heiner & Co., August 14, 1974

Other companies with a demonstrated interest in Utah coal resources are the following:

Company	Location	Use
Peter Kiewit Co.	San Juan County	Electric Power or Gasification
Coastal States Energy Co.	Emery County	Electric Power
Inspiration Development Co.	Emery County	Electric Power
Western America Energy Corp.	Grand County	Electric Power

If a substantial number of these projects or others materialize, it is evident that enormous demands will be placed upon state and local governments to absorb the increase. Thus, it becomes quite apparent that such developments would cause changes in the number, character, and distribution of our population, including social, economic, political and cultural adjustments. (See Appendix for Projected Employment Resulting from Coal Mining in Utah).

Petroleum and Natural Gas Resources

Utah's petroleum and natural gas resources are located in two major fields--greater Red Wash and the Greater Aneth Field in San Juan County. There are 25 billion barrels of tar sand deposits near Glen Canyon Recreation Area, in San Juan County, and the Uintah Basin.

Presently, Utah is the fourth largest producer of uranium in the United States; however, it produces 30 percent of the total national reserve. With increasing stress being placed on the use of nuclear generation to supply electrical energy, uranium production will remain important.

In 1972 Utah produced 412,000 tons of ore containing 819 tons of high grade ore. Utah is fifth in reserve tonnage, and its ore grade is the richest in the nation. Uranium ore is mined in San Juan, Grand, Emery, and Garfield Counties.

San Juan County's major industry is uranium mining. Although mining had declined since the late 1950's, the demand for uranium is now increasing. The demand is based on defense requirements which are subject to national and international policy considerations.

Grand County will experience an increased employment activity in the exploration and development of new oil and gas fields in support of our nation's demands for energy fuels. Presently several major oil companies have been successful in their "Wild Cat" drilling for oil and gas, causing increased exploration and drilling in the Cisco and Thompson area, creating an estimated 30 to 60 new jobs during 1976.

Although petroleum production has declined, a large quantity of petroleum remains in the area. In 1965, 183 million barrels were pumped out of the Aneth oil fields; approximately 268 million barrels remain.

Tar Sands

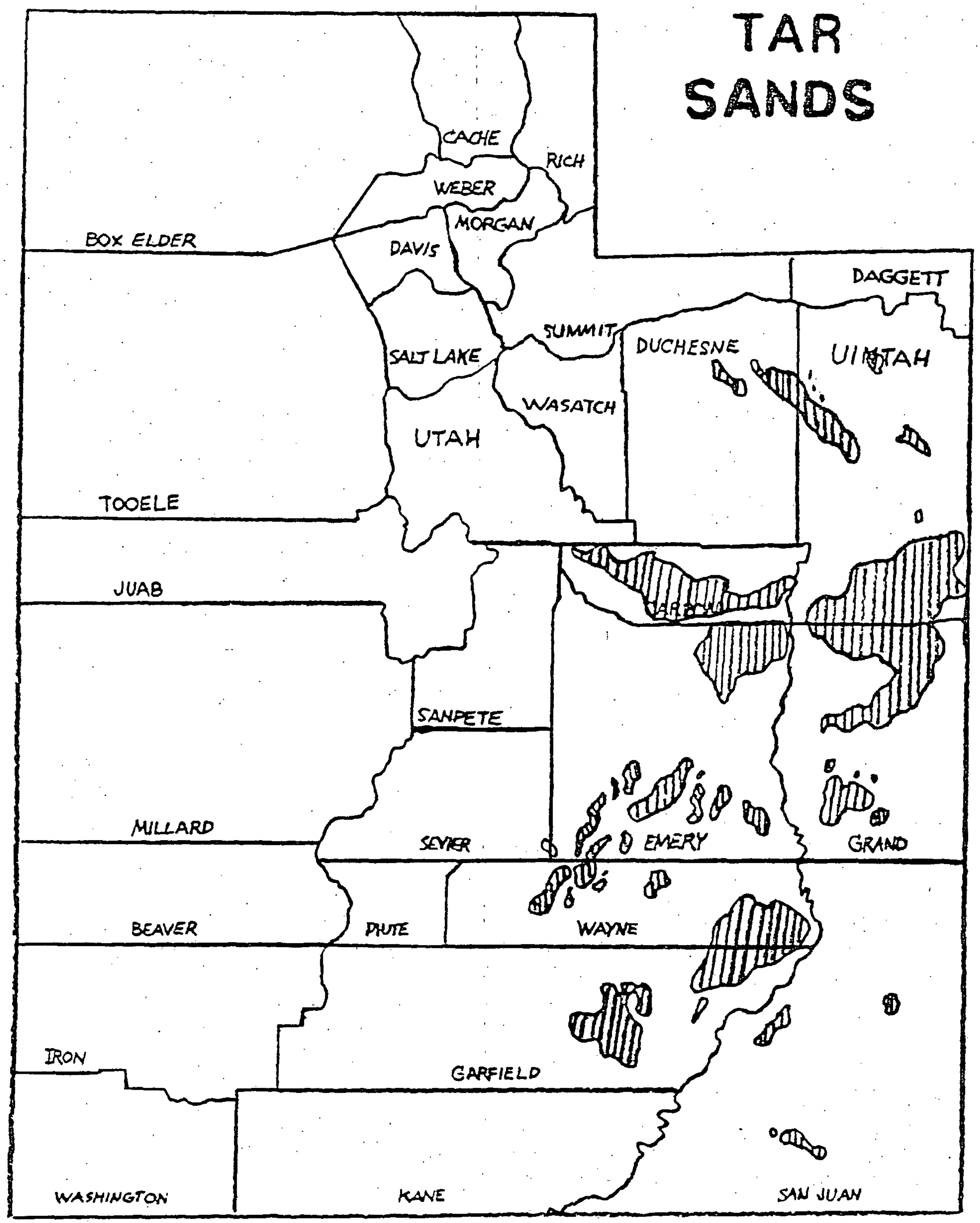
One of the most important deposits of tar sands in Utah is in Wayne and Garfield Counties with an estimated 14 billion barrels in the Tar Sands Triangle-Circle Cliffs area, located west of the confluence of the Colorado and Green Rivers. (See Map)

Tar sand is a sandstone or unconsolidated sand with heavy oil or tar occupying the spaces between the sand particles. The thick or solid tar is a hydrocarbon identical in chemical composition to conventional crude oil except for its low gravity and solid state. It may be referred to as asphaltic sand, bituminous sand, tar sand, or oil sand, as these terms are all synonymous.

Vanadium

Atlas Minerals Division has started construction at their Moab-based plant, on a new vanadium circuit, and expansion of their present uranium mill facilities is to be completed by mid-year, creating an estimated 100

TAR SANDS


CACHE
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DAGGETT
SUMMIT
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UINTAH
SALT LAKE
WASATCH
UTAH
TOOELE
JUAB
SANPETE
MILLARD
SEVIER
EMERY
GRAND
BEAVER
PIUTE
WAYNE
IRON
GARFIELD
WASHINGTON
KANE
SAN JUAN

jobs at the close of 1976. This new mill development is expected to increase both their mill capacity and ore processing capabilities. Ore bodies containing vast reserves of vanadium and uranium ores will be processed. This new development, coupled with the increased market price for copper, vanadium and uranium has caused considerable exploration and development of new copper and uranium mining properties and the reopening of smaller mining operations. This is expected to create an estimated 50 to 75 new jobs by the end of 1976.

Potash Buttes Gas and Oil has started a long range exploration and development of potash mining properties located at the 10-mile area north of Moab. During the next year, their continued exploration activity will create an estimated 18-20 new jobs. Long range development of mine and mill is expected to create an estimated 250 to 300 new jobs by 1978.

Potash consumption in the U.S. has increased 10 percent annually and consumption is anticipated to increase at a 7 percent annual rate to 1970 and at 6.3 percent per year rate from 1970 and 1980.

Potash mining and processing from reserves north of Monticello may eventually increase employment.

Water Constraints

The greatest constraint in developing the energy resources may be the availability of water. Utah has 300,000 acre feet of water unallocated under the Colorado River Compact. For development of energy resources in the upper and lower Colorado River basins, the state engineer has applications totaling more than 1,200,000 acre feet. The prototype oil shale development will require between 150,000 and 200,000 acre feet annually for development. Thus, providing water for energy may require transfers, exchanges, and in some cases reallocation of water rights. For example, farms in Carbon and Emery Counties are being purchased to gain water rights for supplying the Huntington power plant with sufficient water. How can decisions pertaining to development of resources be made in such a way as to optimize the values in land and the constraints of water supply in the arid region? Will water ultimately be diverted from the Central Utah Project for this purpose? If so, how will it be transported? These are questions that will eventually determine the scope and extent of energy development activities in this region.

Near Albion there is Navajo sandstone from which water could be mined as coal is mined. However, it must be extracted 700 feet below the coal. There are 380 million tons of coal in Southeastern Utah. Should this water be mined? Would the drilling for this water consumption be useful in terms of coal and oil shale extraction?

In Emery County the use of ground water to augment surface water does not appear to be feasible because of a vast shale formation which underlies the area retarding the flow of underground water and is also a source of salt contamination.

Water comes from the watersheds in the Wasatch Mountains to the west for irrigation and domestic use. Culinary water is taken from sources in adjacent canyons; to avoid need for treatment, Huntington has developed a spring source in Huntington Canyon, and Emery Town utilizes a well supply.

The sewage gathering system and disposal plant from Castle Gate to Wellington, which was completed several years ago, should accommodate the expected growth in the Price River drainage area for now. Probably the most serious problem in Carbon County is culinary water accumulations and distribution. Studies have been conducted and the Price River Water

Improvement District is planning to construct a water system to accommodate the anticipated growth from Castle Gate to Wellington, as soon as adequate finances can be secured. They will acquire shares of Scofield water from local farmers, set up a water treatment plant in the area of Royal and sell water to established water companies which are presently buying water from Price City to allow additional water hookups for Spring Glen, Carbonville, South Price, Wellington, and Miller Creek.

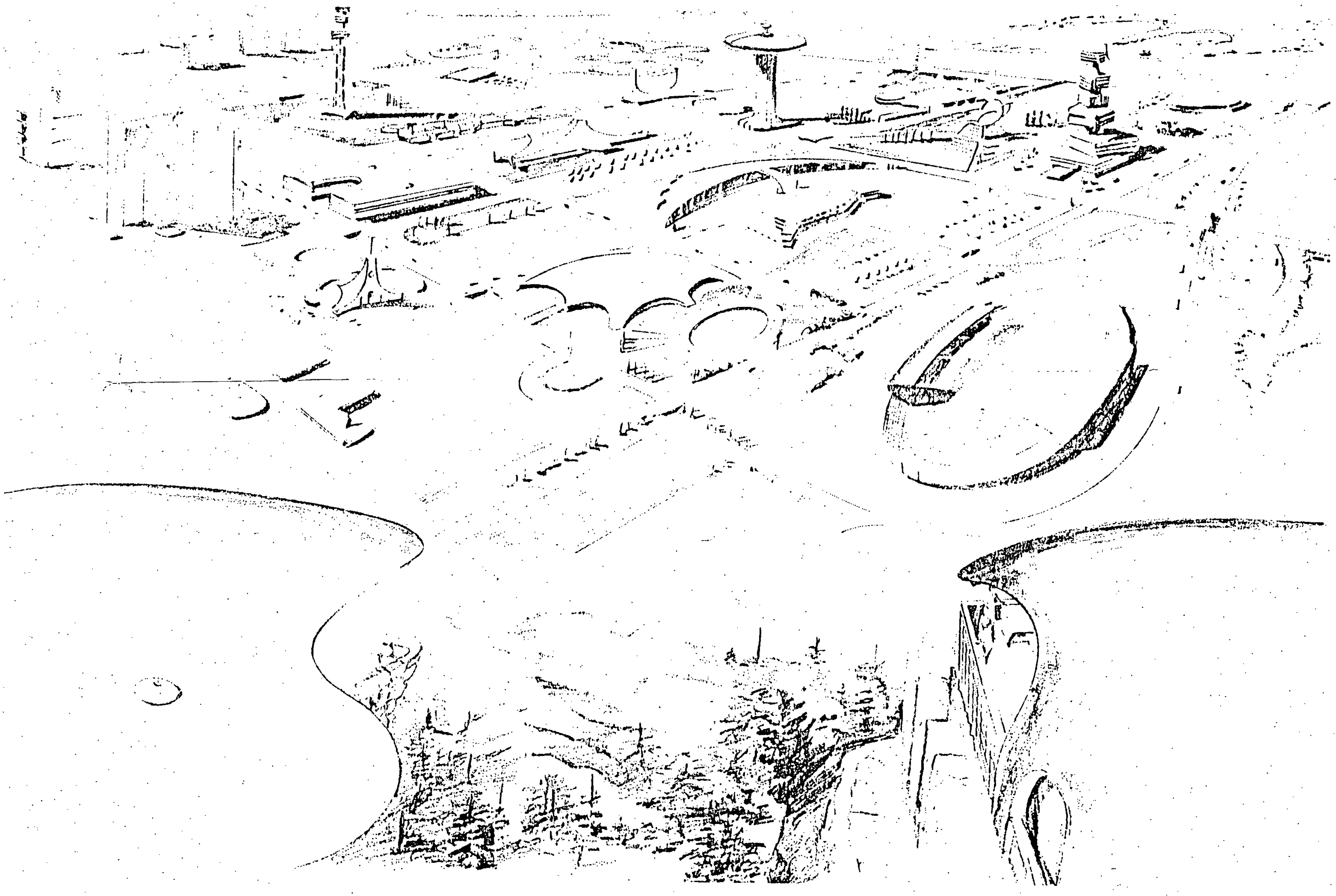
MAJOR ENERGY PROJECTS

CARBON-EMERY COUNTY COAL MINING

The nation's energy crisis has brought into focus the tremendous potential which coal has in satisfying present and future fuel needs. In 1973, the total coal production for all coal industries in Carbon and Emery Counties was approximately 4 million tons. It is expected that in the next few years coal production will increase substantially in this area.

The demand for trained miners is currently critical in the Carbon-Emery Region for two basic reasons:

(1) Approximately 30 to 40% of the present work force employed in the mines are past the UMWA retirement eligible age of 55. Further, there are few miners between the ages of 30 and 50. Consequently, the remainder of the mining labor force consists of young, inexperienced personnel. Much pre-employment training is required to meet industrial standards of the Coal Mine Safety Act of 1969 thus resulting in the quantity of inexperienced miners.



(2) A large quantity of highly trained miners will be needed to fill the foreman positions in the coal mining industry with the present production expansion. To illustrate, it is felt that about 660 new mine foremen will be required by the year 1977. To be a mine foreman, the law specifies that a miner must have four years mining experience and pass prescribed examinations. What this means is that the yearly growth of mine foremen will reduce the total number of personnel already employed in the mines, inasmuch as the foreman candidates are those people who have been employed during four prior years.

To emphasize the socio-economic impact of expanded coal production in the Carbon-Emery area, the following examples are sited. McCullough Oil (carbon fuel) Company recently signed a letter of intent with American Electric to supply them with coal. McCullough Oil has estimated that within four years the peak yearly shipment to American Electric will be 6 million tons annually within the next four years. This is a 25-year contract. To accomplish this, McCullough will have to increase its work force from 225 in 1974 to 625 in 1975 to 1,050 in 1976 to 1,275 in 1977.

McCullough is presently constructing a new coal washing plant located at Castle Gate which will handle 20,000 tons of coal per day. Castle Gate was an existing community, and the company re-located the people and their homes to another nearby town. In addition to the washery, four unit train loading facilities are planned by McCullough Oil at Castle Gate. Kaiser Steel's train loading facility can load 83 cars of 100 ton capacity in 53 minutes; therefore, these four new units will have the potential of increasing loading facilities fourfold.

Table VI on the following page illustrates the employment projections for Utah mining industry in Carbon and Emery Counties. As the chart indicates, the total employment for the year 1973 was 1,607 and the projected total for the year 1978 is 4,024. This represents a 150% increase in total employment.

It is important to note that both Carbon and Emery Counties experienced a population decrease between 1960 and 1970. Emery County population dropped 7.4% and Carbon County decreased 26% during the last decade. An area that was near a point of stagnation and decline is now beginning to boom. To illustrate, in 1973, coal production in Utah was between 325 and 340 million tons. Of this amount, 77% was produced from Carbon County and 20% from Emery County. Hence, 97% of the extracted coal in Utah for the year 1973 war produced in the Carbon-Emery area.

Between 1970-1973 the population of Carbon County had grown from 15,647 to approximately 17,000, and 8.0 percent total growth rate. Meanwhile, Emery County grew from 5,137 to 6,800 persons, a 32 percent total growth, 30 percent of which occurred between 1972-1973 (Utah Industrial Development Information System, 1974). This growth can be attributed to renewed mining activity and to power plant construction.

Projected Population Growth

The reversal from past population trends will continue due to the pressure for coal development nationally, the federal drive for

TABLE VI
A

COAL MINE EMPLOYMENT

EMERY COUNTY

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
American Coal	230	270	300	300	300	300	300	300	300	300	300
Peabody Coal	260	400	420	450	475	500	550	600	650	675	700
Browning Coal	140	140	140	140	140	140	140	140	140	140	140
U. S. Steel	300	300	325	325	325	325	325	325	325	325	325
Sun Valley Coal	5	5	5	5	5	5	5	5	5	5	5
Coop Mining	30	30	30	30	30	30	30	30	30	30	30
Utah Power & Light				250	250	500	500	500	500	500	500
Inspiration Copper Co.	Included in Utah Power and Light Co. estimates										
Mountain State Resources (Arizona Electric Power)	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
Total	965	1145	1220	1500	1525	1800	1850	1900	1950	1975	2000

TABLE VI
B

COAL MINE EMPLOYMENT

CARBON COUNTY

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Kaiser Steel Corp.	600	600	600	600	600	600	600	600	600	600	600
U. S. Fuel	187	187	187	187	187	187	187	187	187	187	200
Carbon Fuel	620	1050	1275	1500	1600	1700	1800	1900	2000	2150	2200
Plateau Mining Co.	220	330	480	600	600	600	600	600	600	600	650
Valley Camp Coal	150	200	270	300	300	300	300	300	300	300	300
California - Portland Cement	80	120	120	120	120	120	120	120	120	120	120
Swisher	44	54	59	63	74	84	86	92	97	99	100
U. S. Steel	50	50	50	50	50	50	50	50	50	50	50
Total	1956	2591	3041	3420	3531	3641	3743	3849	3954	4106	4220

energy self-sufficiency, the demand for low sulfur coal and the statements of intent and employment projections in Carbon and Emery Counties. Presently, coal mining and power generating companies are expected to bring 4,741 new mining employees to the Carbon-Emery area by 1979 (not including any associated construction employment.) Between 1973-1974, 561 new miners were employed, a 33 percent increase.

In addition to an increase in mining and power company employment, substantial increases in the service-employment sector are expected.

Population Forecast

For the Carbon-Emery area, the Utah State Department of Employment Security (USDES) has compiled employment projections by company from 1975 to 1985, which are presented in Table II-20. The population of Price may grow 23 percent during the life of the project, if 50 percent of the new population decide to reside in this population center. This is a probable settlement pattern due to Price's size and the generally high availability of goods and services.

If 20 percent of the new population settles in Castle Dale, its population could be doubled from approximately 600-1200 by 1985. Huntington could be the community chosen by up to 10 percent, and grow from 1200-1500.

TABLE VII

POPULATION FORECASTS 1973 - 1977 (Impacted)

CARBON AND EMERY COUNTIES

	CARBON	EMERY	TOTAL
1973	17,000	6,800	23,800
1974	17,600	8,400	26,000
1975	21,300	10,400	31,700
1976	24,900	12,800	37,700
1977	27,600	13,600	41,200

POPULATION FORECASTS 1973 - 1985 (Basic)

CARBON AND EMERY COUNTIES

	CARBON	EMERY	TOTAL
1973	17,000	6,800	23,800
1974	17,600	6,900	24,500
1975	18,500	7,300	25,800
1976	19,400	7,600	27,000
1977	20,300	7,800	28,100
1978	21,300	8,200	29,500
1979	22,200	8,600	30,800
1980	23,300	8,800	32,100
1981	24,400	9,300	33,700
1982	25,400	9,900	35,300
1983	26,500	10,400	36,900
1984	27,500	11,000	38,500
1985	28,500	11,500	40,000

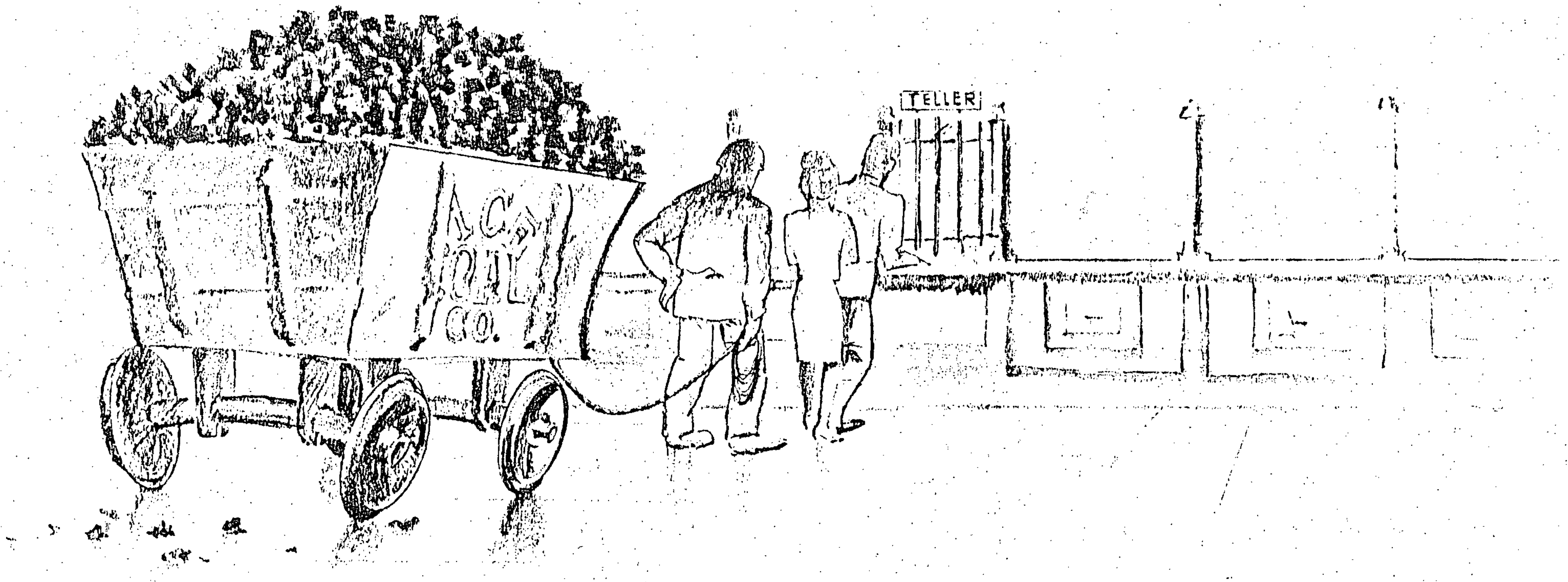
The availability of housing and utilities, however, will determine where settlement will occur and be comfortably absorbed. The current limitations in the area are on available housing and utilities, and this situation has made it difficult to determine the most probable settlement patterns. The development of water purification and treatment plants and the attraction of housing developers to the Carbon-Emery area will determine the final settlement patterns.

The new population generally will come from outside the state or the local community, will be young, and will have small children. The construction-related population will be transient, though some may become miners or for other reasons may choose to remain in the area.

If the Carbon-Emery area economic development is to proceed at the rate at which coal company figures suggest, the resulting coal-boom would require intensified planning efforts in order to accomodate that growth. Boom growth has been defined as anything above 5-7 percent, depending upon the size of the town (DRI, 1974). The small towns of the study area cannot comfortably handle accelerated growth, without adequate supplies of housing, taxes and public facilities, and without the prerequisite lead time to plan for growth or to attract outside investments. These are the additional constraints to rapid growth which should be addressed by the companies involved.

Housing

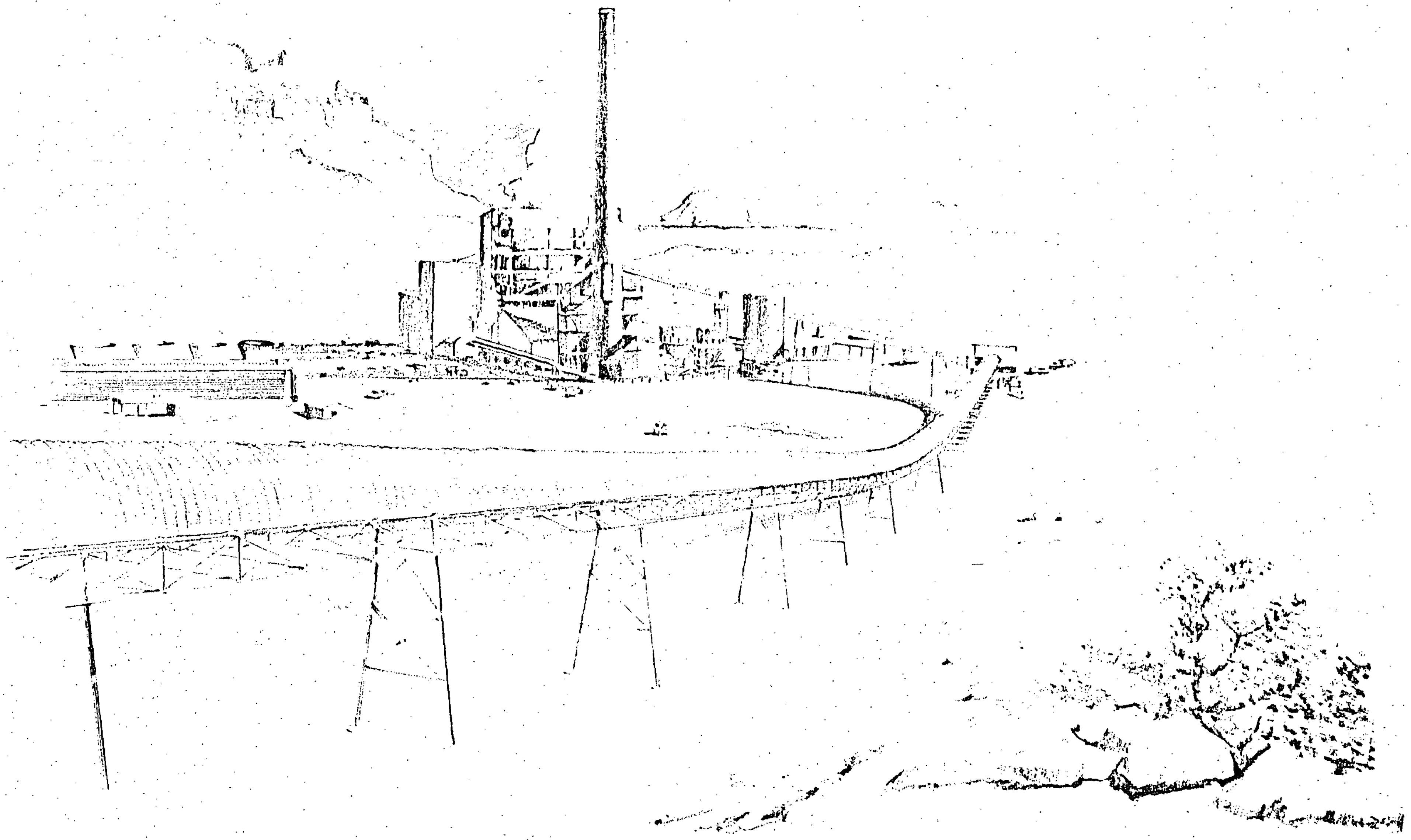
The housing situation in the Carbon-Emery area, primarily in terms of the percent of new housing, housing conditions, and availability will be adversely affected.


TELLER
A.C. COAL CO.

Between 1970 and 1974, the increase in housing demands for new construction and coal mining employees brought on a rapid decline in available housing. In September, 1974, a permanent home was virtually impossible to find at anything but inflated prices in either Price, Huntington, or Castle Dale. Prices in October were at least five times greater than the going prices of approximately five years ago.

Some rental units are available. When available, rents for one-room units average $250.00 a month. Local hotels and motels are renting rooms by the month to facilitate short-term employees. One indication of the shortage of housing was evidenced last spring when all of the motels were filled with construction employees. While mobile home parks do exist, they are in improved areas and offer little in the way of housing alternatives.

The number of available water taps, both for new housing units and trailer units, has been low in both counties. The availability of water taps has directly influenced the number of units that could be constructed, as has the increased cost in building materials. In 1973, the City of Price had 20 conventional and 15 mobile home water taps. As of November, 1974, 30 conventional and 16 mobile home taps had been pruchased in Price for the year. The number of new homes being built in Price in 1973 differed from the indicated water taps (which are usually connected and paid for last); Price records show 59 new housing units constructed with only 35 water taps for the same area. The actual number of housing starts is somewhat indeterminate.



In summary, the pattern of employment will become more industrial, the new labor force will largely be from outside the area, high wage scales will have an inflationary effect on the local economy, the availability of labor for service related jobs will decline and an increased demand for trained employees and vocational training will result from the proposed action.

PROPOSED ENERGY-RELATED DEVELOPMENTS

Several new power generating plants are presently under construction throughout the State. (See Appendix A). It is estimated that each 1,000 megawatts of generating capacity will involve: (1) 3 million tons of coal per year; (2) 15,000 acre feet of water per year; (3) 1,000 workers in coal mines, power plants and equipment maintenance and repair; (4) 2,200 to 2,400 workers total in direct and indirect employment; (5) $400 to $500 million in capital expenditures; and (6) 4,000 to 5,000 total population supported by the above employment. These requirements could vary in individual cases depending on the structure of the local economy, coal mining conditions, etc. It is apparent, however, that regardless of the actual number of plants that ultimately will be constructed, the magnitude on the local area is significant. A brief description of each of the possible plants is discussed in this section.

UTAH POWER AND LIGHT COMPANY - HUNTINGTON PLANT

The first unit of this steam electric plant was begun last year and is now in operation. The second unit is well on its way and is scheduled for completion in 1977. It consists of 430,000 kilowatts and costs approximately $96,000,000. It is referred to as the Huntington Plant because the name of the town near where it is located is Huntington in Emery County. This site was chosen because of the availability of coal and water.

Water is supplied from Huntington Creek and stored in Electric Lake, which was formed by a Utah Power and Light Dam. 1.2 million tons of coal per year is being supplied by the Peabody Coal Company for use at the plant.

The initial unit has a plant efficiency of 82/100ths pounds of coal per kilowatt hour. Pollution control equipment will be installed. It will include particulate removal, cooling towers, and ash disposal methods to prevent air and water pollution.

The two units together will generate a total of 2 million kilowatts. Each of the above units is 430,000 kilowatts. Also, each of the units uses approximately 4,000 tons of coal daily. A yearly projection requires 1.2 million tons of coal for each unit. The four units, when complete, will consume 4.8 million tons of coal annually. Placing this in perspective, total coal production in the State of Utah in 1973 was 5.2 million tons.

The labor force growth in Emery County is all directly or indirectly related to coal mining. In addition to the power plant for Utah Power and Light Company, Mountain States Resources has purchased property in Emery, Utah that may be developed for Arizona Electric Power. The employment at coal mines in Emery County is expected to increase from 1,165 in 1975 to 1,365 in 1976 and 2,000 by the year 1985.

Additionally, it is expected that Consolidated Coal Company will take over the Browning coal mine in Emery and increase production up to 500,000 tons within less than a year's time. This will mean an increase of 100 jobs, or a total of 140 jobs. It is anticipated that this coal will be shipped out of the State. It is very probably that an approximately 65-mile railroad will be built from the Price-Wellington area to this property close to Emery.

Socio - Economic Impacts

Emery County has need for enlarged and improved water and sewer systems in Huntington, Castle Dale, Orangeville and Emery. Green River and Ferron are in the process of enlarging their distribution systems at present. Cleveland, Elmo and Lawrence have recently completed new water mains from their source of water in Huntington Canyon. All of the communities need better sewage disposal systems.

UTAH POWER AND LIGHT COMPANY - EMERY PLANT

The proposed site of the Emery Electric Generation Plant encompasses approximately 2,000 acres of land located in the west-central portion of Castle Valley, near the town of Emery, Utah. Most of the land is in the Manti-La Sal National Forest, with nine-tenths of the land being privately owned and one-tenth of it being BLM-administered land.

The generating complex will include two 415 megawatt (total of 830MW) coal-fired steam-electric generating units. This plant would utilize coal from the same mine serving the existing Huntington lines currently under consideration for the Huntington Second Unit. Associated with the generating units will be environmental control systems, induced draft wet-dry cooling towers, electrical switch-yard, and office and maintenance buildings. Stacks for these two units are planned to be approximately 600 feet high.

UP&L plans the construction start for the first 415 mw unit by 1975 to meet their demand needs by 1978 or 1979. A short-term construction period of three years will be required for the first unit.

UP&L is the sole applicant. BLM is the lead federal agency for preparation of the EIS.

The company has prepared an environmental report and the Bureau of Land Management has contracted with a consultant to analyze the Company proposal. This analysis has recently been completed and the statement preparation process has been initiated. The next scheduled action is to produce the Draft of the statement by November 1975.

Coal Reserves

UP&L has applied for a lease sale of about 12,000 acres of coal land on North Horn Mountain to supply the Emery generating complex.

The coal reserves, as estimated by the Geological Survey, are tabulated below.

Estimated Coal in Place, 6 Feet or More in Thickness (Thousand Tons)

Coal Bed	Measured	Indicated	Inferred	Total
Hiawatha	13,240	27,580	13,360	54,180
Blind Canyon	16,130	18,820	------	34,950
Total	29,370	46,400	13,360	89,130

Transport

Coal from the North Horn Mountain coal lease area will be transported by a conveyor belt system from the mine portal to the generating system.

The conveyor will be approximately eight miles long, above ground, and covered. An extension of the Denver and Rio Grande Railroad into the coal fields is being considered.

Water Requirements

Consumptive water use for combined units 1 and 2 (860 mw rated capacity, 830 mw rated output capacity) is estimated to be 10,420 acre-feet per year. Consumptive water use by project component is shown below:

Component	Average Rate (gpm)	Annual Use (acre-feet)
Cooling Tower	3944.	6374.
Ash Handler System	358.	417.
Evaporative Coolers	190.	307.
Sootblowers	60.	97.
Wet Scrubbers	1930.	3120.
Coal Dust Suppression	24.5	40.
Raw Water Basin	25.	40.
Clearwell	3.	5.
Wastewater Pond	10.	16.
Total	6444.5 gpm	10,416. ac. ft.

An additional annual supply of 3,420 acre-feet may be available from Millsite Reservoir if the necessary contractual arrangements can be made. If they cannot, water will have to be conveyed either from Huntington or Cottonwood Creeks whenever additional rights can be acquired.

Economy

The amount of money forecasted to be injected into the local economy from UP&L in 1978 employment will be $17,502,000 as shown in the Table III-3.

TABLE III-3

INCOME GENERATED BY UP&L IN 1978

TYPE OF EMPLOYEE	AVERAGE INCOME	NUMBER OF EMPLOYEES	INCOME (1000)	INCOME MULTIPLIER	TOTALS (1000)
Plant	$12,500	10	$ 125	1.04	$ 130
Mine	12,500	160	2,000	1.66	3,320
Construction	10,000	1,040	10,400	1.14	11,856
Service	8,000	225	1,800	1.22	2,196
TOTALS:			$14,325		$17,502

SOURCE: From data provided by UP&L, THK and Assoc., and the U.S. Department of Commerce and the BLM.

Overall Impact

The counties of Carbon and Emery will be impacted by the proposed plant at Emery because of the new employees and their families who will move into the area. The proposed action will employ 1,210 persons at peak construction in 1978, and will cause an immigration of approximately 3,788 persons to the communities of Price in Carbon County, and Huntington, Castle Dale, Ferron, Orangeville, and Emery in Emery County. The first three communities will receive the major influx, as much as 80-90 percent, and the remainder will settle in the latter three communities, which are generally smaller and offer fewer services . A few may settle outside the communities depending upon the enforcement of county land use controls which requires that larger tracts per unit, 3-5 acres, be developed outside local communities.

INTERMOUNTAIN POWER PROJECT

The Intermountain Power Project is a joint venture by a number of power companies and municipalities to design and construct a coal-fired electric power generating plant to be located in Wayne County. Since this is a sparsely populated area, it is probable that a new community would have to be constructed. The participating members of the combine are the Intermountain Consumers Power Association (26 municipalities in Utah and a consortium of cities in California).

The size of the power plant is intended to be 3,000 megawatts, the same size as Kaiparowits, however, the size may be altered as the results of feasibility studies become available. The proposed schedule for development is shown in Table below.

Phase	Schedule
Feasibility study begun by City of Los Angeles	March 1974
Receipt of company proposal	October 1975
Feasibility study to be completed	December 1975
Begin construction of Unit #1	January 1978
Unit #1 Operational	June 1981 or 1982

Subsequent units will become operational at twelve to eighteen month intervals thereafter.

Total cost of the project is estimated to be $1.5 billion; however, if the present rate of inflation continues the cost could easily be in the $2.0 billion range.

The Salt Wash area of Wayne County is the preferred plant site at this time. It is approximately 10 miles north of the town of Caineville. State Highway #24 going southeast from Loa, Bicknell, and Torrey passes through Caineville approximately 16 miles west of Hanksville.

It is estimated that 2,500 workers will be required to construct the plant; 1,000 additional construction workers to open and develop coal mines; 3,000 coal miner; and 400 plant operators.

Coal will be obtained a few miles north of the plant site in Emery County, and would be transported either by rail or conveyor belt to the plant. However, the exact coal source has not yet been confirmed.

The plant will require approximately 50,000 acre feet of water, mostly for cooling. Water would be obtained from both surface and underground sources. Test wells have been driven in the area with promising results. It is also proposed to construct a dam on the Fremont River about six miles south of Caineville. The dam would impound 50,000 acre feet of water which would be used jointly by the power plant, agriculture, and recreation.

A 1,700 foot test water well and two small observation wells are presently being drilled for IPP near its study site in south central Utah. The wells will allow project engineers to gain more information about the water bearing properties of the rock and rock fracture systems of the area for the feasibility study. There is the possibility of additional quantities of irrigation water to be available for agriculture as a result of the construction of water storage facilities that could jointly serve the project and local users.

Economic Impact

Economic benefits would accrue to the area from the approximately 450 employees required to staff the completed power plant. Coal mining operations in support of the project will also provide a substantial increase to the region's economy, employing approximately 200 people.

PROJECTED NEW DIRECT EMPLOYMENT RESULTING FROM THE INTERMOUNTAIN POWER PROJECT

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
INTERMOUNTAIN POWER PROJECT	0	0	250	875	1586	2290	2534	2266	1919	1274	691
Plant Construction	0	0	250	875	1586	2290	2534	2141	1562	810	181
Plant Operation								125	357	464	510
Coal Mine	NA										
Water Development	NA										

NOTE: Does not include secondary or service jobs created as a result of new jobs in basic industry. Projections are as of May 1975. Administrative delays, technological or environmental problems, market conditions, or new projects could alter this schedule.

Source: Reports & Analysis, Utah Department of Employment Security

Environmental Considerations

Numerous field programs have been initiated which involve studies of various environmental issues. An estimated $1 million has been allocated for the environmental studies. It is a particularly sensitive project also because of its close proximity to Capital Reef National Park. Another problem concerns securing permission from the federal government to use the water in the Fremont River even though it is part of Utah's Upper Colorado River entitlement. A positive factor is that it is estimated the coal required to generate 3,000 megawatts of power would save 35 million barrels of oil annually.

Westinghouse Environmental System Department of Pittsburgh, Pa., is now engaged in preparing an environmental impact study of the area. The study includes a thorough evaluation of existing conditions and what affects the plant, transmission lines, coal mine, and other features would have upon the physical, social, and economic conditions in the area. The Bureau of Land Management is working with both Westinghouse and the city of Los Angeles in the development of this report.

Studies relating to the population increase, housing and community facilities have not yet been completed.

SOUTHERN UTAH

INTRODUCTION

The southern portion of the state is experiencing an unprecedented demand for its energy related sources resulting from the nation's recent impending problems in energy resources. This area is characterized by undeveloped natural resources and sparse population.

Most of the land in both Kane and Garfield counties, in which many of the proposed energy developments lie, is owned by the federal government. To illustrate, less than 10 percent of Kane County and approximately 5 percent of Garfield County are privately owned. In addition, both Kane and Garfield Counties experienced a decrease in population over the last decade. Between 1960 and 1970, Kane and Garfield Counties had a population decrease of 9.2 percent and 11 percent respectively. The 1970 census data indicates the population of Kane County at 2,427 and Garfield County at 3,157.

The purpose of this section of the report is twofold: (1) to discuss the proposed energy related developments in the area; and (2) to explain the anticipated socio-economic impacts resulting from the energy developments.

DISTRICT PROFILE

KAIPAROWITS POWER PROJECT

The Kaiparowits Power Project is a proposed coal-fired electric generating station consisting of four 750 megawatt units for a combined name plate rating of 3,000 megawatts. The plant will utilize coal mined from the Kaiparowits Plateau, which is about 8 miles northeast of Nipple Bench and approximately 7 miles southeast of Four Mile Bench. (see project area map). The coal will be mined underground; consequently, strip or other surface mining is not planned at this time. The coal will be transported by closed conveyor. The average coal to be utilized in the Kaiparowits Power Project contains about one-half of one percent sulfur. Much of the eastern coal currently being used for electric generation contains as much as five percent sulfur or ten times more sulfur. The Kaiparowits Project will burn about nine million tons of coal a year or a total of approximately 315 million tons during the expected 35-year life of the plant.

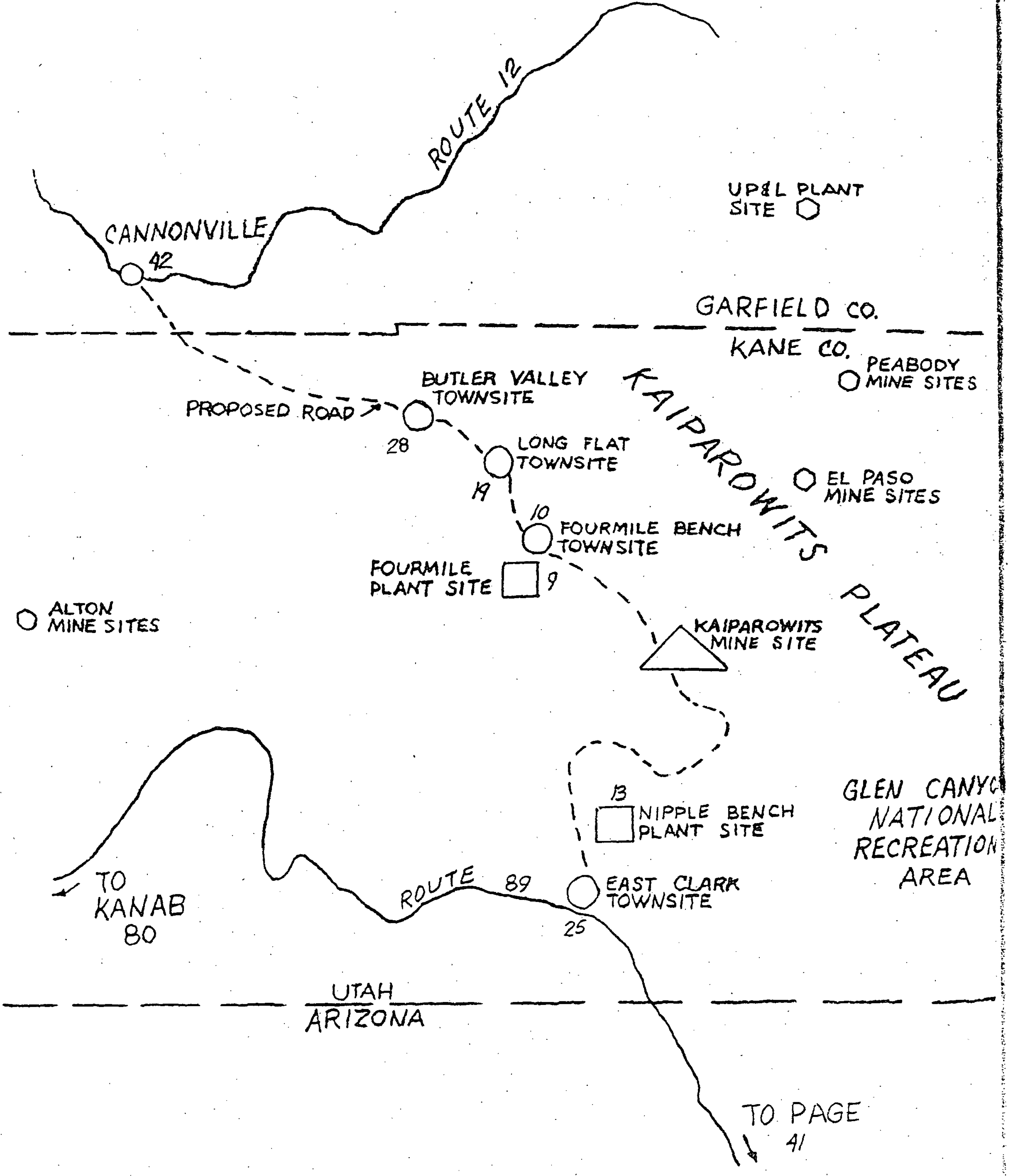
The primary participants in the power project include the following utility companies:

1. Southern California Edison Company
2. San Diego Gas and Electric Company
3. Arizona Public Service Company
4. Salt River Project

Kaiser Engineers, Division of Kaiser Industries Corporation, will be responsible for designing and constructing the coal mines. A new subsidiary of Kaiser Industries Corporation will operate the mines.

Site alternatives began in 1964, and during this 11-year period, nineteen sites on the Kaiparowits Plateau have been identified and investigated. Currently, two sites, Nipple Bench and Four Mile Bench, are under

PROJECT AREA



consideration for ultimate selection. Nipple Bench site is located 10 miles north of the Utah-Arizona border, and approximately 15 miles from Glen Canyon Dam. Four Mile Bench is about 15 miles north of Nipple Bench.

The Governor's Kaiparowits Planning and Development Advisory Council passed a resolution indicating Nipple Bench as the preferred site for two reasons: (1) reduced plant visibility from the city of Page, Wahweap Marina, and Lake Powell: and (2) improved meteorological conditions necessary for proper dispersion of stack emissions due to the higher elevation and unobstructed terrain surrounding the site.

A major criterion in the plant site selection among the alternative sites is visual exposure from the recreational areas. It is envisioned that the plant facilities will be situated so that visual exposure will be minimized through utilization of topographic features of the land. Moreover, access roads, waterlines, and transmission lines will run through existing cooridors to decrease disruption of the natural landscape.

The water for plant cooling will be drawn from Lake Powell. To minimize the effect on the users of the lake and recreation areas, the water intake devices will be below the lake. An agreement with the United States Department of the Interior for the withdrawal of the water from Lake Powell has been consummated. The lake waters will be recycled at the power station through evaporative cooling towers. The water which cannot be recycled will be contained in watertight ponds where it will be evaporated by the sun.

Development Impact

The socio-economic impact generated from the Kaiparowits Power Project will be phenomenal. It is anticipated that a new town of 15,000 must be constructed to house the construction and operation personnel involved with the Kaiparowits Project. This will be a herculean task to plan and develop a viable new community with necessary amenities. Facilities for construction personnel must be ready for occupancy at the time of the construction of the plant. The target date for plant construction is late 1975.

It is important to note that the new town is intended to be more than merely a "company town." Studies are currently being undertaken to determine the feasibility and marketability of various new town sites. The new town will require approximately 2100 acres of land. Of this amount, 1,100 acres will probably be developed for public and recreational purposes.

The following is a tentative breakdown of the land use for the new town:

1. Open space recreation such as golf courses, parks, baseball diamonds, and swimming pools---240 acres.
2. Sanitary land fill located outside of the urban development---200 acres.
3. Sewer and water disposal areas---50 acres.
4. Public shcools including elementary, junior high, and high school---105 acres.
5. Airport---400 acres.
6. Streets---107 acres.

TABLE I summarizes the land use for the new town.

TABLE I

NEW TOWN REQUIREMENTS

Land Use	Acres	% of Total
Public Facilities (Hospital, Civic Center, etc.)	40	2
Schools	105	5
Residential	856	41
Commercial	19	1
Industrial	92	4
Subtotal	1,112	53

Land Use	Acres	% of Total
Streets	107	5
Water and Sewer Treatment	50	2
Sanitary Landfill	200	10
Subtotal	357	17
Parks and Recreation	240	11
Airport	400	19
Subtotal	640	30
TOTAL	2,109	100

TABLE II indicates the expected and optimistic outlook of population, employment, and housing needs for the new town in 1986.

TABLE II

POPULATION, EMPLOYMENT, AND HOUSING NEEDS IN 1986
EXPECTED OUTLOOK COMPARISON

Parameter	Expected Outlook	Optimistic Outlook
Operations Employment	2,090	2,090
Indirect Employment	4,180	4,598
Total Population	13,704	15,234
Conventional Housing	3,209	3,759
Mobile Homes	1,375	1,375
Total Housing	4,584	5,134

Source: Brigham Young University Center for Business and Economic Research

TABLE III provides a breakdown by job title of the expected growth of coal-mining related employment for the Kaiparowits Power Project:

TABLE III

ANTICIPATED COAL-MINING YEARLY GROWTH FOR THE KAIPAROWITS POWER PROJECT

Job Title	FY-76	FY-77	FY-78	FY-79	Total
Mechanics and Electricians	50	85	127	128	390
Foremen and Fireboss	50	180	135	135	500
Entry Occupations		25	43	37	105
Operators, Underground		120	220	145	485
Operators, Outside		20	20	10	50
Other Skilled Occupations		70	55	45	170
TOTAL	100	500	600	500	11,700

TABLE IV illustrates the forecasts for mobile homes and conventional homes based upon an optimistic outlook.

TABLE IV

FORECASTS OF HOUSING UNIT REQUIREMENTS
OPTIMISTIC OUTLOOK

Year	Mobile Home	Conventional Home	Total
1974	11		11
1975	338		338
1976	992	297	1,289
1977	1,663	710	2,378
1978	2,162	1,212	3,374
1979	2,401	1,798	4,199
1980	2,254	2,434	4,638
1981	2,107	2,607	4,714
1982	1,960	2,766	4,726
1983	1,813	2,885	4,698
1984	1,666	3,311	4,977
1985	1,519	3,581	5,100
1986	1,375	3,759	5,134

Source: Brigham Young University Center for Business and Economic Research Estimates.

TABLE V on the following page is a summary of population, housing, school enrollment, and retail sales impact resulting from the Kaiparowits new town, assuming that Four Mile Bench is selected as the plant site.

TABLE V

SUMMARY OF POPULATION, HOUSING, SCHOOL ENROLLMENT AND RETAIL SALES IMPACT OF NEW TOWN (INCREMENTAL INCREASE, ASSUMING FOUR MILE BENCH PLANT)

	Year			
	1975	1980	1985	1995
Population Impact[1/]				
New Town	311	10,531	11,524	14,009
Glen Canyon City, Church Wells, and Vicinity	83	521	409	629
Other Kane County	25	130	135	165
Bryce Valley	58	654	683	838
Other Garfield County	20	130	135	165
Subtotal--Utah	497	11,966	12,886	15,846
Arizona	142	1,085	795	941
Total Population	639	13,051	13,681	16,787
Household Impact				
New Town	173	3,397	3,492	4,245
Glen Canyon City, Church Wells, and Vicinity	46	168	124	203
Other Kane County	14	42	41	50
Bryce Valley	32	211	207	254
Other Garfield County	11	42	41	50
Subtotal--Utah	276	3,860	3,905	4,802
Arizona	79	350	241	285
Total Households	355	4,210	4,146	5,087
School Enrollment Impact				
Kane County	34	2,827	3,071	3,377
Garfield County	9	198	209	229
Arizona	31	273	201	214
Total School Enrollment	74	3,298	3,481	3,820
Retail Sales Impact[2/]				
New Town	$ ----	$24,883	$17,581	$24,642
Other Kane County	149	2,556	1,686	1,831
Subtotal--Kane County	$ 149	$27,439	$19,267	$26,473
Garfield County	349	850	670	740
Subtotal--Utah	$ 498	$28,289	$19,937	$27,213
Arizona	1,813	5,402	2,641	2,451
Out of Area	2,367	13,912	8,205	7,646
Total Retail Sales	$4,678	$47,603	$30,783	$37,310

[1/] While average household size would no doubt be slightly larger in some communities than in others (i.e., higher in Bryce Valley, lower in Arizona), no attempt has been made to estimate -- i.e., same average household sizes used for all communities.

[2/] In constant 1975 dollars.

Source: Development Economics, Inc.

An important factor to consider in planning housing for the new town is the ability of individuals working at the Kaiparowits Plant to afford the housing units supplied. To illustrate, lending institutions throughout the United States currently tend not to lend more than 2.5 times the amount of an individual's annual income for mortgage loans. Accordingly, a plant worker earning $10,000 a year could afford a house costing about $25,000.

Three alternative town sites are currently being considered: (1) Long Flat, (2) Four Mile Bench; and (3) East Clark Bench. Four Mile Bench remains a viable new town site only if the plant site is located at some area other than the Four Mile Bench. The East Clark Bench site is the least desirable for several reasons: (1) it is the most desolate of the three sites with frequent winds; (2) it lacks natural esthetic surroundings for landscaping; (3) of the three sites, it requires the greatest travel time for workers commuting to and from work; and (4) it has the hottest summers and coldest winters. Thus, the two northern sites, Long Flat and Four Mile Bench, appear to have a better potential for adequate living conditions.

In addition, a primary reason for Long Flat or Four Mile Bench being selected over East Clark Bench as the new town site is the economic effect the new town could have on Utah's economy. A new town located at either Long Flat or Four Mile Bench would have the potential of becoming a regional shopping center. However, East Clark Bench is a smaller town site and according to an advanced new town feasibility study, "a town site at East Clark Bench would preclude supporting regional shopping facilities, a larger portion of the residents of East Clark Bench and other towns would do their shopping in other areas of Utah and Arizona (Flagstaff)."

Moreover, if the new town were located on Four Mile Bench or Long Flat, then access from the north would be necessary. This would be most advantageous to Garfield, Piute, and Sevier Counties, as well as the entire State of Utah.

The coal for the Kaiparowits Power Project is in Utah. The water to be utilized for the plant cooling operation is in the State of Utah. Any pollution from the plant would likely be in Utah. Also, Utah will have to deal with and provide for the tremendous influx of people. Consequently, public officials feel strongly that the future new town site be located on either Four Mile Bench or Long Flat to maximize the economic benefits to Utah and not Arizona.

ALUNITE MINE AND PROCESSING PLANT DEVELOPMENT

The location of the proposed alunite mine processing is situated in western Beaver County, Utah, in the southern Wah Wah Mountain Range, approximately 60 miles northwest of Cedar City, and 30 miles southwest of Milford. It is projected that 3,660,000 tons per year of alunite ore will be mined and transported to adjacent processing plants where alumina will be produced as the primary product. The anticipated capacity of the processing plant is 500,000 tons per year of alumina, 370,000 tons per year of potassium sulfate, and 448,000 tons per year of sulfuric acid.

In addition to the mining and processing complex, an extensive infrastructure, including an electric power generation plant with sewage treatment facilities, transportation and utility systems, and administration buildings are also planned. The target date for beginning construction is the latter part of 1975.

During the construction phase of the Alunite Project, a full range of professional, skilled, semi-skilled, and unskilled employees are required. TABLE VI provides an estimated labor force breakdown during the construction phase.

TABLE VI

ALUNITE PROJECT

MANPOWER SUMMARY FOR CONSTRUCTION PHASE

Category	Number	Percent of Total**
Pipefitters	360	30
Laborers	120	10
Operating Engineers	108	9
Carpenters	108	9
Boilermakers	180	15
Ironworkers	108	9
Millwrights	108	9
Electricians	108	9
	1,200*	100

* Total number of construction workers will vary throughout the construction period, but will average about 1200 employees.

** The percentage of each category of worker will vary with the stage of construction and is therefore shown only to provide an approximation of the average need.

It is expected that approximately 1000 employees of all job categories, professional skilled, and unskilled, will be required for full operation. TABLE VII shows the number of employees needed during the operations phase.

TABLE VII

ALUNITE PROJECT

SUMMARY OF MANPOWER REQUIREMENTS DURING THE OPERATIONAL PHASE

Area	No. of Employees
General Management	76
Mining	83
Crushing and Grinding	99
Roasting	40
Leaching and Separation	63
Potassium Sulfate Plant	40
Sulfuric Acid Plant	22
Phosphate Fertilizer Plant	121
Alumina Plant	259
Power Plant	41
Unskilled and Semi-skilled Laborers	150
TOTAL	994

Table VIII illustrates the time schedule for both construction and operating employment.

TABLE VIII

DIRECT EMPLOYMENT, CONSTRUCTION AND OPERATING, 1975-1978

Year	Quarter	Direct Employment		
		Construction	Operating	Total
1975	IV	150	--	150
1976	I	450	--	450
	II	900	--	900
	III	1,250	--	1,250
	IV	1,250	--	1,250
1977	I	1,800	80	1,880
	II	1,800	150	1,950
	III	1,700	230	1,930
	IV	1,200	560	1,760
1978	I	400	800	1,200
	II	-0-	1,000	1,000
	III	-0-	1,000	1,000
	IV	-0-	1,000	1,000

Source: Earth Sciences, Inc.

As previously mentioned, construction activity is tentatively scheduled to begin in the fourth quarter of 1975 with a work force of 150. In the first half of 1977, the labor force will peak at a level of 1800, after which it will decline to zero in the second quarter of 1978 when construction will essentially be complete. Permanent employment in the plant will tentatively begin in the first quarter of 1977 with a work force of 80. In early 1978, the number of operating or permanent personnel will increase steadily reaching an initial capacity level of about 1,000. The combined labor force will reach a peak of approximately 1,950 in the second quarter of 1977.

Direct employment at the mine represents only part of the total employment impact in the project region. Table IX provides an estimated indirect employment projection based upon operating employment multipliers and construction employment multipliers. Table X provides yearly totals of direct and indirect employment. As shown in Table X, the sum of direct and indirect employment at the end of 1978 is 2,604. It is assumed that there will be a one quarter lag in the response of indirect employment to a change in direct employment.

As a result of the large employment impact, there will also be a substantial increase in population. Figure XI illustrates the expected population impacts. These population impacts are broken out into three components: (1) the impacts associated with construction; (2) impacts generated from operations; and (3) impacts perpetuated from indirect employment change. The first population impact will be incurred during the fourth quarter of 1975 when construction begins. it will increase to a level of approximately 7,000 in the third quarter of 1978.

TABLE IX

INDIRECT EMPLOYMENT IMPACTS, 1975-1978

		Indirect Employment[a]		
Year	Quarter	Construction based[b]	Construction based[c]	Total
1975	IV	--	--	--
1976	I	45	--	45
	II	135	--	135
	III	270	--	270
	IV	375	--	375
1977	I	375	--	375
	II	540	128	668
	III	540	241	781
	IV	510	369	879
1978	I	360	898	1,258
	II	120	1,283	1,403
	III	--	1,604	1,604
	IV	--	1,604	1,604

[a] It is assumed that the response of indirect employment lags the change in direct employment by one quarter.

[b] Based on a total employment multiplier for construction employment of 1.3

[c] Based on a total employment multiplier for operating employment of 2.604.

SOURCE: Earth Science Inc.

TABLE X

DIRECT, INDIRECT AND TOTAL EMPLOYMENT IMPACTS, 1975-1978

Year	Quarter	Direct Employment	Indirect Employment	Total Employment
1975	IV	150	--	150
1976	I	450	45	495
	II	900	135	1,035
	III	1,250	270	1,520
	IV	1,250	375	1,625
1977	I	1,880	375	2,255
	II	1,950	668	2,618
	III	1,930	781	2,711
	IV	1,760	879	2,639
1978	I	1,200	1,258	2,458
	II	1,000	1,403	2,403
	III	1,000	1,604	2,604
	IV	1,000	1,604	2,604

SOURCE: Earth Science Inc.

TABLE XI

POPULATION IMPACTS, 1975-1978

		Population Impacts			
Year	Quarter	Construction[a]	Operating[b]	Indirect[b]	Total
1975	IV	270	--	--	270
1976	I	810		120	930
	II	1,620		321	1,981
	III	2,250	--	722	2,972
	IV	2,250	--	1,003	3,253
1977	I	3,240	214	1,003	4,457
	II	3,240	401	1,787	5,428
	III	3,060	615	2,089	5,764
	IV	2,160	1,140	3,365	6,225
1978	I	720	2,140	3,753	6,428
	II	--	2,675	3,753	6,428
	III	--	2,675	4,291	6,966
	IV	--	2,675	4,291	6,966

---

[a] Based on a population/construction employment multiplier of 1.8.

[b] Based on a population/employment multiplier of 2.68.

SOURCE: Earth Science Inc.

It is anticipated that employee housing will be made available in existing nearby communities. City and county officials are well aware of this fact and consequently, they are planning to upgrade their public services to ameliorate potential future pressures. As a result, there are no plans for establishing a permanent town site or adjacent to the project area. However, during full operation of the project, more new communities will probably have to be established at a future time. One possible site is the existing town of Lund, which is virtually unoccupied.

Consideration should be given to the desire of the people who will be working permanently at the mine and plant complex. Possibly the people working the project may desire to move closer to their work since driving times will be lengthy from all existing population centers.

ALTON COAL MINING PROJECT

A proposal has been made by the Nevada Power Company of Las Vegas, Nevada and the city of St. George in Utah, to work jointly in developing a power project for these two areas. The Nevada Company is proposing approximately a 2,000 megawatt plant to be located near Las Vegas. A 500 megawatt plant is being planned in Warner Valley east of St. George City. The power generating operation for these two proposed projects calls for the construction of a slurry pipeline from the Alton Coal Fields. It is proposed that the coal will be strip mined in the Alton area and that water will be added to the coal in the form of a slurry to carry it from the coal fields to the power operation.

The Alton mining operation will take place approximately 8 to 10 miles east of Glendale and some 6 to 8 miles south of the community of Alton in Kane County. (See project area map).

Developers anticipate that at peak construction of the Alton Slurry Line, 450 construction workers will be needed. Once the construction of the slurry line is completed, then approximately 450 employees will be engaged in the mine operation. Thus, a relatively constant employment force from the construction stage to full operation is generated.

The Alton mining operation will take place in close proximity of existing communities. Consequently, the impacted communities will have to expand their present water and sewer facilities in order to accommodate the immediate growth of the area. However, this project will not have as great a "people impact" as the Kaiparowits Project.

In addition to the mining operation, it is anticipated that secondary enterprises will be developed to accommodate and support those involved in the mining operation. Accordingly, about 900 new jobs and subsequently 900 new families are projected to migrate into the Long Valley area in the next 2 to 5 years. An increase in 900 families implies a population increase of approximately 3,000 persons. This population increase alone would more than double the present population of Kane County. Most of the new families are expected to locate in the areas between Mt. Carmel Junction and Alton.

Some discussion has evolved around the possibility of creating a new town in the Alton area to support the energy development projection. However, it would appear that the development of a new town at this time would not be necessary. The existing communities of Glendale, Orderville, and Mt. Carmel could absorb the additional population influx without additional urban expansion. Furthermore, the open and agricultural lands that exist in Long Valley could still remain in tact.

EL PASO NATURAL GAS COMPANY COAL GASIFICATION PROJECT

Extensive coal leases on and around the Four Mile Bench area in Kane County are held by El Paso Natural Gas Company. Recently, exploration by El Paso has been undertaken to determine the extent of coal available in the area. As mentioned in the introduction of this section, early explorations indicated that there is a rich supply of coal on the north slope of the Kaiparowits Plateau.

Company officials have stated that preliminary plans have been formulated to remove the coal from the area by mining and shipping the product to other markets for gasification or use in steam generating power plants. Further, some serious consideration has been given to the idea of extending a railroad line southward from Marysvale, Utah, some 100 miles north of the Kaiparowits area for the purpose of hauling the coal by train.

Presently there is a permanent crew of about 35 men involved with this operation. A few of the workers live on the Kaiparowits Plateau while the other workers come to the site on a daily basis.

It is conceivable that several hundred miners could become permanently employed if an extensive mining operation were undertaken within the area. However, due to the uncertainties involved, it would not be realistic at this time to attempt to determine whether Bryce Valley area would be capable of supporting the proposed El Paso Gas Company Project. When additional information is available indicating the extent of the El Paso coal reserves and until more definitive planning has taken place relative to their disposition, the socio-economic impacts are difficult to assess.

Depending on the size of the project, the Bryce Valley area should be able to accommodate this development. If Bryce Valley is not able to cope with the influx of workers, then Butler Valley should be considered as an alternative site for urban development.

TENNECO OIL DEVELOPMENT

Tenneco Oil Company currently has about 35 oil wells in operation in Garfield County. Company officials have indicated that these wells will continue to be in operation for at least another 10 years. Also, during this time, other wells will no doubt be drilled in this area. About 50,000 barrels a day of crude oil are presently being produced from the 35 wells. Tenneco Company does not anticipate the construction of any processing facility in the county. Accordingly, they ship their oil by truck and possibly in the future they plan to ship by pipeline to refining facilities.

Tenneco Oil Company currently is not a large employer. In the event that oil exploration is successful, it is not anticipated that there would be a large increase in permanent employment in the area.

Because Tenneco Company is the largest single customer of GarKane Power for electrical power service for their well sites, Tenneco could be considered to be an indirect employer. With increases in oil field operation, additional increases in the GarKane work force would no doubt result.

UINTAH BASIN

INTRODUCTION

Utah's Uintah Basin consists of Daggett, Duchesne, and Uintah Counties.

The current population of the Uintah Basin according to estimates made in 1973 is 29,400 with 700 in Daggett County, 13,800 in Duchesne County and 14,900 in Uintah County.

DISTRICT PROFILE

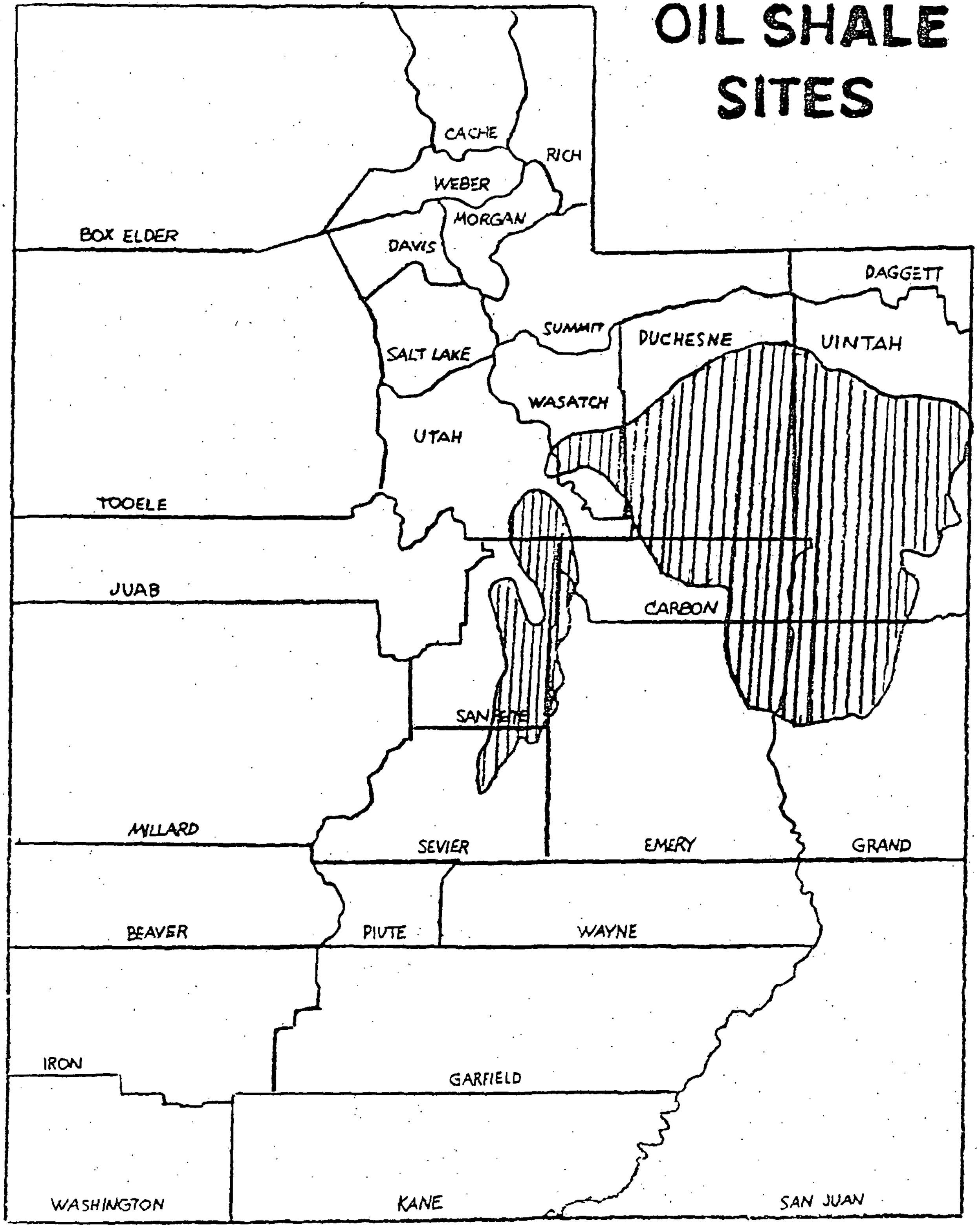
Oil Shale

The greatest possibilities for energy development in the Uintah Basin is keyed to oil shale. Total oil in Basin shale is estimated to be 900-1,300 billion barrels. (Present oil consumption in the U. S. is less than 10 billion barrels per year.)

The "richest" oil shale is located in the southern half of Uintah County. These reserves are estimated to be about 25 feet or more thick, and contain at least 25 gallons of crude oil per ton of oil bearing rock. The entire oil shale area covers about 1,200 square miles and is estimated to contain 90-115 billion barrels of crude oil. For location of areas of potential oil shale development, see Figure 1.

The Bureau of Land Mangement (BLM) has set aside certain of its lands which are underlaid by "rich" oil shale. The Bureau has proposed a prototype oil shale leasing program which involves two sites in Utah.

OIL SHALE SITES



Sites have also been proposed in other states. Recently, the Colorado lands were leased by oil companies for the prototype leasing program as outlined by BLM. The two Utah sites are adjacent to each other along the White River. Together they cover an area of 10,240 acres. These sites lend themselves to either the in-situ process (which involves the processing of shale while it is still in the ground) or conventional mining methods. The overburden of the sites are such that strip mining is also feasible.

Other natural resources in the Uintah Basin include coal in southern Uintah County and western Duchesne County, phosphate in Daggett County, oil in Duchesne and Uintah Counties, and gilsonite in Uintah County.

Plans to develop oil shale are centered primarily in the southeastern part of the Basin in three different areas by three different groups. The largest oil shale project will be developed along the White River by three oil companies which have formed the White River Oil Shale Corporation. The Corporation will lease tracts of land from the Bureau of Land Management. The refining would be done in a retort using what is known as the Paraho Process. This process produces oil and leaves a rock residue called "spent shale." The refinery would be built near the shale tracts. Petroleum, electricity and nitrogen rich fertilizer will be produced. The entire operation will require perhaps 2,000 employees and will cost about $1 billion. A new town may be built near the oil shale project to house workers and employees of supporting businesses and industries. A dam may be built on the White River to provide water for the project and the town.

A second major oil shale project contemplated is on state land near the Colorado border and will be developed by the American Gilsonite

Company. Oil will be produced from the shale by what is called the "in-situ" process. "The in-situ process involves pumping hot gasses into the ground causing the shale to fracture and melting out the oil. Once the oil is melted out of the shale, it can be pumped to the surface." This process uses considerably less water than other methods. About fifteen employees are involved in this project at the present time. In yet another project the Oil Shale Company of America is considering the possibility of developing oil shale on state land just south of the eastern flank of the Uintah and Ouray Indian Reservation. However, an inadequate water supply is available for developing oil shale at the present, but the proposed dam on the White River could provide sufficient water resource.

The final environmental statement for the federal prototype oil shale leasing program completed indicates that the oil shale industry could produce 60,000 barrels per day at first and expand to 375,000 per day after the industry is totally developed. "The Department of Interior estimates that there is approximately 107,000 acre feet per year of water available for oil shale development in the Uintah Basin. An oil shale industry producing 350,000 barrels per day would have to be introduced into the Basin in order to use all of this 107,000 acre feet per year if all other industry is held at present levels. According to the Department of Interior the area will not support an industry this heavy with the present state of technology.

Crude Oil

Some projections have indicated that crude oil production in the Uintah Basin would top out about 1980, but recent discoveries have assured an expanding industry beyond this date. If the new fields are developed to the fullest extent, the ultimate recovery could amount to as much as one billion barrels making the Uintah Basin one of the ten largest onshore discoveries in the United States. However, development of crude oil in this area is somewhat difficult due to the location including the physical nature of the hydrocarbon, the amount of gas which can legally be flared off, and high drilling costs. Many of these obstacles can be overcome especially in the face of the current crude oil shortage.

Natural Gas

Recoverable natural gas supplies in the Uintah Basin have been estimated to be between 1,000,000 and 2,000,000 MCF (thousand cubic feet). At the present time, Mountain Fuel Supply Company's service area is the only reasonable market and the main purchaser of Basin produced natural gas. Another pipeline from the coast to tap Colorado markets is presently being planned. This pipeline is still in the planning stages. Plans now exist for a natural gas refinery at Ioka in Duchesne County.

Several gas fields have been developed in natural gas reservoirs below oil bearing rock in the "rich" oil shale areas. At present, the Uintah Basin has not been completely explored for crude oil and natural gas. The sediments below the presently explored deposits may contain undiscovered natural gas as well as crude oil reserves.

Phosphate

The Mead Peak Phosphatic Shale, a member of the Phosphora Formation, is exposed and is open to strip mining along the north and south slopes of the Uintah Mountains. In some places, the phosphate veins are up to three miles wide. The Birch Creek area is the site of the main phosphate strip mining operation in the area. The main market for this mine is a fertilizer plant in Salt Lake County, but outlets are maintained throughout the Western United States.

The future of the phosphate industry appears to be good at the present time due to an increasing demand for commercial fertilizer. Recently, however, there have been some environmental objections to heavy use of phosphate fertilizers. Even though the firm owning the mining operation has not openly proclaimed expansion plans, it is known that water has been committed from the Jensen Unit of the Central Utah Project for additional phosphate production.

Gilsonite

Gilsonite is a solid, soft, tar-like bitumin which appears in nearly vertical veins extending to the surface around the town of Bonanza in the southern part of Uintah County. The veins run from thicknesses of a fraction of an inch to 20 feet, extend vertically to 1,800 feet, and are as long as 14 miles. The original gilsonite deposit was estimated to be about 45 million tons. Of this, about 36 million tons are left. This is 85 percent of the known gilsonite of the world. Approximately two-thirds of the gilsonite deposits are located in Uintah County and one-third in Duchesne County. Most recently the production of this unique mineral has diminished. Improved technologies have made it possible to substitute liquid hydrocarbons for some gilsonite uses.

Gilsonite is mined from veins in an open-pit operation and taken to a slurry preparation plant. Once in the slurry, the gilsonite is transported by pipeline from Bonanza to a refinery at Grand Junction, Colorado 72 miles away. At any given time, when the pipeline is in operation, there are about 1,400 tons of gilsonite in the line. The gilsonite is mixed with 240,000 gallons of water. The slurry travels at a speed of about 3 miles per hour. It takes about 24 hours to reach the refinery. Even though technological innovations have slowed the production of gilsonite, it is still a heavy in-basin user of water. The White River is the main source of water for the company town of Bonanza and gilsonite production.

Coal

Deposits of bituminous coal are found in the Uintah Basin but exploration has been on a small scale and coal is mined for local use only. The outcrops of coal occur in three main fields. The Henry Fork Field in Daggett County contains several exposed coal beds ranging in thickness from less than a foot to 10 feet. The thickest is the Fraughton bed which is exposed in four locations with a range of 15 to 28 feet. The remaining beds attain a maximum thickness of 19 feet. The Tabby Mountain Field in Duchesne and Wasatch Counties contains 25 local beds with a range in thickness from half a foot to 28 feet.

Gypsum

There are at least four known gypsum deposits in the Uintah Basin. Exploration and development of gypsum has not been extensive and, therefore, knowledge about the quality and quantity of reserves are limited. The known reserves in the Basin are of low quality and have not been developed.

Bituminous Sands

Various kinds of bituminous sands, sandstone, asphalts and rock are found in the Basin. These sands and asphalts contain up to 15 percent hydrocarbon by weight and have only been used thus far for asphalt in road paving. Approximately 90 percent of the reserve is contained in five major deposits. These deposits generally lend themselves to strip mining and could be a possible crude oil source. These sands have received attention from various sources at different times, but as yet remain essentially undeveloped.

Nahcolite and Trana

These minerals occur in thin, small deposits scattered throughout the Basin. They are not commercially developable alone but will be produced to a limited extent as a by-product of oil shale retorting.

SOCIO - ECONOMIC IMPACTS

As in the case in other regions in the state, the central question is, "How will development of the energy resources affect the social and economic life of the communities in the Uintah Basin?" According to a recent study conducted by the State Planning Office, if the oil shale reaches its full potential by 1980, the population will increase by over 14,000 persons. (See Table # 7). Such an increase in population will significantly alter all services provided by government including water and sewer facilities, medical facilities, police and fire protection, recreation facilities. An overview of existing public facilities already being impacted by new growth indicates the following status:

Public Services

Water and Sewer

Duchesne City has recently completed a study on water and sewer projects. The report indicated that the city system can handle a population

UINTAH BASIN M.C.D.

	POPULATION					NUMBERS EMPLOYED					SCHOOL AGE POPULATION					DWELLING UNITS REQUIRED				
	1975	1980	Change Over 1975	1985	Change Over 1975	1975	1980	Change Over 1975	1985	Change Over 1975	1975	1980	Change Over 1975	1985	Change Over 1975	1975	1980	Change Over 1975	1985	Change Over 1975
Alternative Future IV includes oil shale and Central Utah Project	35,633	49,870	+14,237	46,899	+11,266	14,888	21,369	+6,481	19,898	+5,010	9,551	11,320	+1,769	10,851	+1,300	10,025	14,799	+4,774	14,522	+4,497
Alternative Future 0 (most likely) Expanded petroleum exploration and production only.	35,434	37,133	+1,699	36,440	+1,006	14,799	15,619	+820	15,467	+668	9,503	8,382	-1,121	8,761	-742	9,971	11,158	+1,187	11,406	+1,435
(IV-0) (Impact of IV)	+199	+12,737	+12,538	+10,459	+10,260	+89	+5,750	+5,661	+4,431	+4,342	+48	+2,938	+2,890	+2,090	+2,042	+54	+3,641	+3,587	+3,116	+3,062
School Age Population = Primary and Secondary only.																				

up to 9,000 people (population 1970 - 1,094). Any new water developments would involve taking water from the Duchesne River. The sewer system is reported to be adequate.

Roosevelt City has need to expand its water system, and it is currently negotiating with the Ute Tribe on developing a pipeline from Big Springs. If the tribe gives permission, this pipeline might be funded by a grant from the Economic Development Administration. The existing water line system is inadequate, but the city is in the process of replacing the lines. Roosevelt owns wells which are not in use but prefers to wait on developing them until it can be seen if the Big Springs project will be built. The sewer system has been labeled inadequate by the Environmental Protection Agency (EPA); EPA is also funding a new sewer lagoon.

No water and sewer studies have been done for Vernal but the systems are considered to be adequate for the present.

Daggett County and Manila have been unsuccessful thus far in obtaining funding from federal agencies for water and sewer projects. However at present, both jurisdictions have all the water they require, but the storage capacity is limited. During the peak tourist season, water often runs short and should be pursued through obtaining additional finances.

Road Development

Roosevelt and Vernal both need an alternate route for trucks. Oil drillings, pumpings, and the construction of the oil pipeline in the Altamont-Bluebell region have so increased the traffic on those roads that the roads system there badly needs to be upgraded. If the oil shale industry proceeds, then roads serving it will have to be paved and brought up to standard. Since the State Highway Department needs five years to plan road construction, the time lag may cause problems if this scheduling is strictly adhered to. Roads would then need to be improved before there could be plans made or dollars allocated.

Medical Facilities

Studies are being made on hospital and doctor care in the Basin. Services in Roosevelt, Vernal, and Ashley Valley are adequate. Duchesne City has the services of two doctors three days per week who are flown in from the Wasatch Front. There is no physician or hospital care available in Manila or Daggett County. If the Basin were to experience a large influx of permanent residents, an expansion of medical facilities should be logically expanded.

Zoning

Although all of the communities and counties in the Basin have zoning ordinances, there is inadequate enforcement in some jurisdictions due to the lack of trained personnel. The small tax resources in Daggett County particularly make hiring an enforcer difficult. Vernal City and Uintah County have the best enforcement of zoning ordinances in the Basin. If energy development brings in large numbers of persons, stricter zoning would be required for orderly development.

Environmental Impact

Environmental impact due to oil production has not been high. There have been isolated cases of streams being polluted by oil spills from trucks or wells. The oil refinery in Roosevelt has caused complaints from nearby property owners about the smoke and smell from the burning of waste oil.

New Town

If the oil shale development should prove feasible to justify its full potential, there exists a possibility that a new town may be built to accomodate the influx of workers. At this time, however, plans for a new town site are indefinite. Should the town be constructed, it would have to be self contained including public utilities, housing, schools, commercial and recreational facilities.

UTAH'S STRATEGY IN PLANNING AND COORDINATING ENERGY RELATED ACTIVITIES

UTAH'S STRATEGY IN PLANNING AND COORDINATING ENERGY RELATED ACTIVITIES

INTRODUCTION

As previously mentioned, the energy related developments are having and will have a substantial impact on Utah's physical and economic social patterns. Utah State government officials have developed a framework and and process to provide intergovernmental planning coordination in order to ameliorate adverse community development impacts occurring within Utah.

Two other steps which have been taken by public officials to assist local governments in alleviating the problems attendant to energy resource development in the state are: (1) State financial contributions from the Four Corners Regional Commission to the impacted areas; and (2) State legislation oriented toward assisting affected communities. Each of these state contributions will be discussed in the following section.

Intergovernmental Planning Coordination System

The elements in the Utah intergovernmental planning coordination system include the following: (1) multi-county districts; (2) multi-county associations of government; (3) Governor's Advisory Council on Community Affairs; (4) state agencies; and (5) state/local planning and coordination. Inasmuch as these elements in the system have been sufficiently discussed in a previous document, this report will merely make mention of their existence. For a detailed discussion of this intergovernmental planning coordination system, it is recommended that the reader obtain a copy of the publication prepared jointly by the Utah State Department of Community Affairs and the Office of State Planning Coordinator entitled, Intergovernmental Planning Coordination: The Utah Experience.

However, during the past year a new element has been added to the Utah Intergovernmental Planning Coordination System. This element is referred to as Energy Planning and Development Advisory Councils.

Energy Planning and Development Advisory Councils

In anticipation of significant energy impact occurring within the state, the local and state officials have recognized the importance of providing a means whereby all proposed energy developments are coordinated and reviewed. As a result, the Governor in August, 1974, signed an executive order which created a Kaiparowits Planning and Development Advisory Council to guide and coordinate activities related to the Kaiparowits Power Project in Southern Utah. Also, in November, 1974, the Governor signed a similar executive order that established a planning and development advisory council for the Uintah Basin oil projects.

The Kaiparowits Planning and Development Advisory Council is composed of local officials, state agency staff, federal representatives, state senators and representatives, and company representatives. Appendix contains the full text of the Governor's executive order which created the Kaiparowits Planning and Development Advisory Council.

The Uintah Basin Advisory Council is somewhat different in structure from the Kaiparowits Council. It consists of local officials and state representatives. However, to augment the council, a technical committee was established at the same time the council was created. The technical committee contains representation from state agencies, federal agencies, University of Utah, Utah State University, and private enterprise. It should be mentioned that the technical committee operates on the request of and in response to the council. Moreover, this committee is intended to prepare specific studies requested by the Council. Appendix includes the complete executive order creating this council.

In addition to these two councils, Emery, Grand, and Carbon County public officials have requested the establishment of a similar planning and development advisory council to ensure meaningful planning and coordination relative to coal development in their areas. Once the local officials determine the format and membership for their council, then an executive order will be drafted and signed by the Governor.

The primary purpose of these development advisory councils is to provide a framework through which all available resources can be directed to make certain that proper planning and orderly growth and development occur. Thus, joint planning and decision making among federal, state, and local governments and the developers are enhanced through the utilization of this concept of advisory councils. Further, each council provides a forum, consisting of a host of disciplines whereby the struggle between energy and ecology can be reconciled. Moreover, the differing points of view are discussed and integrated to ensure that they are consistent with the overall best interests of the state.

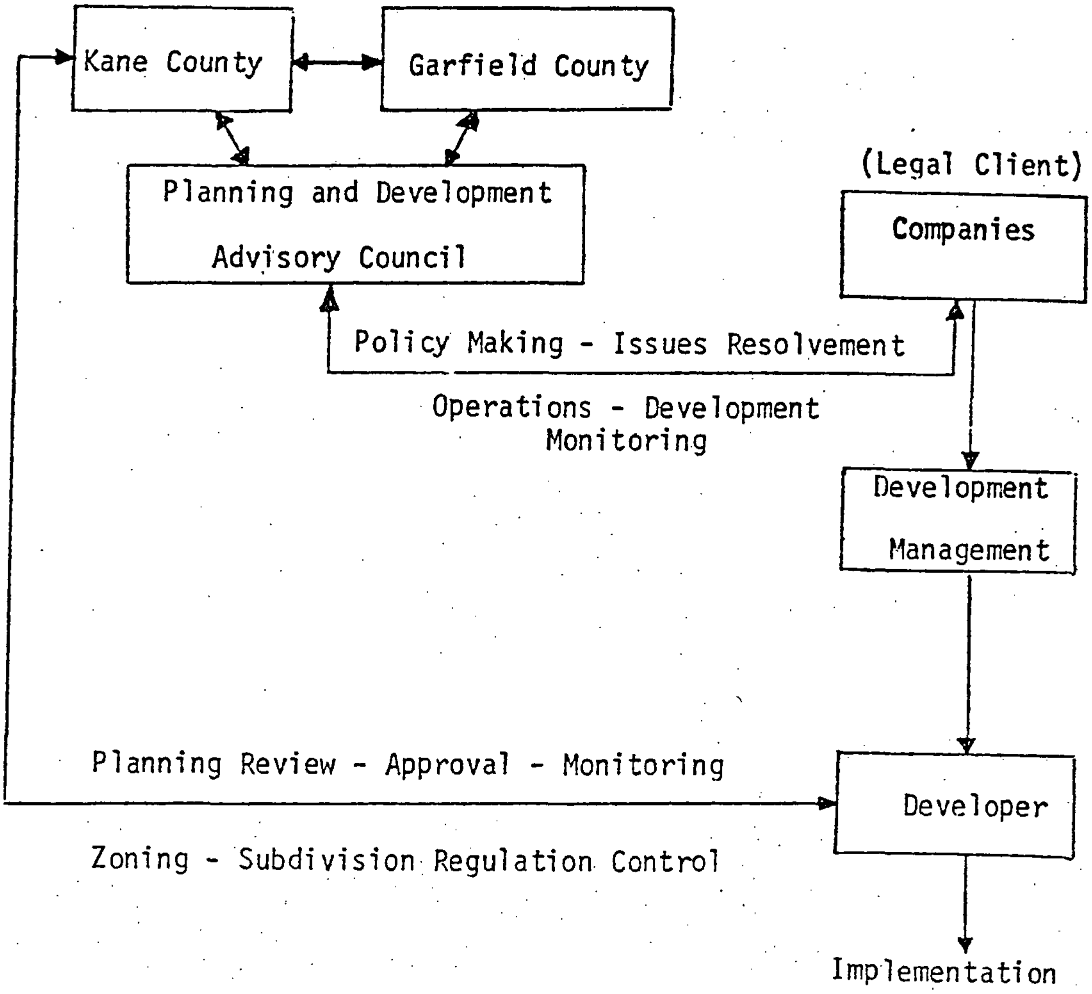
Figure 4 illustrates the policy making and management relationsip of the Kaiparowits Planning and Development Advisory Council with respect to Kane and Garfield Counties and the companies. As the chart indicates, policy making and issue resolution flows between the advisory council and the companies. Kane County will retain power

FIGURE 4

Policy Making - Monitoring And Management

Related To New Community Development

Organization - Relationship Chart



and control of its traditional governmental functions of final site planning review, approval, and monitoring, since the proposed energy project will occur in Kane County.

STATE RESOURCES CONTRIBUTED TO ENERGY IMPACTED AREAS

Financial resources contributions from federal and state funds for energy impacted communities have been significant for fiscal year (FY) 1975. The primary funding source for energy impacted communities has been the Four Corners Regional Commission (FCRC). The Four Corners Regional Commission is composed of Utah, Colorado, New Mexico and Arizona. Since the inception of the Commission in 1967, the emphasis in allocating the federal money appropriated to the Commission has been on the construction of public projects considered essential to economic advancement of communities in the region. For FY 1975, the proportion of funds allocated to Utah was $1,357,850. Of this amount, 43 percent was awarded to communities in Utah experiencing an influx of energy related development. The following is a break out of the amount of money allocated to each community. The funds were allocated under two classifications: (1) technical assistance and (2) supplemental grants. Technical assistance money is for specific public works studies. Supplemental grants, as the name implies, supplement other federal grants for actual construction of a project.

Technical Assistance Grants

		Four Corners Reg. Commission Funds	Total Project Costs
1.	Uintah Basin energy impact study	$44,000	$44,000
2.	Virgin Town culinary water study	10,000	10,000
3.	Wayne County Master Plan	20,000	20,000
4.	East Carbon City Master Plan	10,000	10,000
5.	Kenilworth Town culinary water study	7,500	7,500
	TOTAL	$91,500	$91,500

Supplemental Grants

1.	Uintah Basin Vocation Training Center	$20,000	$60,000
2.	Beaver City sewer treatment facility	26,600	542,700
3.	Beaver City sewer collection facility	53,000	1,060,900
4.	Ouray Park Town culinary water system	75,000	300,000
5.	Glendale Town culinary water system	27,500	232,500
6.	Roosevelt City culinary water system	200,000	250,000
7.	Bicknell culinary water system	92,000	389,000
	TOTAL	$494,100	$2,835,100

In addition to the above funds distributed to energy impacted communities, the State contributed $25,000 for the staffing of an energy regional office in Denver. The purpose of this regional office is to coordinate energy activities occurring within each of the States in the Region.

Additionally, the state has received financial assistance from the Federal Energy Administration to assist in energy related planning and development. Following is a breakout of the funds allocated to various state agencies relating to energy research:

1.	Department of Business Regulations	$21,005.56
2.	Department of Natural Resources	7,532.85
3.	Utah Geological & Mineral Survey	6,110.00
4.	State Planning Coordinator	12,249.25
5.	Department of Community Affairs	12,764.05
6.	University of Utah	
	Research: Tar Sands	7,162.34
	Data Bank	3,333.24
	TOTAL	$70,157.29

STATE LEGISLATION AFFECTING ENERGY RESOURCE DEVELOPMENT

During the 1975 session of the Utah State Legislature, several bills dealing with energy resource development in the state were discussed. The following is a brief description of the key pieces of legislation passed.

RESOURCES DEVELOPMENT ACT

This act allows a company which is building an industrial plant to pre-pay its sales and use taxes. In Utah, sales tax and use tax are four percent state assessments on any goods sold within the state. However, the use tax is one that applies to items purchased outside the state which are brought in to be used. A credit is given to the company prepaying the taxes at the time when the company would normally pay the tax. A special account will be maintained within the state general fund from which funds will be appropriated.

BUILDING SCHOOLHOUSES ACT

This Act provides a means whereby school districts can raise money for school construction and expansion that is caused by the development of new industrial plants that require large numbers of workers for their construction and operation. It further requires a school district confronted with increases in enrollment to the extent that new buildings must be erected to:

1) bond to its maximum capacity (at least once every other year) until building needs are met;
2) maintain an annual property tax levy for capital outlay and debt service combined of not less than 18 mills;
3) act to get as many state and federal funds as are available for building construction.

If the school districts are unable to provide minimal facilities, they are authorized to enter into lease-purchase agremenets or lease with option to buy agreements with private builders who will construct minimal facilities. If the school distirct cannot find builders, then it may enter into an agreement with developers of an industrial plant to build schools under a lease purchase agreement.

SPECIAL SERVICE DISTRICT ACT

This act implements an amendment to the Constitution of the State of Utah which was approved by the voters in 1974.

The Special Service District Act is designed to help those counties, cities, and towns which do not have broad tax bases to bond for public improvements without exceeding their debt limitations. Previously, Utah's smaller rural areas were strapped with single purpose districts which had to meet stringent debt limitations.

Under the provisions of the subject act, special service districts may issue bonds up to 12 percent of the fair cash value of the assessed property within the district. However, a district may also issue guaranteed bonds in addition to and in excess of the 12 percent limitation.

The use of guaranteed bonds allows one or more taxpayers within the district to guarantee debt service. The bonds are especially useful to those local jurisdictions which anticipate new towns or rapid development due to above normal industrial and economic growth.

LOANS FOR MUNICIPAL WATER SYSTEMS

This bill appropriated $2 million dollars to the Board of Water Resources to be used as supplemental money for cities and towns to construct and improve their water supply systems. The money is to be loaned to the cities and towns and guaranteed by bonds. In setting priorities and determining how the money should be allocated, preference was given to cities and towns in the state which have experienced heavy increases in population as a result of new industry--particularly energy related.

APPENDIX

FIGURE I

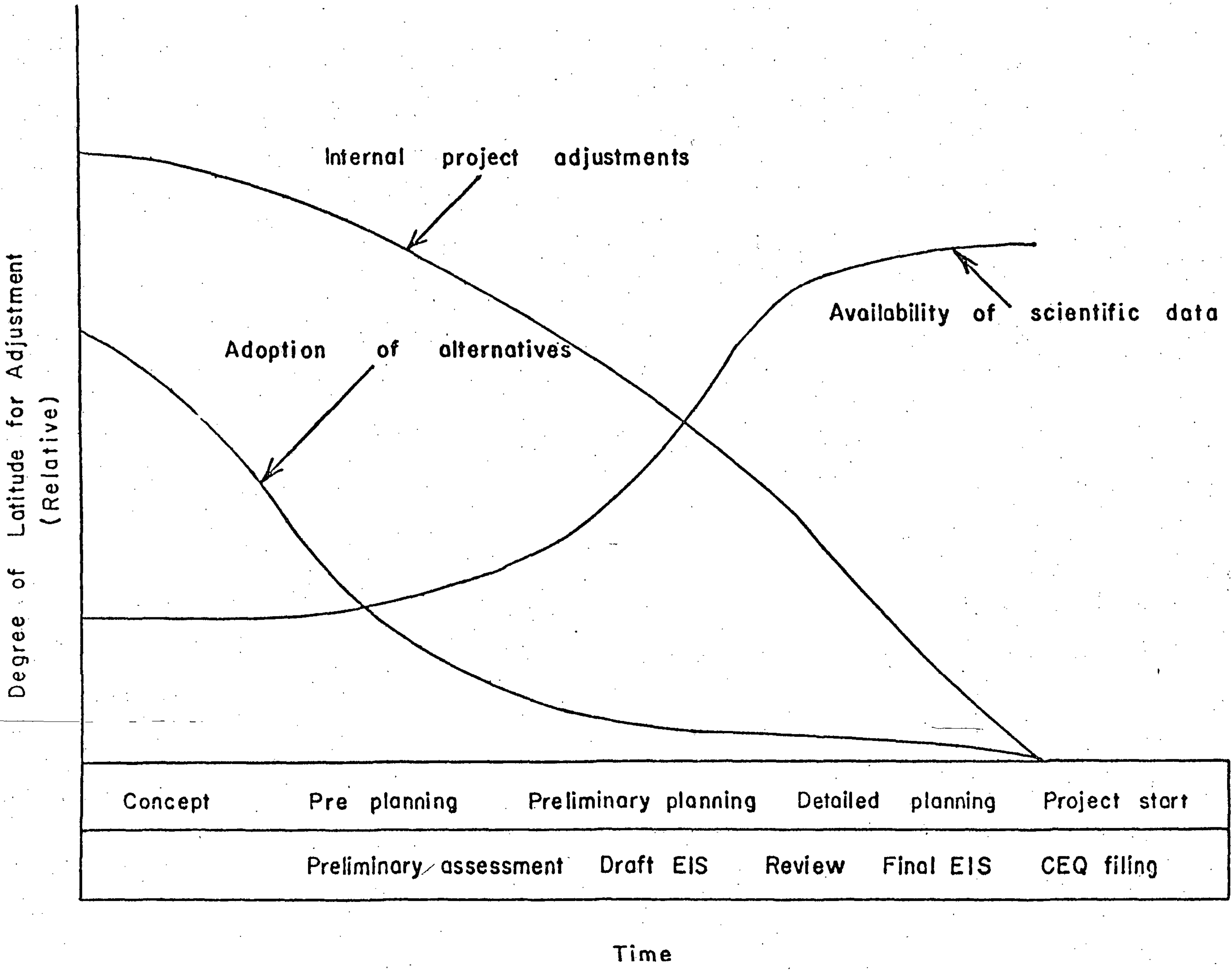

Internal project adjustments
Availability of scientific data
Adoption of alternatives
Degree of Latitude for Adjustment (Relative)
Concept
Pre planning
Preliminary planning
Detailed planning
Project start
Preliminary assessment
Draft EIS
Review
Final EIS
CEQ filing
Time

FIGURE 2

THE NATIONAL ENVIRONMENTAL POLICY ACT

PURPOSE

Sec. 2. The purposes of this Act are: To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality.

TITLE I

DECLARATION OF NATIONAL ENVIRONMENTAL POLICY

Sec. 101. (a) The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans.

(b) In order to carry out the policy set forth in this Act, it is the continuing responsibility of the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs, and resources to the end that the Nation may—

(1) fulfill the responsibilities of each generation as trustee of the environment for succeeding generations;

(2) assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings;

(3) attain the widest range of beneficial uses of the environment without degradation, risk to health or safety, or other undesirable and unintended consequences;

(4) preserve important historic, cultural, and natural aspects of out national heritage, and maintain, wherever possible, an environment which supports diversity and variety of individual choice;

(5) achieve a balance between population and resource use which will permit high standards of living and a wide sharing of life's amenities; and

(6) enhance the quality of renewable resources and approach the maximum attainable recycling of depletable resources.

(c) The Congress recognizes that each person should enjoy a healthful environment and that each person has a responsibility to contribute to the preservation and enhancement of the environment.

Sec. 102. The Congress authorizes and directs that, to the fullest extent possible: (1) the policies, regulations, and public laws of the United States shall be interpreted and administered in accordance with the policies set forth in this Act, and (2) all agencies of the Federal Government shall—

(A) utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decisionmaking which may have an impact on man's environment;

(B) identify and develop methods and procedures, in consultation with the Council on Environmental Quality established by title II of this Act, which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations;

(C) include in every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on—

(i) the environmental impact of the proposed action,

(ii) any adverse environmental effects which cannot be avoided should the proposal be implemented,

(iii) alternatives to the proposed action,

(iv) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and

(v) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

Prior to making any detailed statement, the responsible Federal official shall consult with and obtain the comments of any Federal agency which has jurisdiction by law or special expertise with respect to any environmental impact involved. Copies of such statement and the comments and views of the appropriate Federal, State, and local agencies, which are authorized to develop and enforce environmental standards, shall be made available to the President, the Council on Environmental Quality and to the public as provided by section 552 of title 5, United States Code, and shall accompany the proposal through the existing agency review processes;

(D) study, develop, and describe appropriate alternatives to recommended courses of action in any proposal which involves unresolved conflicts concerning alternative uses of available resources;

(E) recognize the worldwide and long-range character of environmental problems and, where consistent with the foreign policy of the United States, lend appropriate support to initiatives, resolutions, and programs designed to maximize international cooperation in anticipating and preventing a decline in the quality of mankind's world environment;

(F) make available to States, counties, municipalities, institutions, and individuals, advice and information useful in restoring, maintaining, and enhancing the quality of the environment;

(G) initiate and utilize ecological information in the planning and development of resource-oriented projects; and

(H) assist the Council on Environmental Quality established by title II of this Act.

Sec. 103. All agencies of the Federal Government shall review their present statutory authority, administrative regulations, and current policies and procedures for the purpose of determining whether there are any deficiencies or inconsistencies therein which prohibit full compliance with the purposes and provisions of this Act and shall propose to the President not later than July 1, 1971, such measures as may be necessary to bring their authority and policies into conformity with the intent, purposes, and procedures set forth in this Act.

Sec. 104. Nothing in Section 102 or 103 shall in any way affect the specific statutory obligations of any Federal agency (1) to comply with criteria or standards of environmental quality, (2) to coordinate or consult with any other Federal or State agency, or (3) to act, or refrain from acting contingent upon the recommendations or certification of any other Federal or State agency.

Sec. 105. The policies and goals set forth in this Act are supplementary to those set forth in existing authorizations of Federal agencies.

TITLE II

COUNCIL ON ENVIRONMENTAL QUALITY

Sec. 201. The President shall transmit to the Congress annually beginning July 1, 1970, an Environmental Quality Report (hereinafter referred to as the "report") which shall set forth (1) the status and condition of the major natural, manmade, or altered environmental classes of the Nation, including, but not limited to, the air, the aquatic, including marine, estuarine, and fresh water, and the terrestrial environment, including, but not limited to, the forest dryland, wetland, range, urban, suburban, and rural environment; (2) current and forseeable trends in the quality, management and utilization of such enivornments and the effects of those trends on the social, economic, and other requirements of the Nation; (3) the adequacy of available natural resources for fulfilling human and economic requirements of the Nation in the light of expected population pressures; (4) a review of the programs and activities (including regulatory activities) of the Federal Government, the State and local governments, and nongovernmental entities or individuals, with particular reference to their effect on the environment and on the conservation, development and utilization of natural resources; and (5) a program for remedying the deficiencies of existing programs and activities, together with recommendations for legislation.

Sec. 202 There is created in the Executive Office of the President a Council on Environmental Quality (hereinafter referred to as the "Council"). The Council shall be composed of three members who shall be appointed by the President to serve at his pleasure, by and with the advice and consent of the Senate. The President shall designate one of the members of the Council to serve as Chairman. Each member shall be a person who, as a result of his training, experience, and attainments, is exceptionally well qualified to analyze and interpret environmental trends and information of all kinds; to appraise programs and activities of the Federal Government in the light of the policy set forth in title I of this Act; to be conscious of and responsive to the scientific, economic, social, esthetic, and cultural needs and interests of the Nation; and to formulate and recommend national policies to promote the improvement of the quality of the environment.

Sec. 203. The Council may employ such officers and employees as may be necessary to carry out its functions under this Act. In addition, the Council may employ and fix the compensation of such experts and consultants as may be necessary for the carrying out of its functions under this Act, in accordance with section 3109 of title 5, United States Code (but without regard to the last sentence thereof).

Sec. 204. It shall be the duty and function of the Council—

(1) to assist and advise the President in the preparation of the Environmental Quality Report required by section 201;

(2) to gather timely and authorative information concerning the conditions and trends in the quality of the environment both current and prospective, to analyze and interpret such information for the purpose of determining whether such conditions and trends are interfering, or are likely to interfere, with the achievement of the policy set forth in title I of this Act, and to compile and submit to the President studies relating to such conditions and trends;

(3) to review and appraise the various programs and activities of the Federal Government in the light of the policy set forth in title I of this Act for the purpose of determining the extent to which such programs and activities are contributing to the achievement of such policy, and to make recommendations to the President with respect thereto;

(4) to develop and recommend to the President national policies to foster and promote the improvement of environmental quality to meet the conservation, social, economic, health, and other requirements and goals of the Nation;

(5) to conduct investigations, studies, surveys, research, and analyses relating to ecological systems and environmental quality;

(6) to document and define changes in the natural environment, including the plant and animal systems, and to accumulate necessary data and other information for a continuing analysis of these changes or trends and an interpretation of their underlying causes;

(7) to report at least once each year to the President on the state and condition of the environment; and

(8) to make and furnish such studies, reports thereon, and recommendations with respect to matters of policy and legislation as the President may request.

Sec. 205. In exercising its powers, functions, and duties under this Act, the Council shall—

(1) consult with the Citizens' Advisory Committee on Environmental Quality established by Executive Order numbered 11472, dated May 29, 1969, and with such representatives of science, industry, agriculture, labor, conservation organizations, State and local governments, and other groups, as it deems advisable; and

(2) utilize, to the fullest extent possible, the services, facilities, and information (including statistical information) of public and private agencies and organizations, and individuals, in order that duplication of effort and expense may be avoided, thus assuring that the Council's activities will not unnecessarily overlap or conflict with similar activities authorized by law and performed by established agencies.

Sec. 206. Members of the Council shall serve full time and the Chairman of the Council shall be compensated at the rate provided for Level II of the Executive Schedule Pay Rates (5 U.S.C. 5313). The other members of the Council shall be compensated at the rate provided for Level IV of the Executive Schedule Pay Rates (5 U.S.C. 5315).

Sec. 207. There are authorized to be appropriated to carry out the provisions of this Act not to exceed $300,000 for fiscal year 1970, $700,000 for fiscal year 1971, and $1,000,000 for each fiscal year thereafter.

FIGURE 3

KAIPAROWITS ENERGY PLANNING AND DEVELOPMENT COUNCIL

EXECUTIVE ORDER

STATE OF UTAH

Executive Department

EXECUTIVE ORDER

WHEREAS, the introduction of new oil activities into Daggett, Duchesne, and Uintah Counties will have an impact of considerable magnitude on the existing pattern of development; and

WHEREAS, in anticipation of this impact, there exists a need for a coordination process to facilitate planning and decision making between federal, state, and local governments; and the private sector concerning oil resource development; and

WHEREAS, the local elected officials of Daggett, Duchesne, and Uintah Counties recognize the importance of providing a means by which all proposed activities having a direct influence on the future development of the area should be reviewed and taken into consideration:

NOW, THEREFORE, I, Calvin L. Rampton, Governor of the State of Utah, by virtue of the authority vested in me by the Constitution and Laws of the State of Utah, do hereby order as follows:

Under the direction of the Uintah Basin Association of Governments, there is hereby created a Planning and Development Advisory Council, to guide and coordinate activities related to oil development and report its recommendations and findings to the Association of Governments.

The purposes of the Council are:

1. Function as a local clearinghouse for oil planning and development activities underway or proposed for Daggett, Duchesne, and Uintah Counties.
2. Develop and provide state and county local input to the environment statement being developed by the United States Department of Interior, Bureau of Land Management.
3. Identify and/or secure funding and other resources from participating governmental and private agencies, to assist in planning and development efforts related to the Uintah Basin oil projects in the three counties, as needed.
4. Direct and/or carry out specific oil development related planning or development activities, as requested by the counties or other participating governmental units.

5. Function as the liaison and communication body between private development corporations, federal, state, and local agencies directly related to the Uintah Oil projects in Daggett, Duchesne, and Uintah Counties.

6. Implement a process whereby community input may be received and reviewed by the Council and a continuing public education program is carried out.

7. Coordinate Uintah Basin and other oil construction and development planning with county planning and municipal development so as to attempt to prevent an influx of workers and related population to areas where there are not adequate and attractive housing and related facilities.

The Council shall consist of thirteen (13) representatives as follows:

Hollis G. Hullinger, Chairman, Uintah Basin Association of Governments
Warren Richardson, Chairman, Uintah County Commission
J. Rulon Anderton, Chairman, Duchesne County Commission
Albert H. Neff, Chairman, Daggett County Commission
Harvey Madsen, Chairman, Vernal City Planning Commission
Orlan Cook, Uintah County Planning Commission
Lawrell Jensen, Roosevelt City Planning Commission
Wilmer Murray, Duchesne County Planning Commission
Dale Workman, Duchesne City Planning Commission
Carl Collett, Daggett County Planning Commission
Glade Sowards, State Representative
James Drollinger, Mayor, Vernal
Daniel Dennis, State Representative

To augment the Planning and Development Council, a Technical Committee shall be established to:

1. Operate on the request of and in response to Uintah Basin Planning and Development Advisory Council.

2. Prepare specific data, studies, and documents, as requested by the Council related to oil development.

The Technical Committee shall consist of twenty-four (24) representatives as follows:

Milton L. Weilenmann, Department of Development Services
William Kremin, Employment Security, Vernal
Clair Huff, Division of Wildlife Resources, Vernal
Mark H. Crystal, Division of State Lands
Ed Lovelace, State Highway Department, Orem
David Behrens, Forestry and Fire Control, Heber
Charles R. Henderson, Tri-State Oil Shale Commissioner
Rees C. Madson, Environmental Affairs Coordinator and Field Representative, White River Shale Oil Corporation
Dale Carpenter, Department of Natural Resources
Barry Saunders, Division of Water Resources
Robert F. Guy, Division of Water Rights, Vernal
William G. Bruhn, Department of Community Affairs
Burton L. Carlson, State Planning Coordinator
Dr. Robert F. Logan, Department of Economics Utah State University
Dr. Richard E. Turley, Mechanical Engineering, University of Utah

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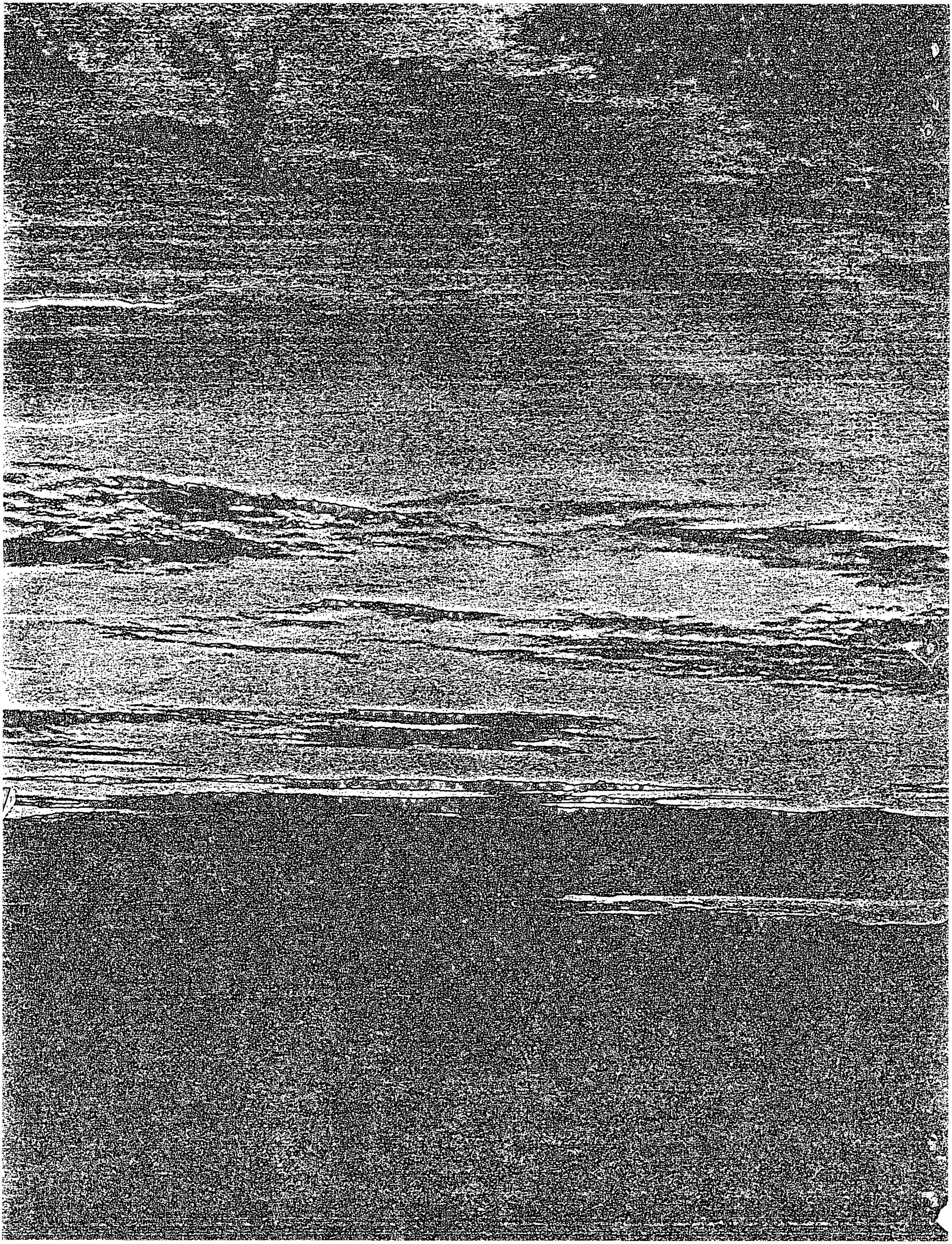

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Crustal Structure Along the Great Basin–Colorado Plateau Transition From Seismic Refraction Studies

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A seismic refraction profile was recorded along the southern Wasatch front in Utah to investigate crustal structure in the transition zone between the Great basin and Colorado plateau provinces. Interpretation of both refracted and reflected phases indicates a thin (~25-km) crust, a low *Pn* velocity (~7.5 km/s), and a crustal low-velocity layer in the approximate depth range of 8–15 km. Correlation with previous geophysical studies suggests that these features are present throughout the transition zone and that a mantle upwarp extending at least 50 km east of the boundary between these provinces (Wasatch front) is present. This upwarp may be of considerable tectonic significance, since it approximately coincides with a zone of high seismicity, the intermountain seismic belt.

During the summer of 1972 the University of Utah conducted a detailed seismic refraction survey along the boundary between the Great basin portion of the Basin and Range province and the Colorado plateau of the western United States (Figure 1). The refraction line (Figure 1, line 1-2) extended 245 km south from a shot point in the Great basin and crossed the Wasatch front into the Colorado plateau approximately 140 km south of the shot point. We will use the term Wasatch front in a general sense to refer to the physiographic boundary between the Great basin and Colorado plateau-Middle Rocky Mountains in Utah.

Fundamental differences in tectonics and crustal and upper mantle structure between the Great basin and Colorado plateau have been recognized by several workers (*Eardley* [1962], *Roy et al.* [1972], *Prodehl* [1970], *Bucher and Smith* [1971], and others). The Great basin is generally characterized by high heat flow (2 HFU (heat flow unit) or more), thin crust (~30 km), low *Pn* velocity (~7.8 km/s), and extensive late Cenozoic volcanism and normal faulting. The Colorado plateau is characterized by lower heat flow, a thicker crust (~40 km), and Cenozoic epeirogenic uplift. However, little is known about the detailed crustal structure along the transition zone between the two areas. For this reason a seismic refraction survey was conducted along the tectonic boundary between the Great basin and the Colorado plateau to investigate the degree of continuity of crustal structure between these two distinctly different tectonic provinces and to delineate the extent and characteristics of the transition zone.

DATA ACQUISITION AND ANALYSIS

Quarry blasts from the Bingham canyon copper mine, 30 km southwest of Salt Lake City, Utah, were used as energy sources for the refraction survey. The blasts were recorded at [illegible] stations along a 245-km-long profile (Figure 1, line 1-2) with an average station spacing of approximately 3.5 km. Stations were never more than 2–3 km from a line representing a due south azimuth from the shot point. Vertical, in-line, and transverse seismometers were employed at each station. The data were recorded on analog tape and later digitized. Procedures for data acquisition and reduction are similar to those described by *Braile et al.* [1974].

The digitized seismograms were migrated and corrected for elevation differences to a 1.5-km above sea level datum prior to plotting on reduced travel time record sections. Band-pass filtering from 2 to 5 Hz was applied to the data as an aid in enhancing later arrivals. However, arrival times for analyses were picked on the original unfiltered records.

Arrival times were determined for phases corresponding to both first and later arrivals of refracted and reflected phases. These times were used as input to a program that computed an

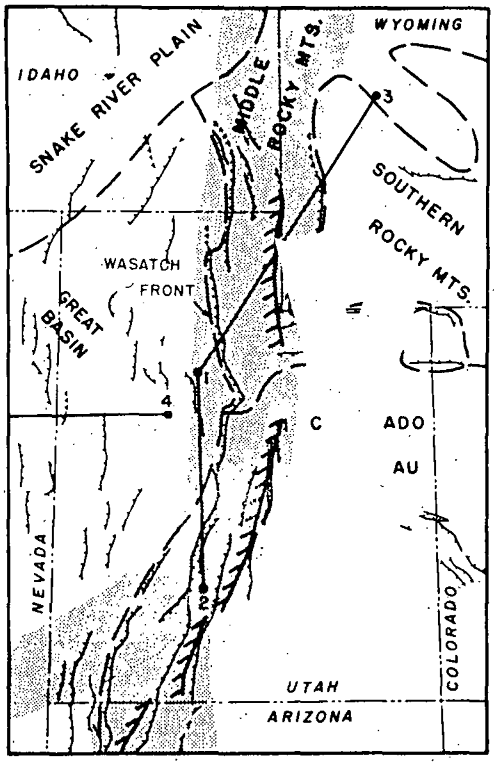

Fig. 1. Index map of study area. Line 1-2 shows profile location of this study; line 1-3, profile location of *Braile et al.* [1974]; and line 4, Delta-West profile [*Eaton et al.*, 1964]. The stations in this study were fairly evenly spaced and never more than 2–3 km from line 1-2. Shaded pattern represents intermountain seismic belt; light hachured lines, Cenozoic faults; heavy lines with slant hachures, easternmost extent of the upper mantle upwarp; and heavy dashed lines, boundaries between physiographic provinces.

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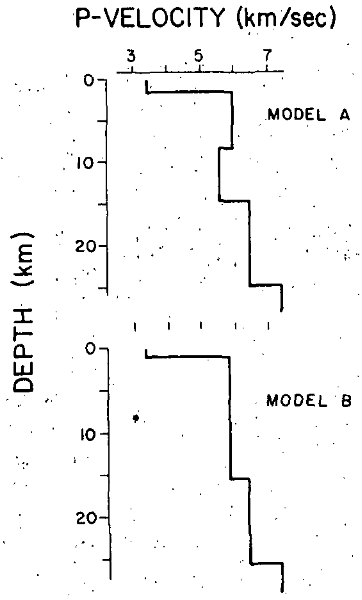

THICKNESS (KM)	P VELOCITY (KM/SEC)	S VELOCITY (KM/SEC)	POISSON'S RATIO
1.7	3.4	2.0	0.25
6.7	6.0	3.5	0.24
6.3	5.5	2.9	0.31
10.0	6.5	3.5	0.29
TOTAL	7.4	4.0	0.28
24.7			

THICKNESS (KM)	P VELOCITY (KM/SEC)	S VELOCITY (KM/SEC)	POISSON'S RATIO
1.4	3.4	1.9	0.25
14.1	5.9	3.5	0.24
9.9	6.4	3.2	0.33
TOTAL	7.4	4.0	0.28
25.4			

Fig. 4. Velocity-depth models derived from interpretation of both *P* wave and *S* wave refracted and reflected arrivals.

counted for by model A with a pronounced *S* wave LVL corresponding in depth to the *P* wave LVL. The *S* velocities in model A were derived by using the layer thicknesses determined from the *P* wave data and varying velocities until observed and theoretical travel times for the *Sg* and *SnR* arrivals from both the in-line and the transverse component could be matched. In a similar fashion, the late *SnR* arrivals could only be accounted for in model B by assigning a high Poisson's ratio (0.33) to the lowest crustal layer. This situation resulted in an *S* wave LVL corresponding to this layer for which there was no additional evidence.

DISCUSSION

Inspection of Figure 4 demonstrates that models A and B have several features of tectonic significance. These include a relatively thin crust, a low *Pn* velocity, anomalously low *S* wave velocities, and, in model A, a crustal LVL.

The anomalously low *Pn* velocity of 7.4 km/s is well established on our record sections. However, if the Moho were dipping, this velocity would represent an apparent velocity. A crustal thickness less than 30 km in northern and western Utah is well established [*Berg et al.*, 1960; *Eaton et al.*, 1964; *Prodehl*, 1970; *Mueller and Landisman*, 1971; *Braile et al.*, 1974]. The southern end of our profile is located east of the Wasatch front within the Colorado plateau where crustal thicknesses of approximately 40 km have been reported [*Roller*, 1965]. Thus any dip along our profile would be expected to be to the south, the result being a higher true velocity. In the extreme case of a 25-km crust at the shot point and a 40-km crust at the southern end of the profile the true upper mantle velocity could be as high as 7.7 km/s. However, we feel that the lack of evidence for abrupt crustal discontinuities such as the crustal thickening observed by *Braile et al.* [1974] in northern Utah and the thin crust (25–30 km) interpreted for the eastern portion of the Delta-West line [*Eaton et al.*, 1964; *Mueller and Landisman*, 1971; *Landisman et al.*, 1971] indicates that significant dip along our profile is unlikely. Further, for individual traces the ratios of the amplitudes of *Pn* and *PnR* at distances beyond 150 km are similar when the synthetic and observed record sections are compared. This observation indicates that at least the velocity contrasts at the M discontinuity in the derived models are approximately correct. Hence we suggest an upper mantle velocity along our profile of 7.5 ± 0.1 km/s.

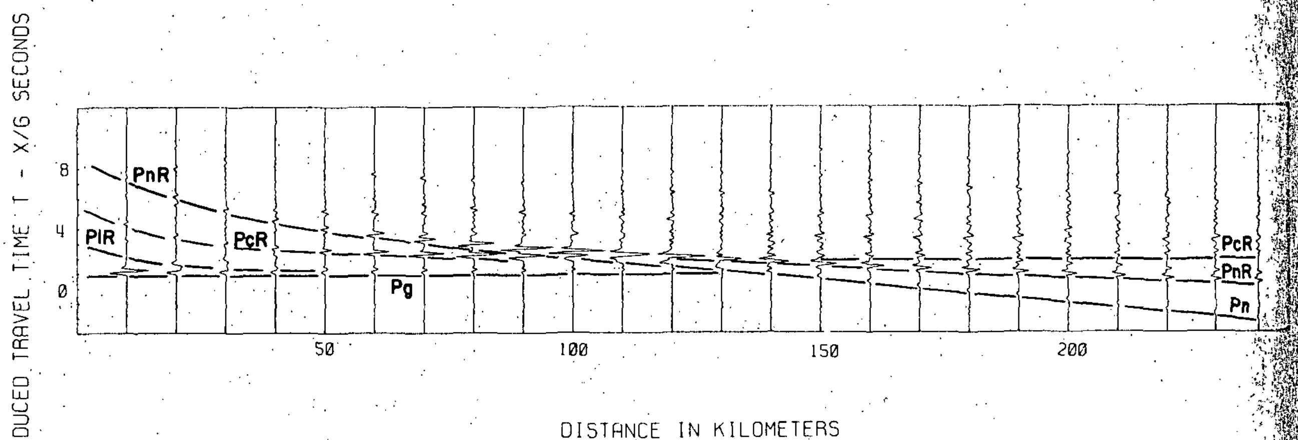

Fig. 5. Record section of vertical component synthetic seismograms computed by the reflectivity method [*Fuchs and Mueller*, 1971]. Lines correspond to theoretical *P* wave arrival times calculated for model A.

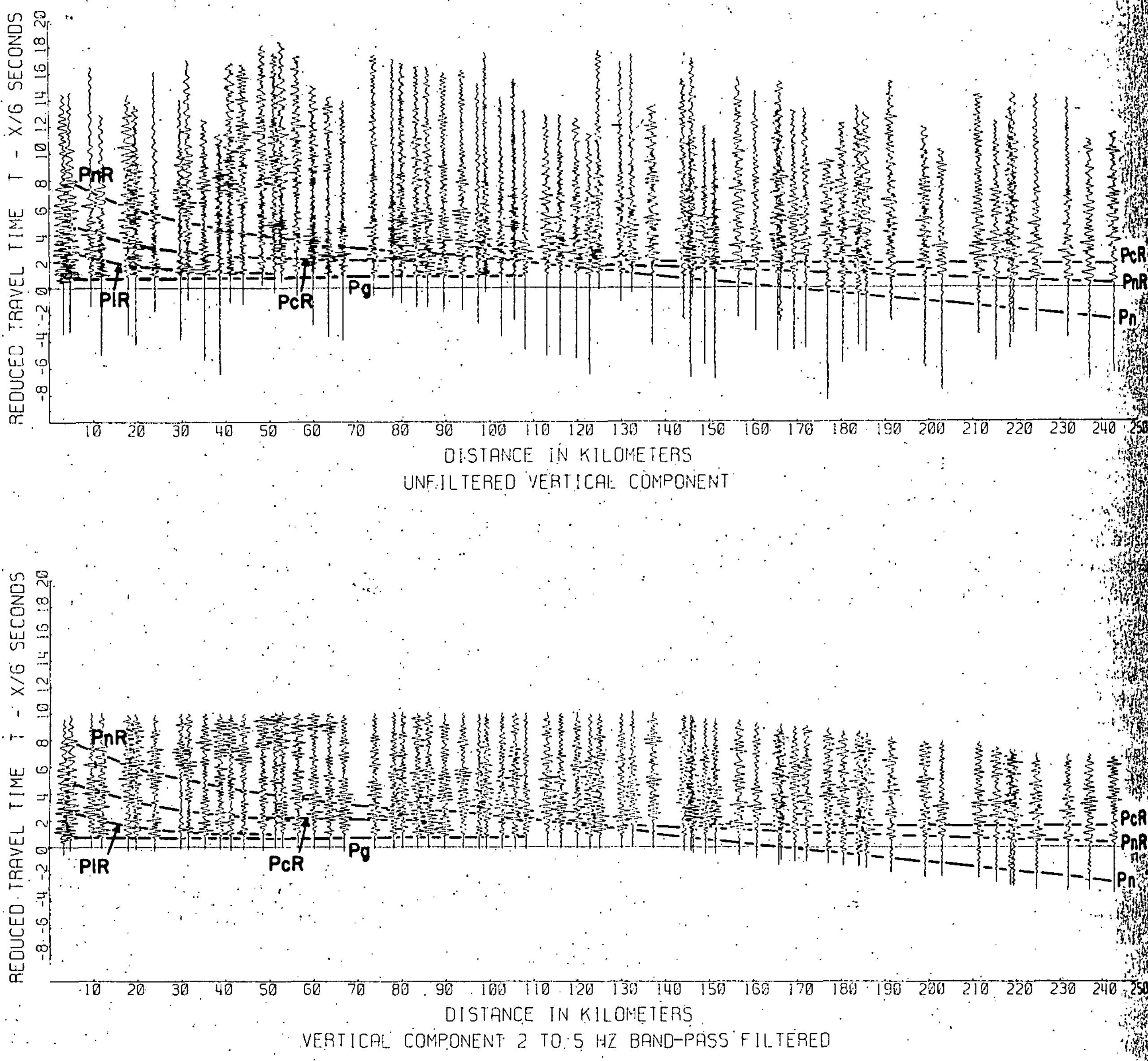

Fig. 2. Vertical component record sections (reducing velocity 6 km/s). Upper section is unfiltered; lower section is band-pass filtered from 2 to 5 Hz. Lines correspond to theoretical *P* wave arrival times calculated for model A.

optimum velocity model by a generalized linear inversion method [*Braile*, 1973]. The vertical component seismograms were then compared to theoretical seismograms generated for the optimum models by the reflectivity method [*Fuchs and Mueller*, 1971]. In computing the synthetic seismograms a simple 2-Hz wavelet was used as a source wavelet so that individual arrivals could be distinguished. This choice was also predicated on the variability of the true source wavelet between blasts.

INTERPRETATION AND RESULTS

In discussing the data the following notation is used for identification of individual phases: *Pg* (*Sg*) is refraction from the top of an upper crustal layer with *P* (*S*) wave velocity of approximately 6.0 (3.5) km/s, *Pc* (*Sc*) is refraction from the top of the lower crustal layer with *P* (*S*) velocity of approximately 6.5 (3.5) km/s, and *Pn* (*Sn*) is refraction from the upper mantle-crust boundary (Moho) with *P* (*S*) velocity of approximately 7.4 (4.1) km/s. An *R* following the symbols denotes a reflection from the top of the corresponding layer; *PlR* denotes a reflection from the top of a low-velocity layer (LVL).

Several phases are identifiable on the vertical component seismograms (Figure 2). The *Pg* arrivals are readily observed from 10 to beyond 100 km. The phase *Pn* becomes a first arrival at approximately 145 km and is identified to the end of the profile. The *PnR* phase is well defined as later arrivals from 100 km to the end of the profile. Later arrivals (1.0–1.5 s after *Pg*) interpreted as *PcR* are distinguishable from 50 to 90 km, and less well defined later arrivals interpreted as *PlR* are observed from about 20 to 50 km. Beyond approximately 50 km the *PlR* travel times closely approach those of *Pg*, so that these two arrivals are not distinguishable.

With the exception of *Sg* arrivals from 10 to 65 km the transverse and in-line record sections (Figure 3) generally lacked arrivals that could be correlated for a significant distance. However, poorly defined *SnR* arrivals may be distinguished from 100 to 150 km.

The velocity models derived from the interpretation of the observed data are shown in Figure 4. Layer thicknesses and *P*

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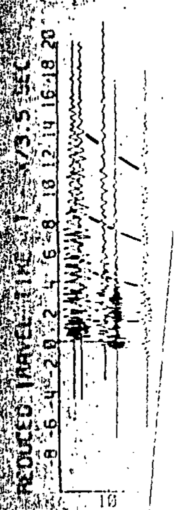

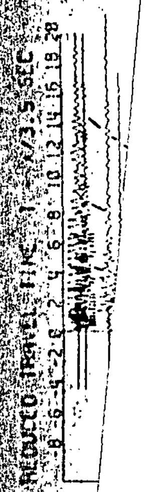

velocities were determined by the inversion technique using P wave travel times for both refracted and reflected waves. When arrivals interpreted as *PlR* were included in the inversion, model A, which contains an upper crustal low-velocity layer, was obtained. However, if the *PlR* arrivals are not included in the inversion, model B containing no LVL is obtained.

A model similar to a model A has been interpreted along the Delta-West refraction profile (Figure 1, line 4,) by *Mueller and Landisman* [1971], *Landisman et al.* [1971], and *Mueller and Mueller* [1972]. Using the inversion technique, we interpreted the Delta-West data and obtained a model with a 28-km crust and an LVL in the depth range of 8.5–13 km. This model is similar to both model A and *Mueller and Landisman*'s [1971] original interpretation.

Similar to the Delta-West profile, large-amplitude arrivals interpreted as reflections from the bottom of the LVL (*PcR*) are identifiable on our record sections from 60 to 90 km (Figure 2). The synthetic seismograms for model A are shown in Figure 5 and predict large-amplitude *PcR* arrivals in this same distance range. In fact, if each trace is looked at individually, the ratios of the amplitudes of *Pg* and *PcR* in this distance range are similar when the synthetic and observed record sections are compared. Thus on the basis of inversion results and comparison of the synthetic seismograms with the observed data, model A including the LVL is preferred. The correlation between model A and the Delta-West profile models also favors model A.

Our generalized interpretation of the *S* wave data is tentative because of the paucity of coherent *S* wave arrivals. The weak *SnR* reflections observed from 100 to 150 km (Figure 3) arrived almost 2 s later than would be predicted by assuming the *P* velocities and layer thicknesses of either model A or B and assigning a Poisson's ratio of 0.25 to all layers. The *Sg* arrivals define the *S* velocity of the upper crust to be approximately 3.5 km/s, requiring a Poisson's ratio near 0.25. Thus the late *SnR* arrivals suggest that Poisson's ratios lower in the crust are greater than 0.25. Delayed *SnR* reflections, also observed by *Braile et al.* [1974] for northern Utah, are ac-

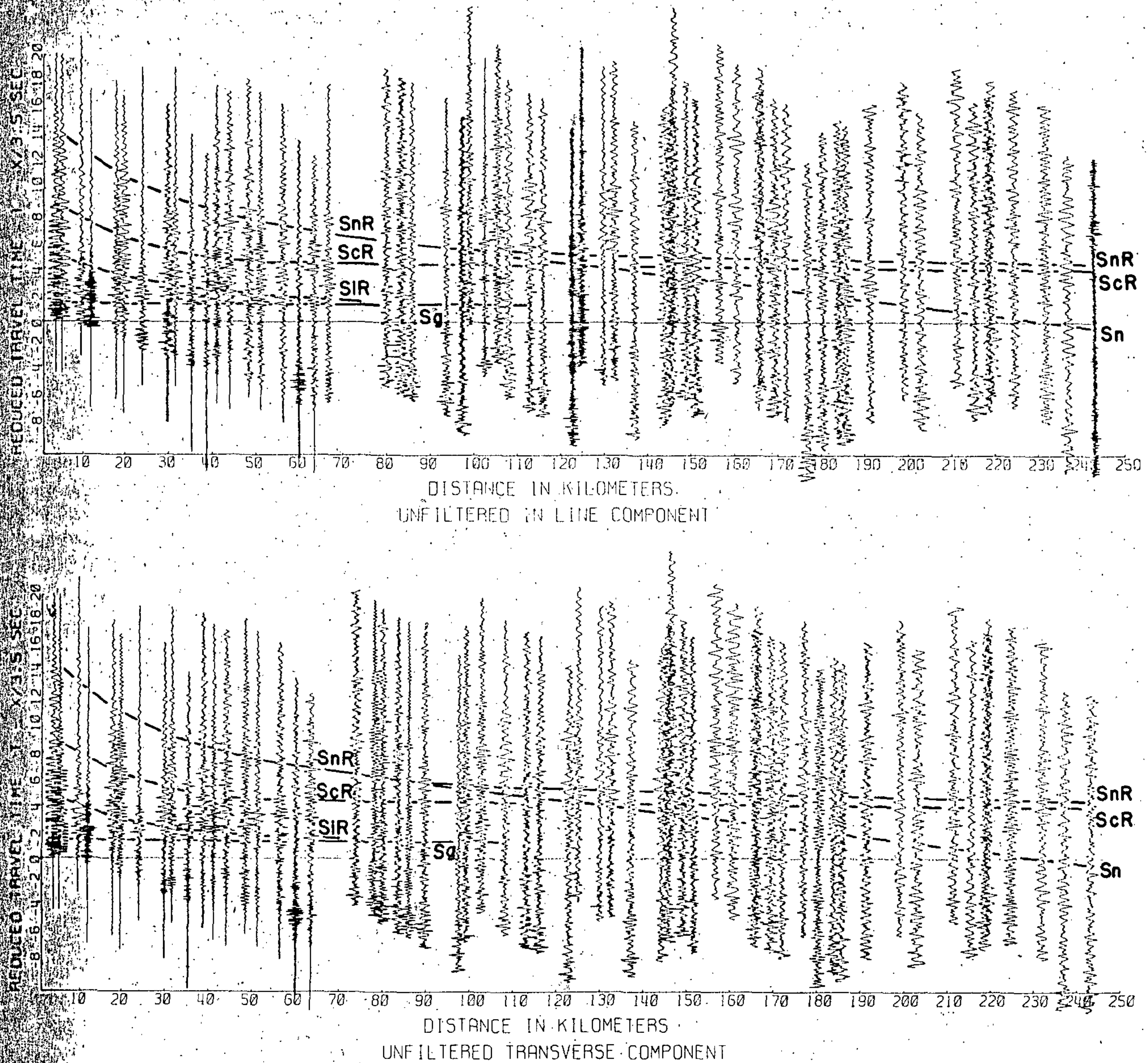

Fig. 3. Horizontal component record sections (reducing velocity 3.5 km/s). Upper section is in-line component; lower section is transverse component. Lines correspond to theoretical *S* wave arrival times calculated for model A.

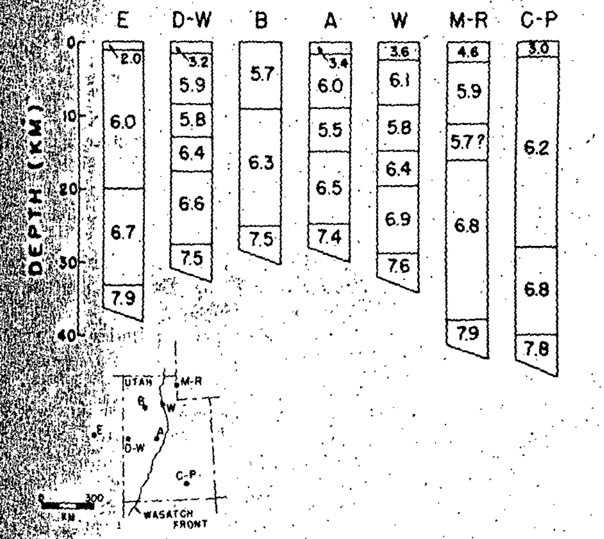

Fig. 6. Crustal models from refraction studies in the region of the transition zone between the Great basin and Colorado plateau–Middle Rocky Mountains provinces. From left to right, as is shown in inset map, the models are arranged in west to east order. Model E is for east central Nevada (after the model from Eureka, Nevada, of *Hill and Pakiser* [1967]), D-W is the model for the area of the Nevada-Utah state line and far west central Utah (our interpretation of the Delta-West profile), B is the model for the area surrounding the Great Salt Lake [after *Berg et al.*, 1960]; A is model A of this study, W is the model for the area of the Wasatch Mountains in northeastern Utah [after *Braile et al.*, 1974], M-R is the model for the Middle Rocky Mountains in northeastern Utah and southwestern Wyoming [after *Braile et al.*, 1974], and C-P is the model for the Colorado plateau in southeastern Utah [after *Roller*, 1965]. The large numerals are P velocities in kilometers per second.

The major difference between model A and model B is the absence of a crustal LVL, and our preference for inclusion of this layer is based upon several observations. If PIR arrivals are identified and their travel times included in the inversion scheme, then an LVL is present in the derived model. Large-amplitude arrivals that are delayed by 1.0–1.5 s relative to Pg are present and are interpreted as reflections from the bottom of the LVL (PcR). Model A correlates well with velocity models derived for nearby areas that include an upper crustal LVL. Persistence of the Pg phase beyond 100 km may be due to wide-angle PIR arrivals arriving nearly simultaneously with Pg.

CONCLUSIONS

The crustal velocity models in Figure 6 depict the variations in crustal structure across the transition zone between the Great basin and the Colorado plateau–Middle Rocky Mountains. These models suggest a mantle upwarp of low-velocity material (~7.5 km/s) roughly centered beneath the Wasatch front and approximately coincident with a zone of high seismicity, the intermountain seismic belt [*Smith and Sbar*, 1974]. The exact width and configuration of the mantle upwarp are difficult to ascertain. However, our refraction profile begins 30 km west of the Wasatch front and terminates 50 km east of this boundary (Figure 1). Because this profile shows no evidence of significant changes in crustal structure, a minimum width of at least 80 km for the upwarp is suggested.

Magnetic variation data taken on an east-west profile across the Great basin–Colorado plateau transition [*Porath*, 1971] show an upwarp of high-conductivity material centered beneath the Wasatch front. Moreover, heat flow data [*Sass et al.*, 1971; *Roy et al.*, 1972; *Costain and Wright*, 1973] show the Great basin–Colorado plateau transition in a zone of high heat flow. Together these data suggest a mantle upwarp associated with low Pn velocity, high heat flow, and low resistivity.

An implication of the east-west extent of the mantle upwarp is that the physiographic boundary (Wasatch front) between the Great basin and Colorado plateau is clearly west of the transition in crustal structure between these provinces. This observation is in accord with similar conclusions drawn from other refraction studies [*Ryall and Stuart*, 1963; *Braile et al.*, 1974]. Also *Shuey et al.* [1973] have recently documented a lateral change in crustal magnetization between the Great basin and Colorado plateau that occurs 50 km east of the physiographic boundary.

The presence of the upper crustal low-velocity layer may be related to the mechanism of Cenozoic faulting and seismicity. As was proposed by *Shurbet and Cebull* [1971], an LVL could provide a region of low rigidity capable of absorbing the large displacements associated with Cenozoic block faulting characteristic of the Great basin. Thus the presence of an LVL east of the Wasatch front could provide an explanation for the presence of Cenozoic block faulting east of the province boundary (Figure 1). The shallow seismicity characteristic of the intermountain seismic belt [*Smith and Sbar*, 1974] also extends east of the Wasatch front and is roughly coincident with the easternmost zone of Cenozoic normal faulting. The shallow nature of the seismicity could be due in part to the LVL acting as a low-rigidity layer in which the occurrence of earthquakes would be reduced.

We conclude that a mantle upwarp is suggested along th
transition zone (Figure 1) between the Great basin and th
Colorado plateau. This conclusion is based upon observa
tions of a thin crust (~25 km), a low Pn velocity (~7.5 km/s
high heat flow, and high seismicity along the transition zone.
we assume that this feature continues further north along t
intermountain seismic belt, as was suggested by *Smith a*
Sbar [1974] and *Braile et al.* [1974], and is relatively fixed w
respect to a westward moving North American plate, we
speculate that the Great basin is actively growing eastwar
the expense of the Colorado plateau.

Finally, we suggest that an upper crustal LVL is pr
throughout the transition zone between the Great basi
Colorado plateau–Middle Rocky Mountains provinces
correlation of high heat flow, low resistivity, shallow se
ity, Cenozoic normal faulting, and anomalous magnet
with the crustal LVL suggests a genetic relationship,
data are not sufficient to define the mechanism.

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Chronology of Mid-Tertiary Volcanism in High Plateaus Region of Utah

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ABSTRACT

Potassium-argon age determinations on volcanic rocks, including some from recently defined stratigraphic units, from central and southwestern Utah provide a chronology of volcanism of Oligocene to middle Miocene age in this region. These data demonstrate the feasibility of, and provide a framework for, correlation throughout the High Plateaus region and adjacent areas of the Basin and Range province.

INTRODUCTION

Potassium-argon age determinations were made on samples of volcanic rock from the southwestern High Plateaus of Utah (southern Sevier Plateau, northern

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and central Markagunt Plateau, and southern Tushar Mountains) and adjacent areas of the Basin and Range province. These determinations were made in the potassium-argon laboratory at Ohio State University. Figure 1 illustrates the Tertiary stratigraphy of the central Utah region, as determined by Anderson and Rowley (1975), who collected the samples used in this study.

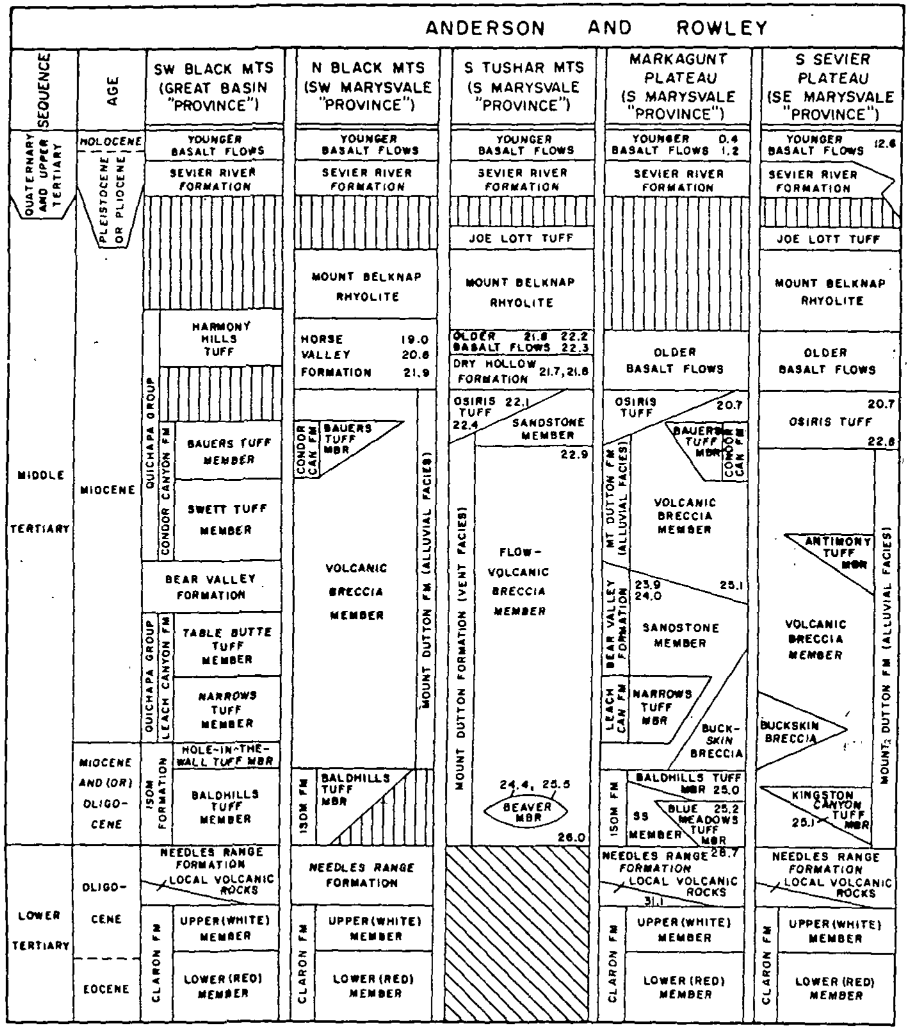

Figure 1. Correlation chart of Cenozoic stratigraphy of central Utah (after Anderson and Rowley, 1975).

POTASSIUM-ARGON AGE DETERMINATIONS

Thirty samples were analyzed by the potassium-argon method and are reported in Table 1. Potassium was determined by flame photometry, using a Zeiss PF-5 instrument and standard procedure for chemical separation of alkali metals for analysis (Cooper, 1963). Two independent potassium analyses were made on each sample. Whole-rock, hornblende, and most of the feldspar samples were powdered to less than 100 (Tyler) mesh, homogenized, and two splits were taken for analysis. Biotite, which is difficult to powder because of its cleavage, was split in a microsplitter, giving adequately reproducible results. Variances were calculated from the data for each sample, using standard techniques. Coefficients of variation were used to compensate for real differences in potassium content. Assuming that all samples of a given type of material (for example, biotite and whole rock) have a common variance when treated as percentages, a pooled estimate of the variance of each was made in the manner described by Crow and others (1960, p. 68). Coefficients of variation calculated for each type of material are plagioclase, 0.78 percent; biotite, 0.56 percent; and whole rock, 0.70 percent. If it is assumed that all potassium analyses have a common coefficient of variation (irrespective of composition), then a group estimate can be made, yielding a coefficient of variation of 0.65 percent. It will be noted that $(n-1)$ was used instead of (n) in determining the variance of each pair of analyses. This has the effect of doubling the estimate of variance in these samples, where $n = 2$, and increasing the estimated standard deviation (s_o) by a factor of $\sqrt{2}$. The estimated coefficient of variation of all analyses would be 0.46 percent, if n were substituted for $(n-1)$.

Argon analyses were made by isotope dilution, using extraction systems similar to those described by Dalrymple and Lanphere (1969) and Evernden and Curtis (1965). Tracers used were manifold or "batch" tracers, calibrated with a precision of about 1 percent (coefficient of variation). Isotope ratios were measured on a Nuclide, 6-in. radius, 60° sector mass spectrometer, operated in the static mode. The reproducibility of argon analyses by the Ohio State laboratory is generally within ± 2 percent, as has been demonstrated previously (Fleck and others, 1972). Single argon determinations were made in this study because of the number and variety of samples and because stratigraphic control provided a monitor of internal consistency. Error estimates shown in Table 1 were made in a manner similar to that described by Cox and Dalrymple (1967), using the percentage of radiogenic argon in the individual analyses, standard deviations of replicate potassium analyses and tracer calibrations, and estimated confidence intervals ($1\ \sigma$) on the isotope ratios determined for each spectrometer analysis.

DISCUSSION OF RESULTS

Of the 13 different geologic units shown in Table 1, two have a definite range in age and represent sequences accumulated over a significant period of time. The Mount Dutton and Horse Valley Formations (Anderson and Rowley, 1975) together represent deposition of a wide range of volcanic and sedimentary strata from at least 26 m.y. B.P. until about 19 m.y. B.P. With the exception of the basalts and the old andesite (R-21), the remaining units probably represent discrete

TABLE 1. POTASSIUM-ARGON AGE DETERMINATIONS

Geologic unit[*]	Sample no.	Lat (N)	Long (W)	Area[†]	Material[§]	K$^+$ (%)	Moles ^{40}Ar[#] (per gram × 10^{-10})	^{40}Ar[#] (%)	Age[**] (m.y.)
Younger basalt	R-29	37°51.8′	112°46.4′	MP	W	1.727, 1.701	0.0134	11.0	0.44 ± 0.04
Iron Point intrusion	R-28	37°50.9′	112°42.1′	MP	W	1.268, 1.272	0.4481	27.2	19.7 ± 0.5
Horse Valley Formation	R-34	38°04.2′	113°03.6′	NBM	W	3.341, 3.324	1.1349	32.5	19.0 ± 0.6
	R-38	38°06.7′	113°00.1′	NBM	W	2.679, 2.668	0.9865	62.7	20.6 ± 0.4
	R-31	38°04.8′	113°10.5′	NBM	B	6.961, 6.961	2.7291	73.5	21.9 ± 0.4
Dry Hollow Formation	R-32	38°16.9′	112°26.8′	STM	B	7.032, 6.931	2.7114	71.2	21.7 ± 0.4
	R-16	38°16.5′	112°28.0′	STM	S	7.149, 7.201	2.8002	80.8	21.8 ± 0.4
	EM-1	38°57.5′	111°48.2′	WP	B	6.963, 7.020	2.7366	66.5	21.8 ± 0.4
Older basalt	R-17	38°14.3′	112°28.8′	STM	W	2.385, 2.418	0.9370	86.7	21.8 ± 0.4
	R-20	38°12.3′	112°23.4′	STM	W	2.788, 2.788	1.1125	86.9	22.3 ± 0.4
	R-22	38°12.0′	112°26.7′	STM	W	2.844, 2.785	1.1181	85.9	22.2 ± 0.4
Osiris Tuff	R-3	38°09.9′	112°01.8′	SSP	B	7.207, 7.184	2.9377	65.4	22.8 ± 0.4
	R-12	38°11.6′	112°36.3′	STM	B	6.945, 6.884	2.7345	68.8	22.1 ± 0.4
	R-24	38°10.5′	112°30.6′	STM	B	7.056, 6.962	2.8156	78.7	22.4 ± 0.4
	ES-1	38°57.5′	111°48.2′	WP	B	7.163, 7.137	2.8518	51.8	22.3 ± 0.4
Bauers Tuff	R-11	37°50.0′	112°31.0′	MP	P	1.010, 1.006	0.3999	41.5	22.1 ± 0.6
Mount Dutton Formation	R-27	37°45.3′	112°40.6′	MP	W	1.374, 1.385	0.5109	51.5	20.7 ± 0.5
	R-23	38°11.4′	112°29.6′	STM	W	1.695, 1.691	0.6932	82.4	22.9 ± 0.4
	R-15	38°12.7′	112°33.8′	STM	P	0.649, 0.649	0.2839	26.7	24.4 ± 0.8
	R-5	37°57.1′	112°34.7′	MP	W	1.249, 1.244	0.4659	41.2	25.1 ± 0.7
	R-13	38°09.5′	112°35.9′	STM	P	0.842, 0.858	0.3888	38.6	25.5 ± 0.5
	R-19	38°15.1′	112°15.4′	STM	H	0.794, 0.794	0.3696	38.8	26.0 ± 0.8
	R-1	38°12.1′	112°06.2′	SSP	B	6.595, 6.550	2.9530	66.4	25.1 ± 0.4
Bear Valley Formation	R-9	37°51.7′	112°33.6′	MP	P	0.844, 0.842	0.3610	36.1	23.9 ± 0.5
	R-10	37°52.2′	112°32.0′	MP	B	7.197, 7.243	3.1024	56.1	24.0 ± 0.4
Isom Formation (Baldhills)	R-8	37°51.3′	112°34.0′	MP	P	1.000, 0.998	0.4476	56.2	25.0 ± 0.4
Isom Formation (Blue Meadows)	R-7	37°58.2′	112°26.0′	MP	P	1.016, 0.997	0.4546	33.1	25.2 ± 0.4
Needles Range Formation	R-25	37°42.4′	112°46.0′	MP	B	7.202, 7.176	3.7000	62.7	28.7 ± 0.5
Post-Claron Tuff	R-4	38°00.4′	112°32.5′	MP	B	6.826, 6.784	3.7946	66.8	31.1 ± 0.5
Andesite	R-21	38°11.8′	112°26.5′	STM	W	1.884, 1.901	1.1159	84.7	32.8 ± 0.5

[*] After Anderson and Rowley (1975).

[†] After Anderson and Rowley (1975); NBM = northern Black Mountains; STM = southern Tushar Mountains; MP = Markagunt Plateau; SSP = southern Sevier Plateau; WP = Wasatch Plateau.

[§] B = biotite; W = whole rock; H = hornblende; P = plagioclase; S = sanidine.

[#] Radiogenic.

[**] Error estimate, made in manner similar to that of Cox and Dalrymple (1967), represents one standard deviation.

TABLE 2. COMPARISON OF K-AR RESULTS WITH ANALYSES REPORTED BY OTHER LABORATORIES

Geologic unit	Previous K-Ar age(s) (m.y.)*	K-Ar age (m.y.) (Table 1)	Best estimate of age (m.y.)
Bauers Tuff Member	21.5(a)	22.1	21.7
Osiris Tuff	20.3(d)	22.4	22.4
Isom Formation (Baldhills)	25.0(a)	25.0	25.0
Isom Formation (Blue Meadows)†	25.8(a)	25.2	25.5
Needles Range Formation	29.1§ (a); 28.6(h); 29.3(k)	28.7	28.9

*Letters indicate age reported by (a) Armstrong (1970); (d) Damon (1968); (h) R. K. Hose (1974, oral commun.; analyses by J. D. Obradovich); (k) Kistler (1968). Ages are mean values if multiple determinations are reported.

†Armstrong's value was reported to be for "Roger Park Breccia," but is considered Isom Formation by Anderson and Rowley (1975). Localities are identical.

§Armstrong's samples 831, 170B, 834B, and 183B were included here, although omitted from his (1970) average.

"events." That is, any range in age has not been demonstrated by radiometric dates, although the low precision of determinations on the Needles Range Formation would permit an interpretation of real age differences among cooling units. A comparison of results obtained in this study with age determinations reported by others is shown in Table 2.

The age obtained on biotite from the Needles Range Formation (28.7 m.y.) compares favorably with previously reported determinations. As noted by Mackin (1960) and Cook (1965), and as demonstrated by Grommé and others (1972), Best and others (1973), and Nairn and others (1975), the Needles Range Formation is composed of several members of at least slightly different ages. Armstrong (1970) has suggested from a statistical standpoint that any age difference among members is, however, not demonstrable, as the precision of analyses of this unit is lower than normally expected. This low precision (about 4 percent coefficient of variation) may be due in part, however, to real age differences. Additional (unreported) analyses by J. D. Obradovich, U.S. Geological Survey, Denver, for R. K. Hose show a similarly large variation, but a similar mean. These samples, DKA numbers 1009-1013, from the Confusion Range (lat 39°19.5′ N., long 113°41.5′ W.) yield ages of 29.7 ± 1.2, 29.8 ± 1.2, 29.0 ± 1.1, and 26.5 ± 1.1 m.y., respectively (R. K. Hose, 1974, oral commun.). If the ages from all sources (excepting three excluded by Armstrong, 1970) are pooled, a mean value of 28.9 m.y. with standard deviation of 1.2 m.y. (4.3 percent coefficient of variation) is obtained from the 18 available determinations. The "true age" of the Needles Range Formation may be slightly older, as suggested by Armstrong (1970). However, until a complete study relates dated samples to the proper cooling units, or additional information adequately disqualifies some of the determinations, the 28.9 ± 1.2-m.y. value should be considered the best estimate of the radiometric age of the formation.

Our age determination of plagioclase from the Baldhills Member of the Isom Formation (25.0 m.y.) is identical to that obtained by Armstrong (1970) from a whole-rock sample. Armstrong considered that determination to be too young, based on stratigraphic correlations placing the dated unit below the "Roger Park Breccia," upon which ages of 25.8 and 27.2 m.y. were obtained. Our sample number R-7, from almost exactly the same locality as Armstrong's sample 167 (25.8 m.y.), gives an age of 25.2 m.y. on plagioclase. Sample R-7 was collected from the Blue Meadows Tuff Member of the Isom Formation, which is probably the same unit as that sampled by Armstrong. As with the Baldhills Member, the age dates obtained by the two laboratories on different material are indistinguishable within experimental error. Because of the large difference in potassium content between our samples and those of Armstrong (0.999 percent versus 4.76 percent K^+ for the lower member), incomplete argon loss after formation is extremely improbable. If loss did occur, it must have been complete loss (resetting) at about 25 m.y. B.P. and must have occurred over an extremely large area. This is even less probable, as older units would also be totally reset, and this is not observed. For these reasons, the average ages of 25.0 m.y. and 25.5 m.y. for the Baldhills and Blue Meadows Members of the Isom Formation, respectively, must be considered representative of the times of emplacement. Armstrong's determination of 27.2 m.y. cannot be explained with existing information and must await further investigation. The age, however, is well within the range of analyses on the Needles Range Formation, which also contains abundant biotite and hornblende.

Four samples of Osiris Tuff were analyzed in this study, three collected by Anderson and one (ES-1) by Edward Erb while he was a graduate student at Ohio State University. These analyses are consistent, with a mean age of 22.40 m.y. and standard deviation of 0.25 m.y. (1.1 percent). A sample reported to be Osiris Tuff was analyzed by Damon (1968), who reported a value of 20.3 ± 0.5 m.y. That this age represents the time of formation for the Osiris Tuff is improbable, as it is much greater than three standard deviations from the mean of the other analyses.

The Dry Hollow Formation, as restricted by Anderson and Rowley (1975), is composed of gray and brown porphyritic rhyodacite(?) lava flows. This follows the original definition of the Dry Hollow Latite of Callaghan (1939), which was later redefined by Callaghan and Parker (1962) to include a variety of mafic and intermediate lava flows and tuff units of different ages. The redefinition by Anderson and Rowley (1975) restricts the Dry Hollow Formation to flows of intermediate composition that postdate the Osiris Tuff (Tuff of Osiris; Williams and Hackman, 1971) and predate the Mount Belknap Rhyolite. Strata below the Osiris Tuff and above the Needles Range Formation in the Sevier Plateau region are referred to the Mount Dutton Formation by Anderson and Rowley (1975).

As indicated by Table 1, in this context the Dry Hollow Formation marks a distinct time horizon that apparently is present (perhaps discontinuously) from the southern Tushar Mountains to the area of Salina, Utah, on the Wasatch Plateau. Our three samples give essentially identical ages, averaging 21.8 m.y. Armstrong (1970) reported an age of 24.5 m.y. for "Dry Hollow Latite," which he considered equivalent to the Isom Formation. Armstrong's sample (170) was collected near Glenwood, Utah, where he also sampled the Needles Range Formation (170B), and only a short distance southwest of Salina, Utah, where Edward Erb collected samples (Table 1) of the Osiris Tuff (ES-1) and the Dry Hollow Formation (EM-1). The 24.5-m.y. age obtained by Armstrong (1970) is significantly older than the Osiris Tuff and probably represents a unit in the older part of the Mount Dutton Formation of Anderson and Rowley (1975) and not the Dry Hollow Formation. The age and stratigraphic position of the sampled unit are similar to those of the Beaver Tuff and Kingston Canyon Tuff Members of the Mount Dutton Formation (Anderson and Rowley, 1975), from which samples R-1, R-13, and R-15 were collected. As mentioned by Armstrong (1970), they are also similar to those of the Isom Formation. However, these units are considered to be derived from local sources, physically separate from those of the Isom Formation (Anderson and Rowley, 1975).

The ages of the Needles Range Formation at the base of the volcanic sequence (28.9 ± 1.2 m.y.), the Osiris Tuff (22.4 ± 0.3 m.y.), and the Dry Hollow Formation, as restricted (21.8 ± 0.1 m.y.), are now well established. These units and the Mount Belknap Rhyolite, dated by Bassett and others (1963), are lithologically distinctive and cover large areas of the High Plateaus region, providing a basis for extending the mid-Tertiary stratigraphy through much of the remaining Marysvale volcanic center. Combined with data compiled by Armstrong (1970), the determinations reported here demonstrate that the same stratigraphic units can be traced well into the Basin and Range province.

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PRECAMBRIAN GEOCHRONOLOGY OF THE NORTHWESTERN UNCOMPAHGRE PLATEAU, UTAH AND COLORADO

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Abstract.—During an orogeny about 1,700 m.y. ago a sequence of sedimentary and volcanic rocks was folded and metamorphosed. The basement on which these rocks were deposited has not been recognized, and any history prior to 1,700 m.y. ago has been obscured by the intensity of this orogeny. Precambrian sedimentary rocks less than 1,700 million years old are unknown in this area. Gneissic granodiorite was intruded approximately 1,670 m.y. ago. No further record exists until after the emplacement of a batholithic mass of Vernal Mesa Quartz Monzonite approximately 1,480 m.y. ago. A later biotite-muscovite granite was probably intruded about 1,400 m.y. age. This chronology correlates with chronologies determined for other parts of Colorado.

The Uncompahgre Plateau is a tectonic and physiographic high that extends northwestward from the San Juan Mountains in southwestern Colorado to the Uinta basin in east-central Utah. Precambrian igneous and metamorphic rocks are exposed in the deeper canyons along the northwest half of the plateau. Case (1966) has recently made a combined geological and geophysical study of the northwestern part of the plateau. A geochronological study of these rocks, because of their location, provides a stepping stone for the construction of regional correlations of Precambrian events. The closest other exposures of Precambrian rocks are in the Black Canyon of the Gunnison River 60 miles to the east (Hansen and Peterman, 1968) (p. C80–C90, this chapter) and in the San Juan Mountains about 100 miles to the southeast (Silver and Barker, 1967; Bickford and others, 1967).

GEOLOGY OF PRECAMBRIAN ROCKS

Four major units of Precambrian rocks with characteristic lithology and geophysical properties have been recognized by Case (1966). The oldest unit consists of thousands of feet of complexly folded metamorphic rocks. This unit can be subdivided into feldspathic gneiss, amphibole gneiss, porphyroblastic biotite-microcline gneiss, and biotite gneiss (Case, 1966, fig. 1, p. 1428–1429). The relative ages within this sequence are unknown, but the structural relations suggest that the feldspathic gneiss is the oldest unless the whole sequence has been overturned. The entire sequence has been folded repeatedly and metamorphosed to a high grade. These rocks are interpreted as being largely metasedimentary, but some parts may represent metamorphosed igneous rocks, and some of the amphibolites were probably emplaced as mafic sill-like intrusions.

The second major unit is composed of gneissic granodiorite. This rock intruded the sequence of metamorphic rocks. It varies in composition from granodiorite to quartz monzonite and varies in texture from foliated to massive.

In the central part of the area mapped by Case (1966) there is an elliptical pluton of metagabbro and metadiorite. It also intruded the metamorphic sequence, but is nowhere in contact with the gneissic granodiorite.

The Phanerozoic rocks on the southwest flank of the Uncompahgre Plateau, in this area, are apparently underlain by coarsely porphyritic biotite-quartz monzonite, the fourth major unit. Exposures of this rock are widespread (Case, 1966; Shoemaker, 1956). These exposures and the rock's unusually high magnetic susceptibility enabled Case (1966, fig. 11, p. 1441) to delineate an elongate batholith trending northwest along the southwest flank of the plateau. This rock has a very distinctive appearance. Shoemaker (1956) first noted its striking similarity to the Vernal Mesa Quartz Monzonite of the Black Canyon of the Gunnison River 60 miles to the east (see Hansen and Peterman, 1968). The lithologic similarity is so impressive that we believe that they are correlative, although perhaps not a single, continuous mass at depth.

The Vernal Mesa Quartz Monzonite is generally massive. It intruded both the metamorphic rocks and the gneissic granodiorite. These facts and its more dis-

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cordant style of intrusion suggest that it is the youngest of the four major units.

Although not occurring in the area mapped by Case, another type of granite crops out in the eastern part of Unaweep Canyon. It is a pinkish-gray medium-grained two-mica granite which locally contains garnet. Shoemaker (1956) believed it to be the youngest granite in the area, and we have seen intrusive contacts of this granite into the Vernal Mesa Quartz Monzonite. This young granite is practically identical with the typical Curecanti Quartz Monzonite of the Black Canyon and strongly resembles some of the bodies of Silver Plume Granite exposed in the Front Range.

AGE DETERMINATIONS

Four rock units were dated by the whole-rock Rb-Sr method. These were the feldspathic gneiss and porphyroblastic gneiss members of the metamorphic sequence, the gneissic granodiorite, and the biotite-quartz monzonite. The metagabbro was unsuitable for Rb-Sr dating. Hornblendes from a satellite hornblendite and from an amphibolite within the metamorphic rocks were dated by the K-Ar method. Sample localities are shown on figure 1.

The Rb-Sr analytical data for all the samples are given in table 1 and the K-Ar data in table 2. Analytical procedures were the same as those described by Peterman and others (1967). The uncertainty in the Rb^{87}/Sr^{86} ratio is ±3 percent and that of the Sr^{87}/Sr^{86} is 0.1 percent. The K-Ar ages have an uncertainty of ±3 percent.

The feldspathic gneiss, which may be the oldest rock in the area, is unfavorable for dating by the Rb-Sr whole-rock method because it has a very low rubidium content and a relatively high strontium content. We used this age method, however, because we decided that this determination would be less affected by obviously later events. The feldspathic gneiss gives an age of 1,630 m.y. (fig. 2) with a very large uncertainty of ±130 m.y., owing to the unfavorable Rb/Sr ratio of the rock.

The porphyroblastic gneiss has a more favorable Rb/Sr ratio and gives an age of 1,670 m.y. (fig. 3) with the smaller uncertainty of ±30 m.y. We interpret these ages as approximating the time of metamorphism rather than the time of deposition (see Hedge and others, 1967).

The gneissic granodiorite, which intrudes the metamorphic rocks and is probably late tectonic, gives an age of 1,670±40 m.y. (fig. 4).

Only two samples of Vernal Mesa Quartz Monzonite fresh enough for dating were obtained from this area. The analytical results are plotted, together with analyses of samples of Vernal Mesa Quartz Monzonite from the Black Canyon, in figure 5. This isochron indicates an age of 1,480±40 m.y. The samples from the two areas all fit the line well within experimental error, thus supporting the lithologic correlation.

TABLE 1.—*Sample locations and whole-rock* Rb-Sr *analytical data*

[Rb and Sr concentrations determined by isotope dilution, except where otherwise indicated]

Sample No.	Location		Concentration (ppm)		Ratios	
	Lat (N.)	Long (W.)	Rb	Sr [1]	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} [2]
			Feldspathic gneiss			
D1265	38°59.0′	109°10.3′	8.63	404	0.0618	0.7040
D1266	38°59.0′	109°10.3′	6.24	344	.0525	.7041
D1267	38°59.0′	109°10.3′	16.65	392	.1229	.7056
D1270	38°59.0′	109°9.8′	2.39	326	.0213	.7028 .7034
D1271	38°59.1′	109°9.7′	18.41	305	.1746	.7060 .7066
D1273	38°56.4′	109°9.2′	11.46	108	.3068	.7097 .7098
D1269	38°59.0′	109°9.8′	[3] .7	[3] 259	-------	-------
			Porphyroblastic gneiss			
D1286	39°2.5′	109°7.5′	84.5	313	0.782	0.7207
D1287	39°2.5′	109°7.5′	117	319	1.063	.7271
D1288	39°2.5′	109°7.5′	126	313	1.163	.7296
D1289	39°2.5′	109°7.5′	92.5	302	.887	.7228
			Gneissic granodiorite			
D1272	38°57.2′	109°3.6′	172	137	3.629	0.7871
D1277	38°56.7′	109°7.9′	167	102	4.747	.8105
D1279	38°56.5′	109°3.2′	142	148	2.779	.7660
D1280	38°56.2′	109°3.3′	108	317	.986	.7239
			Quartz monzonite			
D1290	38°50.7′	108°32.9′	114	287	1.151	0.7280
D1292	38°45.6′	108°54.7′	112	652	.499	.7142
D1291	38°45.8′	108°54.7′	[3] 116	542	-------	-------

Constants: $Rb^{87}\lambda_\beta = 1.39 \times 10^{-11}\ yr^{-1}$
$Rb^{87} = 0.238$ g per g Rb

[1] Normal Sr.

[2] Fractionation effects corrected for by normalizing observed Sr^{86}/Sr^{88} ratio to 0.1194.

[3] Determined by X-ray fluorescence.

TABLE 2.—*Sample locations and* K–Ar *analytical data for hornblende*

Sample No.	Location		K (percent)
	Lat (N.)	Long (W)	
D1268	39°59.0′	109°10.3′	0.367
D1276	38°56.5′	109°8.6′	.395

Sample No.	Ar^{40} (moles/gram)	Radiogenic argon (percent)	Age (m.y.)
D1268	1.44×10^{-9}	97	1,460±50
D1276	1.40×10^{-9}	96	1,360±50

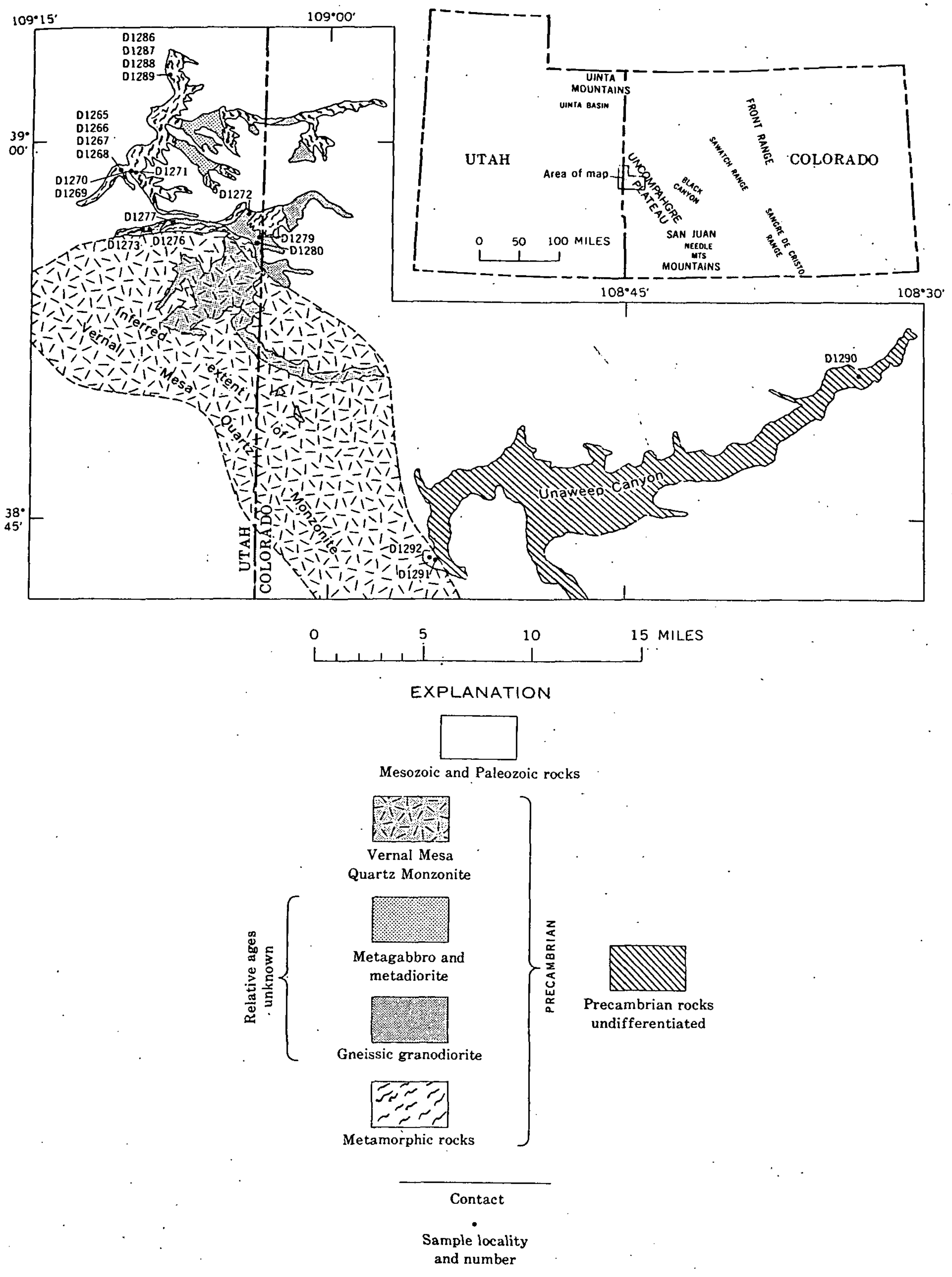

FIGURE 1.—Map of generalized Precambrian geology showing sample localities in the northwestern Uncompahgre Plateau.

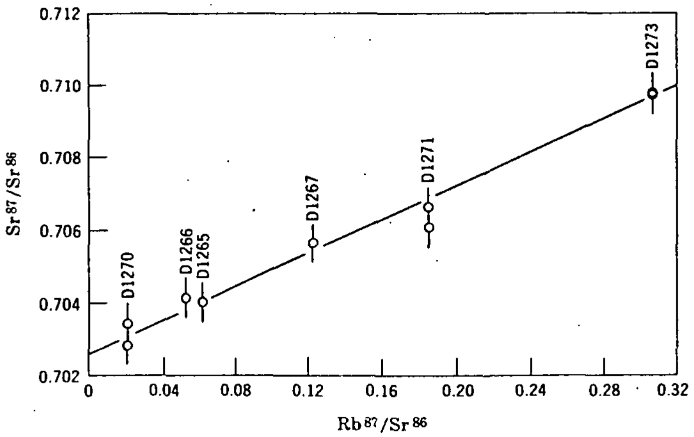

FIGURE 2.—Rb-Sr isochron plot for samples of the feldspathic gneiss from the metamorphic sequence. Age=1,630±130 m.y.; initial Sr^{87}/Sr^{86}=0.7026.

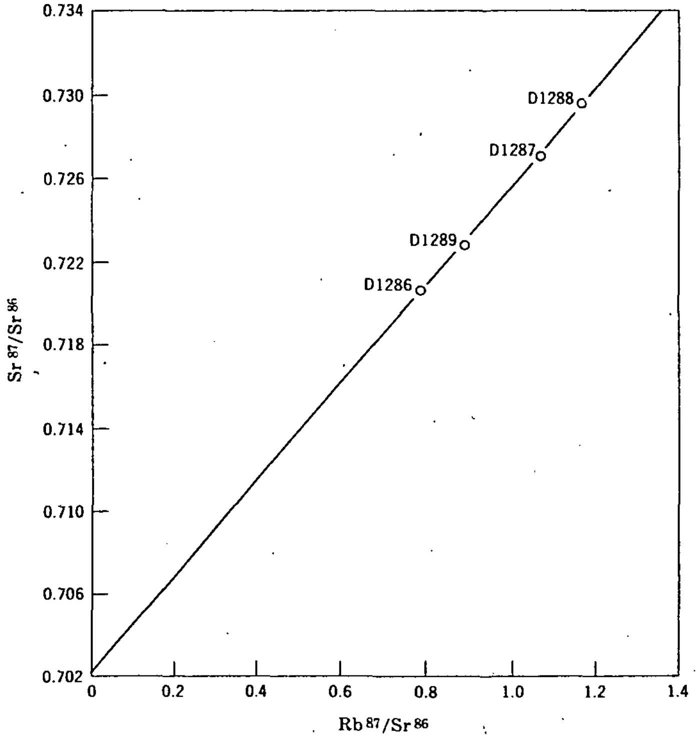

FIGURE 3.—Rb-Sr isochron plot for samples of the porphyroblastic gneiss from the metamorphic sequence. Age=1,670±30 m.y.; initial Sr^{87}/Sr^{86}=0.7022.

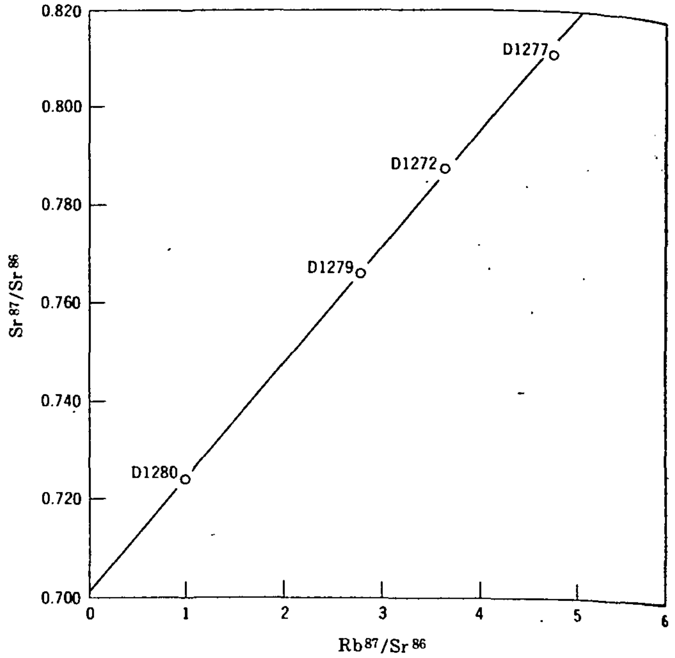

FIGURE 4.—Rb-Sr isochron plot for samples of the gneissic granodiorite. Age=1,670±40 m.y.; initial Sr^{87}/Sr^{86}=0.701.

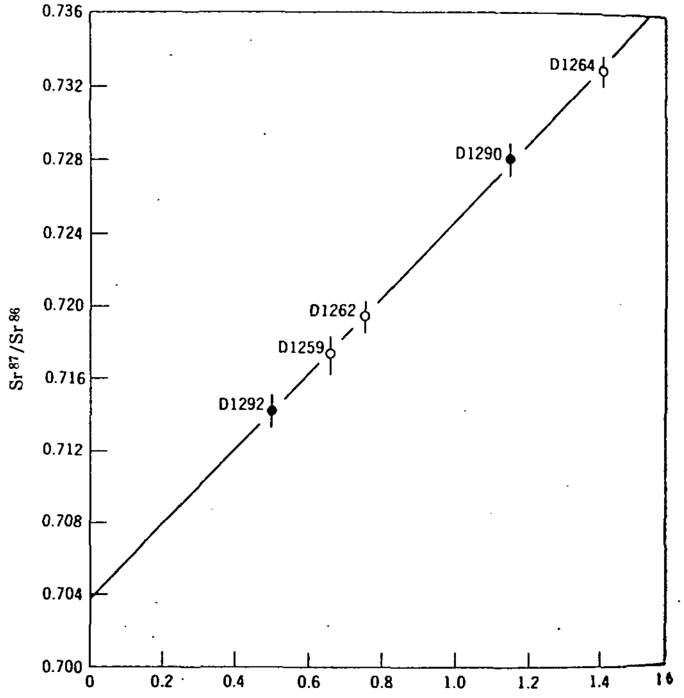

FIGURE 5.—Rb-Sr isochron plot for samples of the Vernal Mesa Quartz Monzonite. Solid dots, samples from the Uncompahgre Plateau; circles, samples from the Black Canyon of the Gunnison River. Age=1,480±40 m.y.; initial Sr^{87}/Sr^{86}=0.7037.

The biotite-muscovite granite from the east end of Unaweep Canyon was not dated as part of this study. Ages from this rock have been published, however, by Aldrich and others (1955, 1958). They reported K-Ar and Rb-Sr ages of biotite of 1,300 and 1,370 m.y., respectively. These same authors reported an isotopic U-Pb analysis of an apatite from this rock. This U-Pb age is rather sensitive to the common lead correction which is chosen. When we use the value which B. R. Doe (oral commun., 1968) found for a similar rock from central Colorado, a Pb^{206}/Pb^{207} age of 1,490 m.y. is obtained. While more dating needs to be done, this rock appears to be approximately contemporaneous with the Curecanti Quartz Monzonite of the Black Canyon (1,410 m.y., according to Hansen and Peterman, 1968) (p. C80–C90, this chapter), which it strongly resembles.

The K-Ar ages of the hornblendes from the amphibolite and the hornblendite are 1,460 and 1,360 m.y., respectively. These do not fit the chronology established by the Rb-Sr ages, and we believe that the K-Ar ages have been reset by what must have been significant regional thermal effects accompanying the emplacement of the younger granites.

SUMMARY AND CORRELATIONS

We interpret the Precambrian history of the northwest Uncompahgre Plateau as follows: A thick accumulation of sedimentary and volcanic rocks was deposited and probably intruded by basic sills prior to 1,700 m.y. ago. A complex history of folding and metamorphism culminated about 1,700 m.y. ago, and late in this orogenic cycle the gneissic granodiorite was emplaced about 1,670 m.y. ago. Although no age was obtained from the metagabbro, its degree of metamorphism and its tectonic setting suggest that it too was emplaced in the 1,650–1,700 m.y. interval.

The next major event was intrusion of the Vernal Mesa Quartz Monzonite 1,480 m.y. ago. This was apparently followed fairly closely by intrusion of biotite-muscovite granite, probably in the 1,400–1,450-m.y. interval—the last major Precambrian event which has been recognized in this area.

A correlation of this history together with that of other areas in Colorado is summarized in table 3. The metamorphic rocks from the Uncompahgre Plateau appear to be slightly younger than those from nearby areas, but the relatively large uncertainties of the ages

TABLE 3.—*Provisional correlation chart for some major Precambrian units of Colorado*

[The position of the geologic name on the chart approximates the radiometric age except where modified by known geologic relationships. A question mark above or below the name indicates that the precise position on the chart is not known. Numbers in parentheses refer to sources of data as follows: (1) Peterman and others (1968); (2) Hutchinson and Hedge (1967); (3) Hedge (1967); (4) T. W. Stern (*in* U.S. Geological Survey, 1964, p. A95); (5) Hedge and others (1967); (6) Pearson and others (1966); (7) B. R. Doe (oral commun., 1968); (8) Wetherill and Bickford (1965); (9) Hansen and Peterman (1968); (10) Bickford and others (1967); and (11) Silver and Barker (1967)]

AGE (m.y.)	FRONT RANGE	SAWATCH RANGE	BLACK CANYON	UNCOMPAHGRE UPLIFT	NEEDLE MOUNTAINS
1,400					
1,450	Silver Plume and Sherman Granites (1,2,3)	[1] St. Kevin Granite (6,7) Pegmatites (8)	Curecanti Quartz Monzonite (9)	? Biotite-muscovite granite ?	
1,500			Vernal Mesa Quartz Monzonite (9)	Vernal Mesa Quartz Monzonite	Eolus Granite, gabbro of Electra Lake, granitic dikes (10,11)
1,550					
1,600					? Uncompahgre Formation (11) ?
1,650		Granite to granodiorite (8)			
1,700	Boulder Creek Granite (1,2,3,4)	Augen gneiss of Trout Creek (Mosquito Range) (2)	Metamorphism (9) Pitts Meadow Granodiorite (9)	Gneissic granodiorite Porphyroblastic gneiss Feldspathic gneiss	
1,750	Metamorphism (5)		Black Canyon Schist (9) ?		Posttectonic granites (10,11) Metamorphism (11)
1,800	Idaho Springs Formation (5) ?				Twilight Granite (11) Irving Greenstone (11) Vallecito Conglomerate (11)

[1] B. R. Doe reports a U-Pb zircon age of 1,420 m.y. for the St. Kevin Granite, compared with a whole-rock isochron age of 1,470 m.y. reported by Pearson and others (1966).

from this area make it possible that the metamorphism is exactly correlative. Muehlberger and others (1966) reported three ages from the buried basement to the north and west of this area. These indicate that the two periods of igneous and metamorphic rocks activity approximately 1,400–1,450 m.y. and 1,700–1,750 m.y. ago affected rocks for an as-yet-undetermined distance north and west of the Uncompahgre Plateau.

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TERTIARY STRATIGRAPHY OF NORTHERN UTAH AND SOUTHEASTERN IDAHO

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INTRODUCTION

The following data are from published material, personal communication with various geologists familiar with the region, and from three months Tertiary reconnaissance by the writer and W. J. Pelletier.

The Tertiary rocks of this region can be conveniently grouped into four broad lithologic types: (1) fluviatile and lacustrine sediments of Late Miocene and Pliocene age, the Salt Lake group; (2) basalt flows of from Middle (?) Miocene to Recent age, the Snake River basalts; (3) an essentially-acidic volcanic series of flows and pyroclastics of Oligocene and Miocene (?) age; and (4) post-orogenic conglomerates, sandstones, and shales of Earliest Paleocene to Early Eocene age, the Wasatch group and upper beds of the Henefer formation. They are not co-extensive in their distribution (see Figure 1). The Salt Lake group is the most widely distributed in the region under discussion, since it can be found in most, if not all of the valleys and along many of the elevated benches on the flanks of mountain ranges. Its distribution is not shown in Figure 1.

Salt Lake Group

This name was originally given by Hayden (1869) to light-gray to white beds outcropping in Salt Lake and Morgan Valleys, Utah. These light-colored beds in Morgan Valley have been subsequently named the Norwood tuff (Eardley, 1944). Because of its lower Oligocene age (vertebrate remains of Titanothere and an artiodactyl), rhyodacitic composition, and largely fluviatile origin, this formation would seem to be more genetically related to the Oligo-Miocene volcanic series mentioned above than to the basinal deposits of the considerably younger remainder of the Salt Lake group (see Figure 2).

In southern Cache Valley Williams (1952) has subdivided the Salt Lake group into the basal Collingston conglomerate, the West Spring formation, and the uppermost Cache Valley formation, all in unconformable contact (see Figure 2). The Collingston conglomerate, 2,500± feet of boulder and cobble conglomerate with a white calcareous and tuffaceous (?) matrix, is well exposed in Hyrum Bench along the southwest side of Cache Valley about 12 miles south of the city of Logan. It is in fault contact with upper Paleozoic rocks in this locality, but at the north end of Wellsville Mountain overlies red Wasatch group. The West Spring formation, exposed only on Hyrum Bench, is described by Williams as 1,200 feet of mostly soft, earthy, gray tuff, occasional pebble conglomerate, and thin compact stromatolitic limestone in the basal portion. Thin-bedded tuff, tuffaceous sandstone, and pebble conglomerate make up the bulk of the Cache Valley formation, 1,000 to 2,000 (?) feet in thickness. Its base is marked by large round stone conglomerate; occasional porous oolitic and bioclastic limestone is present in the formation. Most of the central portion of Cache Valley is underlain by flat-lying beds of the Cache Valley formation. Exposures are plentiful along the banks of the Bear and Little Bear Rivers. On the basis of plant material (Brown, 1949) and a fresh-water molluscan fauna (Yen, 1946), a Middle to Late Pliocene age is assigned to the Cache Valley formation.

In the Mink Creek area of southern Idaho (T. 14 S., R. 40 E.), in the northern end of Cache Valley, Keller (1952) has measured 5,643 feet of Salt Lake group resting upon Cambrian rocks. He recognizes an upper conglomerate member (3,400′±) and a lower tuff member, 2,200 feet of interbedded thin-bedded white limestone and soft tuff. The lowermost 25 to 30 feet of this section are basal pebble and cobble conglomerate. That Williams' breakdown of the Salt Lake group is not recognizable in Keller's section is indicative of the rapid facies changes so common in these Late Tertiary basinal deposits. Keller describes "very fine grained tuffaceous petroliferous limestone" in the upper part of his Tuff member, which may be correlative with an 83 foot unit of "smoke-gray thin-bedded platy petroliferous limestone" measured by Williams (1948) across the Junction Hills horst (Sec. 15, T. 13 N., R. 2 W.).

Exposures of Salt Lake group in Marsh Creek Valley, Bannock County, Idaho, are relatively few because of the development of thick Pleistocene (?) and Recent fans along the valley sides. Near the town of Virginia, in the banks of Marsh Creek, however, 50± feet of horizontal Salt Lake group consist of soft white marl and thin silty limestone. From the bank of an old dump ground one quarter mile south of the town of Downey a jawbone with 4 teeth of Merychippus cf. isonesus date the beds Late Miocene (Bartovian). This fossil is in the University of Utah collection. Further north in the vicinity of McCammon, strata of Salt Lake

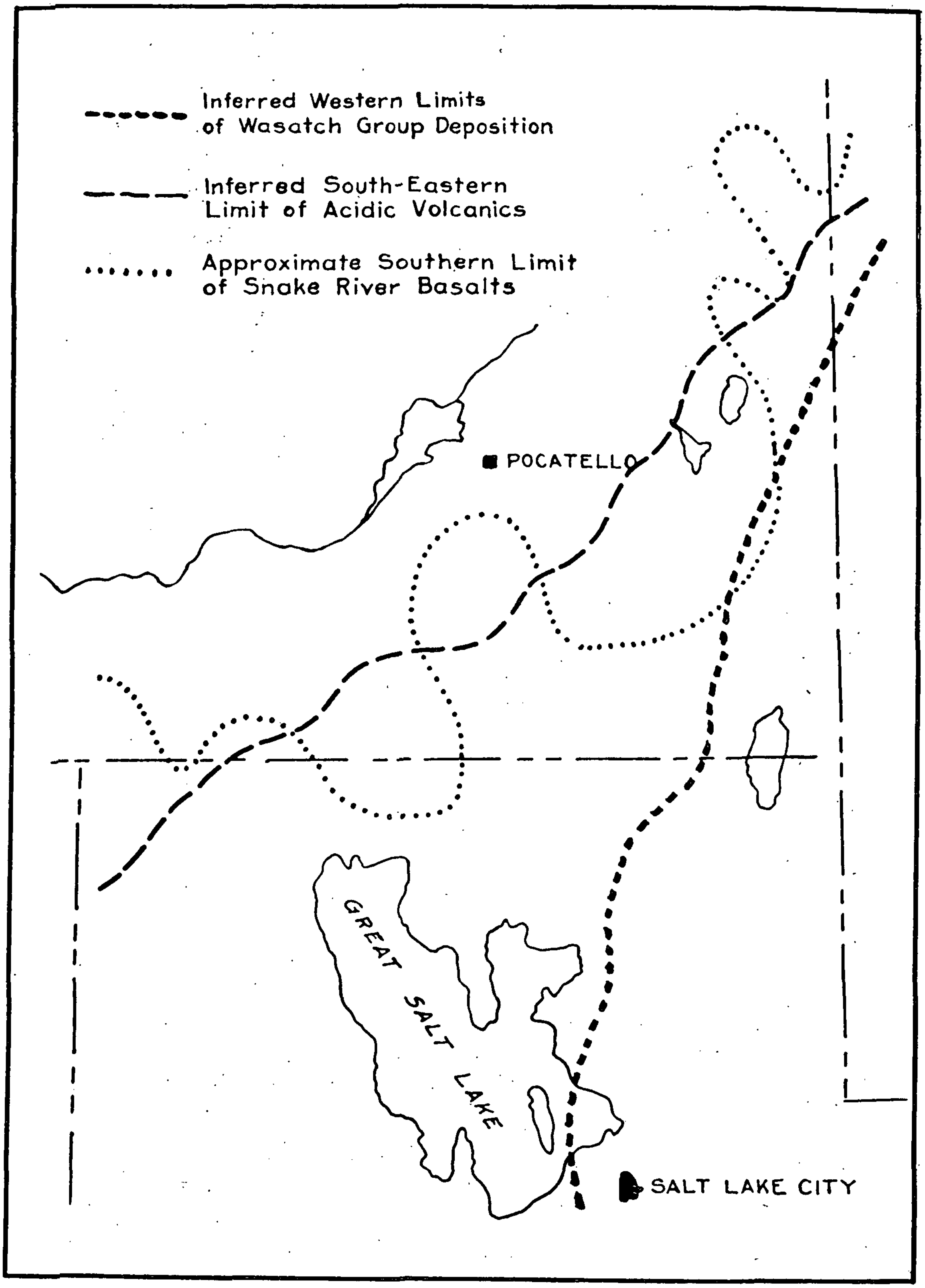

FIGURE 1.—Distribution Map of Tertiary Volcanics and Post-Orogenic Sediments of Northern Utah and Southeastern Idaho.

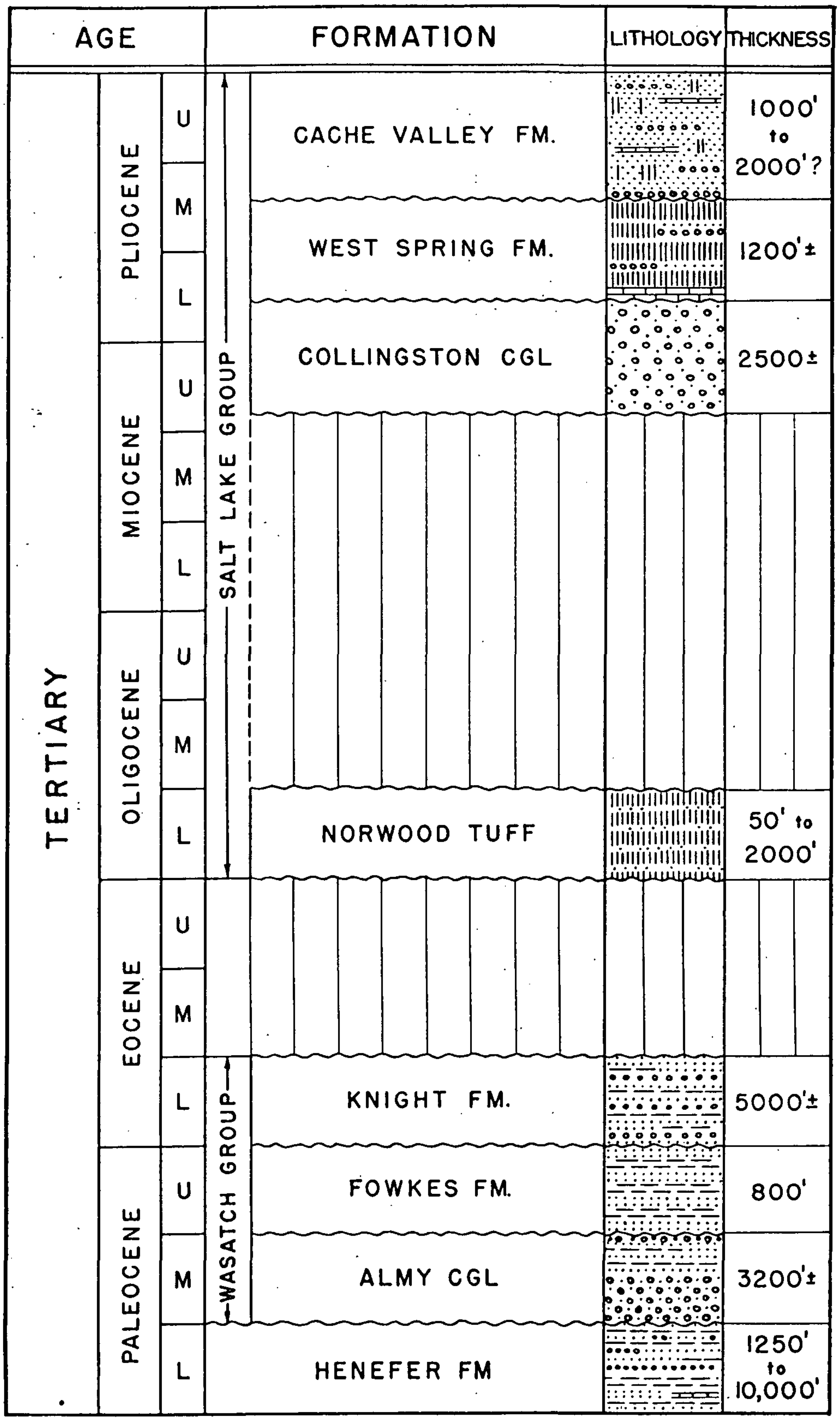

FIGURE 2.—Composite Stratigraphic Column, Tertiary of Northern Utah. (After Eardley, 1944, and Williams, 1952)

group are overlain by 40± feet of Snake River basalt, Pleistocene (?) age, which has flowed southward and southeastward along the valley floor burying the Tertiary lacustrine deposits.

In Bear Lake Valley, particularly near the town of Georgetown, exposures of the Salt Lake group are plentiful in the low hills and road cuts. Largely calcareous light-brown mudstone, greenish tuffaceous shale, and light-gray silty limestone, these beds are abundantly fossiliferous — ostracods, gastropods, pelecypods, fish, and plant remains. Yen (1947) reports a molluscan fauna of Late Miocene age in the vicinity of Georgetown. Traced northward towards Soda Springs the Salt Lake group again passes beneath Snake River basalt flows. The Salt Lake group in Bear Valley probably rests on both Triassic and Eocene rocks and attains a thickness of up to 3,000 feet.

High dips — up to 40 or 50 degrees — in beds of the Salt Lake group in parts of the region under discussion have been produced by rotation of fault blocks and drag along major boundary faults at valley sides. In some local areas, small open folds and anticlinal noses may reflect minor compression associated with "ramp" rather than "graben" valleys. Excluding the Oligocene Norwood tuff, the Salt Lake group is a time equivalent of the Idaho-Payette formations of southwestern Idaho and the Humboldt formation of northeastern Nevada.

Volcanic Rocks

Volcanic rocks outcropping in the area under discussion are the Late Tertiary Snake River basalt and an unnamed Middle Tertiary series of rholitic to andesitic flows and pyroclastics.

The Snake River basalt, so named for its extensive regional development in the plains of the Snake River in southern Idaho, is a series of 12 to 14 (?) thin flows in the type area. The formation represents intermittent basic extrusions occurring probably from Middle Miocent (?) to Recent time. It is dated by the interbedded and overlying fossiliferous basinal sediments, the Idaho formation, Payette formation, Hagerman lake beds, etc. in south-central and southwestern Idaho. In southeastern Idaho, Snake River basalts have apparently flowed southward in local lobes (see Figure 1) confined to present-day valleys. These flat-lying flows rest on Paleozoic to Tertiary rocks and are largely of Late Pliocene and/or Pleistocene age. Their southward thinning and overlying relationship to beds of the Salt Lake group can be seen just north of the town of McCammon, between Soda Springs and Georgetown, and in the northern portion of Grand Valley.

Lower parts of Snake River basalt in the type area are probably correlative with upper flows of the Columbia River basalts of southeastern Oregon.

Few data are available on the "acidic" volcanic series (Oligocene and Miocene ?) of southeastern Idaho. Where seen, however, these interbedded flows and pyroclastics are uplifted with the mountain ranges, topographically higher than the younger Snake River basalts. Dips are generally low or flat. Two localities of notable occurrence are the north ends of the Caribou Range and the Bighole Range. Figure 1 shows the inferred southern limit of thicker acidic volcanics in the area under discussion. As previously mentioned, the Oligocene Norwood tuff of northern Utah may be a local expression of this same period of vulcanism. Andesite tuffs and breccias of the Park City area, also in northern Utah, could be contemporaneous with the Norwood tuff (Eardley, 1944).

Rhyolite flows interbedded with older Snake River basalts of southwestern Idaho seem assignable to this same acidic volcanic series.

Wasatch Group

Early Tertiary deposits of red conglomerate, sandstone, and shale of northern Utah and southeastern Idaho are western equivalents of a generally finer-grained sedimentary series in southwestern Wyoming, named the Wasatch group by Veatch (1907), who subdivided the deposits into the lower Almy formation (Middle Paleocene ?), the Fowkes formation (Upper Paleocene ?), and the upper Knight formation (Lower Eocene ?). In the Morgan Valley area, Morgan County, Utah, Eardley (1944) has mapped these three formations of the Wasatch group and also named a new formation, the Henefer, unconformably below the Wasatch group (see Figure 2). The Henefer formation, red to gray shale, sandstone, and pebble to boulder conglomerate, is probably of latest Cretaceous and earliest Paleocene age since it is above the Upper Cretaceous Frontier formation.

In Morgan Valley Eardley describes the Almy formation as 3,200± feet of chiefly red cliff-making conglomerate but with some sandstone and shale in the upper part; the Fowkes formation as 800 feet of light-gray grit, sandstone, and shale, largely of volcanic origin; the uppermost Knight formation is a series of red conglomerate, sandstone, and shale 5,000± feet in thickness. The Wasatch group thins markedly eastward, from 9,000± feet in Morgan Valley to 3,000-6,000 feet in the Evanston area of southwestern Wyoming (Veatch, 1907). The coarseness of the Early Tertiary sediments in the Morgan Valley area, the truncation of older formations by younger, and the prominent folds in the strata together record recurrent crustal compressions in this region during Early Tertiary time. Even the Lower Oligocene Norwood tuff, which unconformably overlies parts of the Wasatch group, shows some folding.

About 35 miles north of the Morgan Valley area, in the Logan Quadrangle, Williams (1948) reports thin patches of Wasatch group widely spread in the eastern and southern parts of the quadrangle. Its average thickness is about 300 feet. It is not known to which of the three formations in the Wasatch group these beds are equivalent, as Wasatch deposits can not be traced in continuous outcrop from Morgan Valley into Cache Valley in the Logan Quadrangle. Basal Wasatch in William's area is a distinctive brown stromatolitic, pisolitic, or algal limestone from 0 to 83 feet thick (p. 1144). Above the limestone are red pebble to cobble conglomerate.

Extensive outcrops of Wasatch group are known east and southeast of Bear Lake. Scattered outcrops occur about 6 miles north of the town of Georgetown, Idaho, and on the southwest side of Bear Lake near Garden City. The inferred western limit of Wasatch distribution is shown in Figure 1. The upper North Horn formation, the Flagstaff formation, the Colton formation, and the lower part of the Green River formation of the Gunnison Plateau area of central Utah seem to cover approximately the same time interval as the Wasatch group of northern Utah.

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STRATIGRAPHY AND ORIGIN OF THE MOENKOPI FORMATION (TRIASSIC) OF SOUTHEASTERN UTAH[1, 2]

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ABSTRACT: In southeastern Utah, the Triassic Moenkopi Formation is composed mainly of red and yellowish-gray siltstone, sandstone, mudstone, and limestone. Continuity of individual units is one of the characteristics of this formation and provides a basis for regional correlation. For the purpose of this study, the Moenkopi Formation was divided into five members: (1) Hoskinnini, (2) lower slope-forming, (3) Sinbad Limestone, (4) ledge-forming, and (5) upper slope-forming.

The Moenkopi Formation was deposited on a moderately uniform and gentle west slope which was bordered and sometimes covered by an epicontinental sea. Throughout Moenkopi deposition, a number of environments moved across this slope; however, five fairly distinct sequences of deposition can be recognized. The Hoskinnini Member consists of subaqueous but probably nonmarine deposition in an enclosed basin or restricted bay. The lower shallow marine and paralic sequence of rocks includes the lower slope-forming, Sinbad, and basal ledge-forming members. They were deposited in a variety of shallow marine and shoreline environments and contain locally abundant fossils, including the *Meekoceras* fauna. Most of the ledge-forming member consists of deltaic sediments. An extensive deltaic system spread westward into the Sinbad sea. Recognition of this delta is based upon the horizontal distribution of ledge-forming sandstone and the vertical sequence of facies. A marine transgression reworked deltaic sediments and deposited the extremely continuous beds of the upper slope-forming member in a variety of paralic and shallow marine environments. Evidence of a regressive depositional sequence, followed by fluvial deposition, is present at the top of the Moenkopi at several localities.

The petroleum potential of the Moenkopi Formation of southeastern Utah is related to delta front sandstones in and adjacent to the San Rafael Swell, Circle Cliffs, and Teasdale uplifts.

INTRODUCTION

The Moenkopi Formation of Early Triassic age was named by Ward (1901, p. 403) for rocks exposed in the valley of the Little Colorado River southwest of Moenkopi, Arizona. In southeastern Utah and elsewhere on the Colorado Plateau, this unit constitutes part of an extensive redbed sequence that was initiated in the Pennsylvanian Period with the uplift of the Ancestral Rockies and continued into the Late Jurassic or Early Cretaceous. The Moenkopi is composed of red and yellowish-gray siltstone, sandstone, mudstone, and limestone, with minor amounts of conglomerate and gypsum. The terrigenous materials were derived from the Uncompahgre element of the Ancestral Rockies (Fig. 1); this extensive highland is composed of Precambrian gneiss, schist, and granite (McKee, 1954).

Four major uplifts in southeastern Utah - the San Rafael Swell, Teasdale uplift, Circle Cliffs uplift, and Monument upwarp - provided the areas of investigation (Fig. 1). The first two areas, together with the area of confluence of the Green and Colorado Rivers on the Monument upwarp, were those most intensively studied by the author. The majority of the interpretations presented in this paper are based on these field observations.

STRATIGRAPHY

Regional Relationships

The Moenkopi is a wedge-shaped deposit that thickens to the northwest from a zero edge (?) near the Utah-Colorado border. Within the area of study, thicknesses range from about 200 ft in the eastern portion of the Monument upwarp to nearly 900 ft near Torrey, Utah, in the western Capitol Reef area (Fig. 2). The limestone content of the formation also increases to the northwest, ranging from less than 3 ft over most of the Monument upwarp to over 100 ft in parts of the Teasdale uplift area. West of the study area, in western Utah and eastern Nevada, the limestone thickness increases to more than 1500 ft and dominates the section.

In the Circle Cliffs, Teasdale uplift and San Rafael Swell areas, the Moenkopi Formation unconformably overlies the Permian White Rim Sandstone, or the "Kaibab Formation". Relief of from 15-30 ft can be observed locally along this unconformity; regionally,

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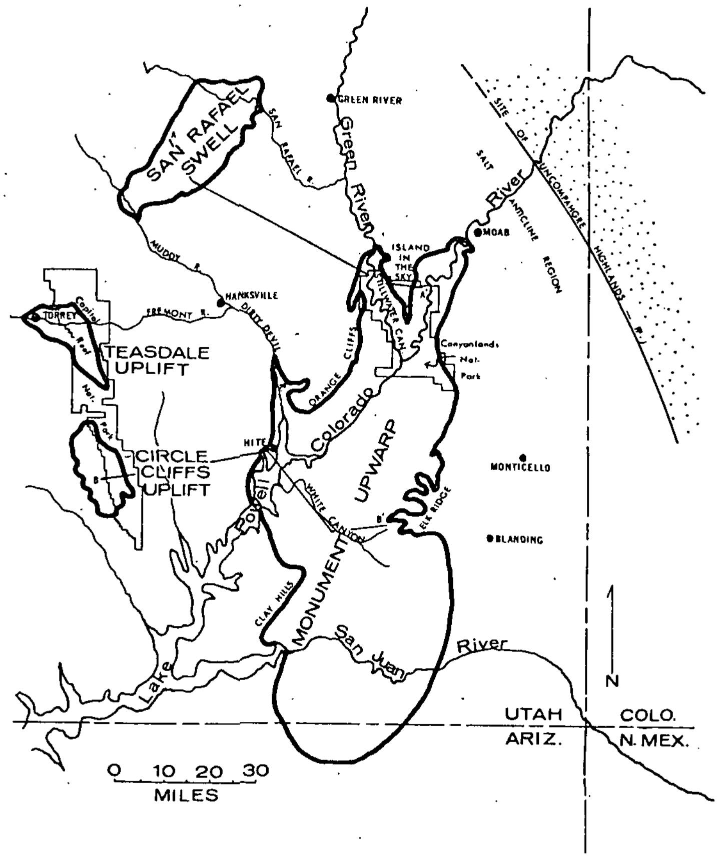


Fig. 1. Index map of southeastern Utah showing the areas of investigation.

the discordance probably is much greater. A detailed account was given by Orgill (1972). In the Monument upwarp, the contact between the Triassic and Permian Systems exhibits complex relationships. Prior to 1959, the Hoskinnini Member was considered to be a tongue of the Permian Cutler Formation, and the Moenkopi Formation was thought to unconformably overlie the Hoskinnini Member. Stewart (1959) demonstrated that the Hoskinnini was more closely related to the succeeding strata, so he assigned this unit to the Moenkopi Formation and considered its age to be Early Triassic(?). Since 1959, most authors have followed Stewart's recommendation, and the Hoskinnini generally is considered to be the basal member of the Moenkopi Formation in the Monument upwarp. The Hoskinnini Member overlies the White Rim Sandstone, the Organ Rock Formation, or the DeChelly Sandstone, all of Permian age. At most localities this contact appears to be unconformable. At the foot of the Orange Cliffs, the Hoskinnini is thin, in places poorly exposed, and locally the same color as the White Rim Sandstone. At that locality, the top of the White Rim is silty and friable, and the nature of the basal Moenkopi contact is obscured.

At all locations, the Upper Triassic Chinle Formation unconformably overlies the Moenkopi. At most localities, the relief on the Chinle-Moenkopi erosional surface ranges from a few ft to a few tens of ft; however, in the central Circle Cliffs area, approximately 300 ft of relief can be demonstrated on this surface by comparing measured surface sections of the upper Moenkopi (Fig. 3). In the San Rafael Swell and northern Monument upwarp areas, the basal Chinle consists of the Moss Back Member, the Monitor Butte Member, or the Temple Mountain Member. In the remaining areas, the basal Chinle normally is the Shinarump Member.

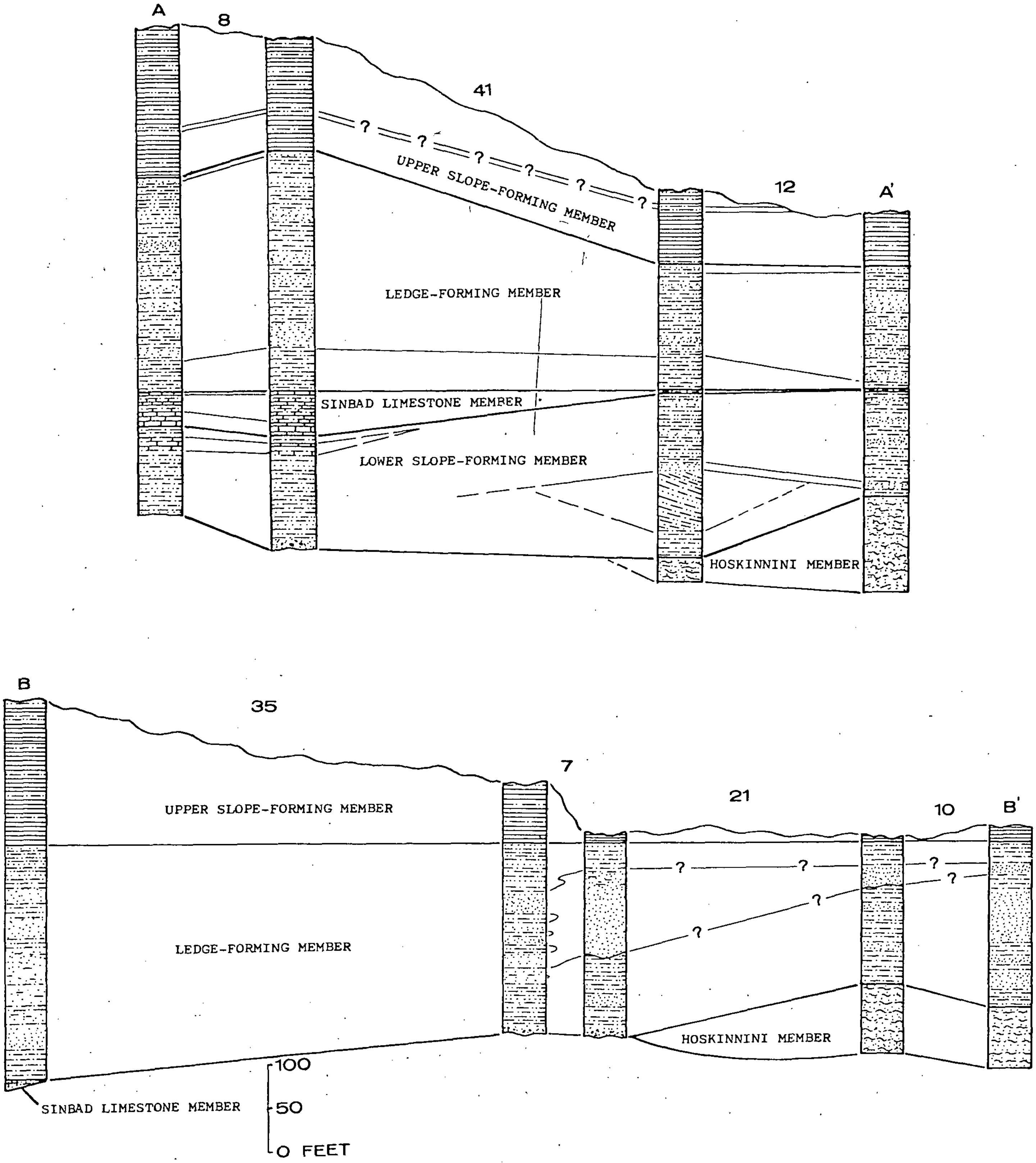
Regional Stratigraphy of Southeastern Utah

The three informal and two formal members used in this study are modified from U. S. Geological Survey terminology (Stewart and others, 1972). The primary basis for correlation is the continuity of the various units, which is demonstrated by key beds that are directly traceable for long distances. The characteristic lithology and landform of the individual members provide easy recognition. A carbonate unit bearing the *Meekoceras* fauna provides an important reference horizon over much of the area. The five members, in ascending order are: (1) Hoskinnini Member, (2) lower slope-forming member, (3) Sinbad Limestone Member, (4) ledge-forming member, and (5) upper slope-forming member. Only the latter two are present over the entire area of study (Fig. 4).

Hoskinnini Member

The Hoskinnini Member, originally defined as a tongue of the Cutler Formation by Baker and Reeside (1929, p. 1422), was placed in the Moenkopi Formation by Stewart (1959), who demonstrated that it can be correlated with the Tenderfoot Member of the Moenkopi Formation in the salt anticline region. In the area of investigation, the Hoskinnini outcrop is restricted to the central and eastern portions of the Monument upwarp. The western pinchout generally lies within five or ten mi east or west of the Green and Colorado rivers (Fig. 4). The Hoskinnini can be distinguished from the upper Moenkopi by its reddish-brown color, which generally is more brilliant than the overlying members. Over most of the Monument upwarp, the Hoskinnini averages 70-100 ft in thickness. It consists of fine-grained, poorly sorted, reddish-brown sandstone and silty sandstone containing well-rounded, medium- to very coarse-grained "floating" quartz detritus that distinguishes the member from other Permo-Triassic redbeds. These grains are scattered throughout individual beds and commonly occur as concentrated pods or stringers. The abundance of these grains decreases upwards, and they generally are absent in the upper 10-30 ft (Stewart, 1959, p. 1859). Common accessory minerals are white mica, feldspar, and lesser amounts of black mica. Most of the unit is well cemented with silica and iron oxide, but locally calcite and gypsum serve as cementing agents.

Bed thicknesses average 2-3 ft and individual beds are continuous for miles (Fig. 5). Strata near the top of the Hoskinnini generally are thinner than those near the base; at many localities, this difference permits dividing the member into two units. Stewart (1959, p. 1860) described a "crinkly" bed which generally marks the horizon of this bedding change in most areas. Faint discontinuous laminations are the only common primary sedimentary structure; they probably represent poorly preserved or partly developed ripple cross-stratification. If viewed on a cut and polished surface, the small-scale sedimentary



Figs. 2A and 2B. Cross sections of the Moenkopi Formation in southeastern Utah showing the relationships of the five members used in this report. The location of the cross sections is shown on Fig. 1.

structures appear as very complex cross-stratification with cut-and-fill structures and indicate that at least some of the Hoskinnini was deposited by currents. Secondary structures related to post-depositional slumping are common in the Hoskinnini. Commonly, a sequence of beds displays a very complexly distorted pattern, with beds above and below completely undisturbed. Slumping structures are described in detail by Stewart (1959) and Thaden and others (1964).

The Hoskinnini Member trends north-south and is present over an area about 40-60 mi wide and 120 mi long. The northern, southern, and eastern edges are concealed beneath younger sediments; however, the western edge commonly is well exposed. The rate at which this western edge thins is unusual and is described in detail by Thaden and others (1969, p. 35-36). Abrupt thinning from over 100 ft to several ft in less than a few mi is common. The western edge of the Hoskinnini Member is conglomeratic and contains angular clasts of white chert up to several in. in diameter. Presumably, this chert was derived from the "Kaibab Formation", which now is absent but possibly once was present on or near the western edge of the Monument upwarp.

Other than the presence of conglomerate along its western edge, the Hoskinnini does not exhibit definite horizontal facies distribution. Mullens (1960, p. 276-277) describes an area of high gypsum and limestone content in the Clay Hills area; and the present author noted a general reduction in grain size north and northwest of White Canyon. At most localities, thinner beds and finer grain size near the top of the member are apparent. Locally, the top of the Hoskinnini Member grades into a lithology similar to that characteristic of the overlying Moenkopi Formation.

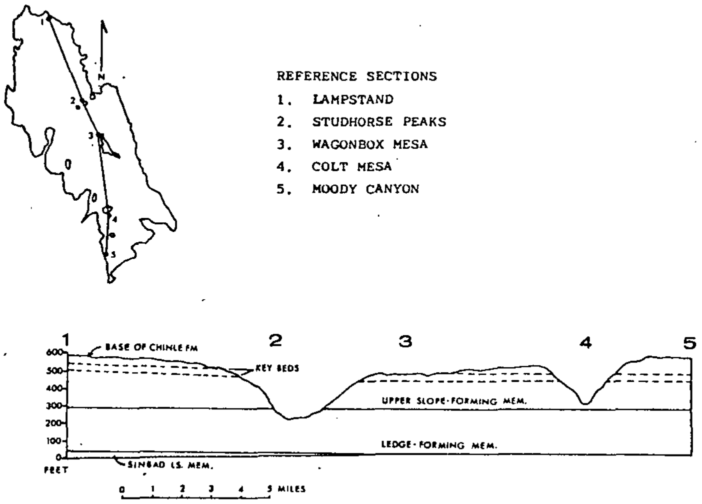


Fig. 3. North-south cross section of the Moenkopi Formation in the Circle Cliffs showing the amount of relief created by pre-Chinle erosion.

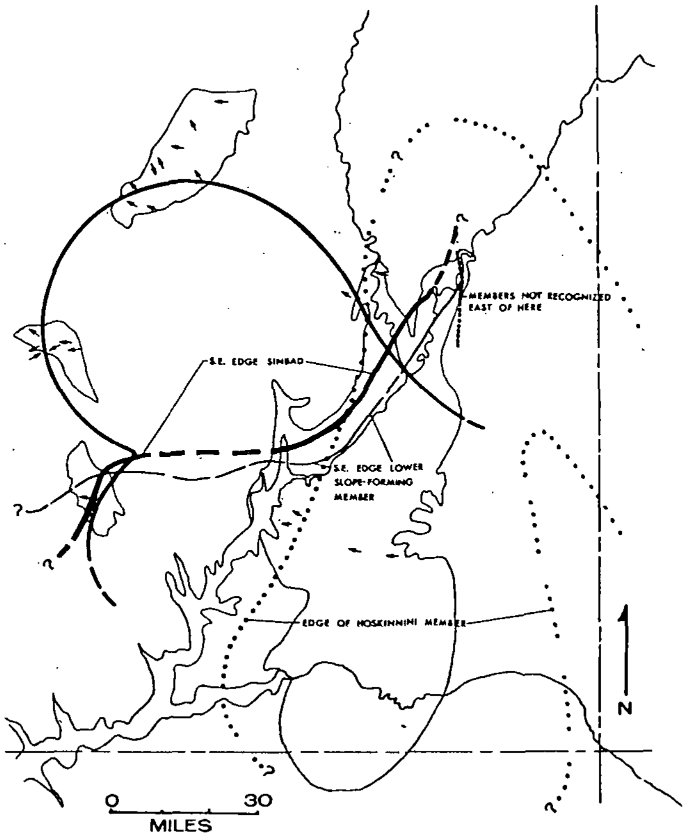


Fig. 4. Map showing distribution of the members of the Moenkopi Formation. The small arrows show direction of sediment transport in the ledge-forming member as shown by sedimentary structures. The bi-lobed line, drawn through points that contain approximately 40 percent by thickness of ledge-forming sandstone and siltstone, is believed to show the position of major deltaic lobes during the deposition of the ledge-forming member. The ledge-forming member and the upper slope-forming member are present over most of the area of study except where the latter has been removed by pre-Chinle erosion.

In White Canyon and the Clay Hills, the Hoskinnini forms a vertical knobby cliff between the underlying slope of the Organ Rock Formation and the overlying slopes and ledges of the Upper Moenkopi. In the Orange Cliffs, Island in the Sky, and Elk Ridge areas the member forms cliffs, ledges, and slopes.

No fossils have been reported from the Hoskinnini, although the writer found some possible wood impressions in White Canyon. To conform with the rest of the Moenkopi, Stewart (1959, p. 1854) assigned a Triassic (?) age to the Hoskinnini Member. Based on stratigraphic position, its age may be either Permian or Triassic; in fact, the systemic boundary may actually lie within this member.

Lower slope-forming Member

The informal term "lower slope-forming member" (or lower member) has been used by many workers, most recently by Stewart and others (1972), for that part of

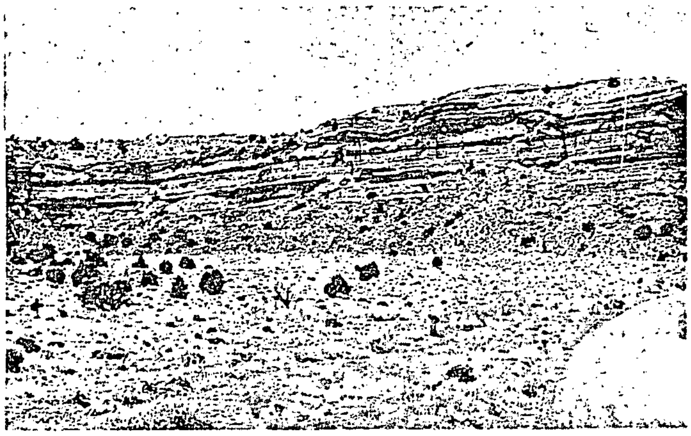


Fig. 5. Photograph of the Hoskinnini Member (Mh) in White Canyon, showing both the contorted or slumped and the even bedding. The Hoskinnini here is about 80 ft thick.

the Moenkopi Formation that lies between the Permian rocks and the Sinbad Limestone Member, or between the Hoskinnini Member and the ledge-forming member. In this report, the lower slope-forming member is restricted to that portion of the Moenkopi which underlies the Sinbad, or traceable Sinbad equivalents. The lower slope-forming member is not recognized in the Clay Hills, White Canyon, or Elk Ridge areas because the Sinbad horizon cannot be identified in these areas. At these localities, the slope-forming unit underlying the sandstone ledges is included in the ledge-forming member because it is considered to be genetically related to this member. The lower slope-forming member is recognized in the San Rafael Swell, Teasdale uplift, northern Circle Cliffs, and northwestern Monument upwarp. Thicknesses range from a few ft near the southeastern pinchout to 235 ft in the northern San Rafael Swell. It is composed of micaceous, ripple-marked, pale reddish-brown to grayish-red or yellowish-gray siltstone, shale, and very fine-grained sandstone, with minor limestone and gypsum. This member exhibits continuous, even beds generally 1-6 in. in thickness. Lenticular beds are extremely rare. Channeling is very small scale (inches to a few feet) and apparently is restricted to the sandy units. At most localities, individual beds can be traced the length of the outcrop, generally from several hundred yards to a mile. Most of the sandstone beds greater than one ft thick display low-angle cross-stratification (less than 10 degrees), and many of the thin beds are ripple marked or show ripple-mark cross-stratification. Mud cracks, common in overlying units, are absent or rare in the lower slope-forming member; but at some localities, gypsum occurs as secondary crosscutting veins or as thin seams parallel to bedding. Pyrite is common in the yellowish-gray beds but apparently is absent in the reddish-colored beds.

The thin carbonate beds are silty or sandy and locally fossiliferous. Mollusks are the dominant macrofauna, and conodonts have been reported by Orgill (1972, p. 155). These carbonate units are most common in the San Rafael Swell near the top of the member and probably intertongue westward with the overlying Sinbad. Other signs of organic activity include bioturbation, burrowing, and various tracks and trails.

The lower slope-forming member thickens irregularly to the north-northwest from a zero isopach that approximately parallels the Colorado River from the northeast corner of Canyonlands National Park to a few miles north of the mouth of the Dirty Devil River, and then westward to the northern Circle Cliffs (Fig. 4).

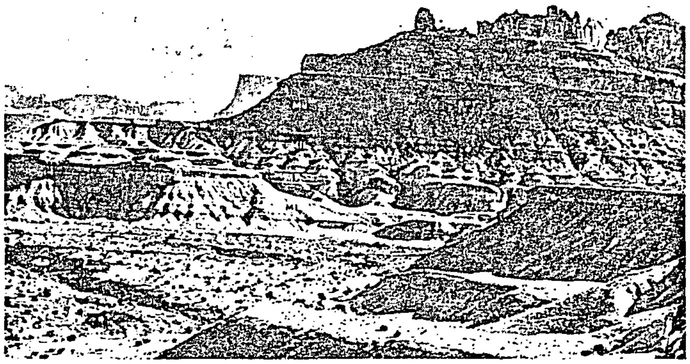


Fig. 6. View of the Moenkopi Formation at the northeastern flank of the San Rafael Swell where Interstate 70 highway enters the "reef". The lower slope-forming member (Ml), the Sinbad Limestone Member (Ms), and the upper slope-forming member (Mu) are typical of exposures elsewhere in southeastern Utah; however, the ledge-forming member (Mlf) contains relatively few ledge-forming units here. The topmost ledge just above the color change can be correlated around much of the Swell. The Moenkopi Formation, which is 866 ft thick here, is overlain by the Chinle Formation and underlain by the Permian Kaibab Formation. Note that the lower two-thirds of the Moenkopi is nonred.

Several distinct facies can be recognized in the lower slope-forming member. In the southern San Rafael Swell, the Teasdale uplift, the northern Circle Cliffs, and the southernmost Orange Cliffs, the member consists entirely of even-bedded siltstone and minor mudstone and limestone, with a few thin sandy beds (Fig. 6). In most of the San Rafael Swell and the Circle Cliffs, the member is not red; in the northeastern and southwestern Swell, the member is partially red; in the Teasdale uplift and southern Orange Cliffs, the member is completely red, with the exception of the lowest and uppermost beds. Local scattered basal chert-pebble conglomerate up to 50 ft thick, and probably related to post-Kaibab topography and erosion, is present in the San Rafael Swell, Teasdale uplift, and southern Orange Cliffs (Orgill, 1972). Fossils, including unidentified conodonts, occur in these beds in part of

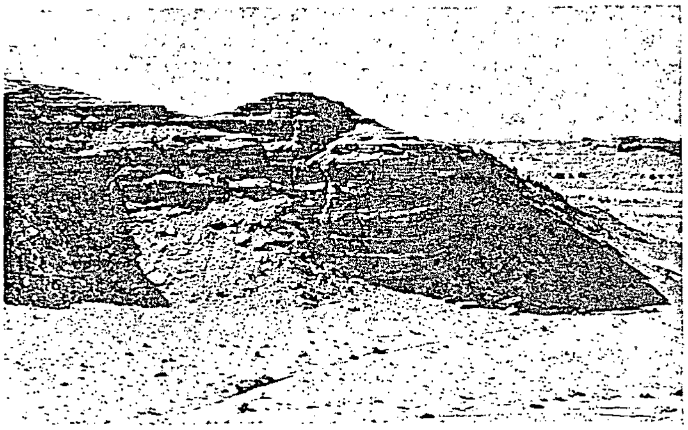


Fig. 7. Photograph of the "angular unconformity" or "delta beds" within the lower slope-forming member in Stillwater Canyon, along the Green River. The angular beds, otherwise identical to the normal flat-bedded units, dip eastward at 10-15 degrees. They are present for at least 20 mi north and south parallel to the canyon and are at least 8 mi wide. This bedform is probably related to delta or estuary deposition. The cliff is about 80 ft high.

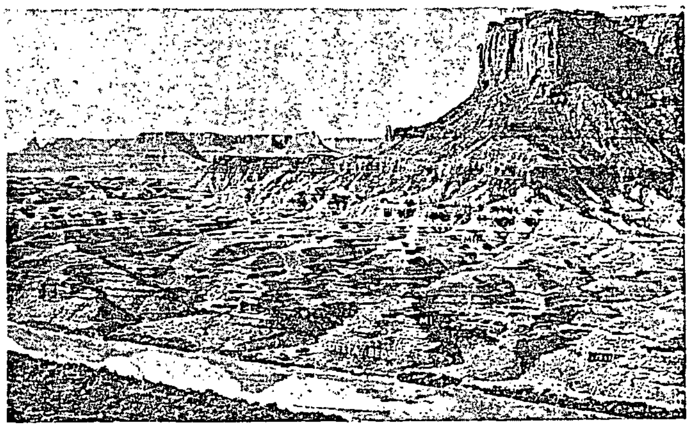


Fig. 8. Photograph of the Moenkopi Formation in Stillwater Canyon near the northern boundary of Canyonlands National Park. The lower slope-forming member (Ml), which comprises nearly one-half of the formation, contains a relatively high proportion of ledge-forming sandstone and siltstone. The Sinbad Limestone (Ms) is less than 5 ft thick and forms a light-colored bench on the red units below. Because of complex intertonguing between the ledge-forming (Mlf) and upper slope-forming members (Mu), the boundary between them is questionable. Note the nonred upper one-half of the 462-ft-thick Moenkopi.

the San Rafael Swell. In the northern Orange Cliffs and Island in the Sky areas, three facies are present. The basal unit is composed of red, even-bedded siltstone with a few minor thin sandstone beds and is similar to the lower slope-forming member of the Teasdale uplift area. This unit is overlain by a typical sequence consisting of red siltstone and sandstone in which all of the beds dip eastward at an angle of about 10 degrees through a vertical thickness of as much as 80 ft (Fig. 7). These beds were believed to be delta foresets by McKnight (1940, p. 54) and are referred to informally in the present paper as the "delta beds". They are exposed in Stillwater Canyon along the Green River for a distance of over 20 mi, where they are overlain with distinct angular unconformity by the alternating sandstone and siltstone facies (Fig. 8). In parts of Stillwater Canyon, over 180 ft of sediment separate the Hoskinnini and Sinbad Members. In the northern San Rafael Swell, the typical even-bedded siltstone facies contains one or more fairly continuous blanket-like sandstone units (Fig. 9). These are believed to be the western equivalents of the uppermost facies in Stillwater Canyon.

In most areas, the lower slope-forming member forms a smooth or slightly irregular slope, except where it forms a cliff beneath the resistant Sinbad. In Stillwater Canyon, the member forms slopes and ledges.

Orgill (1971, p. 155) reported a Lower Triassic conodont, *Neoprioniodus(?)*, from the lower portion of the lower slope-forming member in the western San Rafael Swell. This genus occurs also in the *Meekoceras* beds of Nevada (Orgill, 1971, p. 155). Because the overlying Sinbad contains representatives of *Meekoceras* fauna and is regarded as Lower Triassic, the age of most or all of the lower slope-forming member probably is Lower Triassic.

Sinbad Limestone Member

Gilluly and Reeside (1928, p. 65) applied the term Sinbad Limestone Member to a prominent limestone sequence in the Moenkopi Formation which is exposed in the Sinbad area of the San Rafael Swell. The Sinbad Member is present over the entire Swell, the Teasdale uplift, most of the northern and western Circle Cliffs, and the northwestern portion of the Monument upwarp (Fig. 4). The Sinbad Member is a yellowish-gray or yellowish-brown limestone, dolomite, and calcareous siltstone. The carbonate rock is extremely variable, both vertically and horizontally, and contains micrite (lime mud), oolites, shell debris, unabraded fossils, quartz grains, and dense aphanitic dolomite. In general, dolomite increases in an easterly direction; a yellow color commonly indicates greater dolomite content. Individual beds range in thickness from less than one in. to about three ft.

Sedimentary structures include planar and trough cross-stratification with "sets" up to one ft thick, small-scale ripple-mark cross-stratification that is locally strongly bidirectional (commonly called "herring-bone structure"), mud cracks, numerous tracks and trails, burrowing and other bioturbation, intraformational conglomerate, and several structures believed

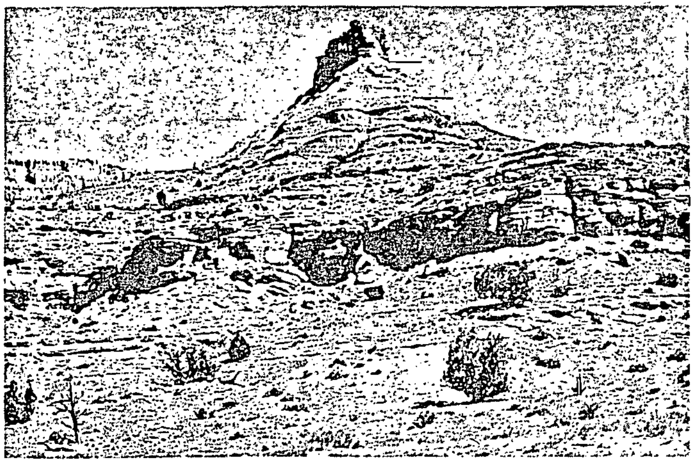


Fig. 9. Photograph of the lower slope-forming (Ml) and Sinbad Limestone Members (Ms) of the Moenkopi Formation near Lockhart Box, in the north-central San Rafael Swell. The prominent sandstone in the middle of the lower slope-forming member is heavily oil-impregnated and is believed to be a beach-bar complex. That part of the section between the 2 black lines consists of alternating siltstone and fossiliferous limestone and probably represents a zone of intertonguing between the two members. About one-half of the unit within the approximately 250 ft of section shown in the photograph is nonred. Five mi to the south and five mi to the west, the entire section is nonred. The lowest beds above the upper line contain the *Meekoceras* fauna.

to be algal in origin. Stromatolite mounds several in. high are found in Stillwater Canyon, and thin layers or mats are common at many localities. Numerous vugs, some of which may be birdseye structures, are characteristic of the thicker carbonate beds.

The Sinbad Member thickens regularly to the northwest and attains a thickness of over 100 ft on the Teasdale uplift. In most sections, the Sinbad Member can be divided into a lower blocky, thick-bedded carbonate rock; a middle thin-bedded, silty carbonate; and an upper dense, medium-bedded pellet-bearing carbonate, usually dolomite. Eastward and southward, toward the shoreline, the Sinbad Member includes more sand grains and generally is more dolomitic. In most outcrop areas, the Sinbad Member forms a cliff or bench (Fig. 9).

The Sinbad Member contains the *Meekoceras* fauna in the San Rafael Swell, Teasdale upwarp and Stillwater Canyon areas (McKnight, 1940). Over 20 ammonites were collected at scattered localities in the San Rafael Swell and Teasdale upwarp; these include *Meekoceras* sp. and *Anasibirites* sp., together with several species not yet identified. Numerous gastropods, pelecypods, a few scaphopods, and echinoderm fragments also were collected at numerous localities. The *Meekoceras* fauna occurs in the *Meekoceras* zone of the Lower Triassic Series (Kummel, 1954; McKee, 1954).

Ledge-forming Member

The ledge-forming member (lower ledge-forming member of Davidson, 1967) is recognized at all localities in the study area. East of the Colorado River, the member constitutes most of the Moenkopi Formation, and to the west it forms from one-half to one-third of the formation. Thicknesses average about 200 ft in eastern sections and 250-350 ft in western sections. It is the only member above the Hoskinnini that is not several times thicker in the western areas than in the east. It is a complex unit, containing nearly every lithology present elsewhere in the Moenkopi Formation, and is composed chiefly of interbedded units of very fine-grained sandstone or silty sandstone and siltstone (Fig. 10). Both lithologies may be red (grayish-red to pale reddish-brown) or nonred (pale yellowish-brown to tannish-gray). The sandstone units form conspicuous ledges and benches that are separated by slopes composed of siltstone similar to that of the lower slope-forming member but generally more intensely ripple-marked. At some localities, mudstone (silt and clay) and, rarely, claystone is interbedded with the siltstone.

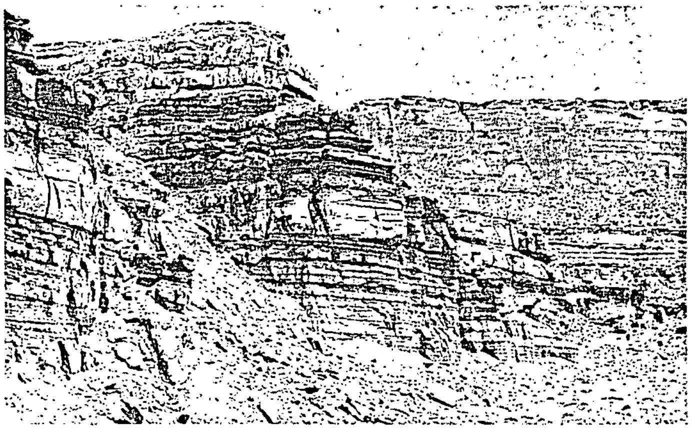


Fig. 10. Photograph of the mostly red ledge-forming member in the extreme southeastern San Rafael Swell, showing prominent ledge-forming units. The cliff is over 80 ft high. This figure, together with Nos. 11, 12, and 13, demonstrate the decrease in ledge-forming units along a south-to-north line 30 mi in length in the San Rafael Swell.

The ledges are composed of three intergradational lithologies. The most common is fine- to very fine-grained sandstone composed of quartz and feldspar. The sand grains are fairly well-sorted, generally angular, and are embedded in a fine silt matrix that generally is red in color. The sandstone typically is very micaceous and well indurated. Cementing agents are calcium carbonate, iron oxide, and, probably, silica. The second most common lithology is very similar to the first but is slightly coarser and occasionally

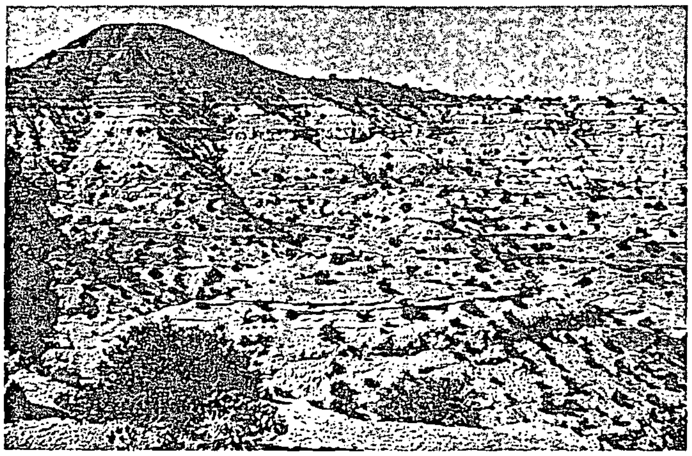


Fig. 11. Photograph 10 mi north of Fig. 10, showing increasing amount of siltstone and decreasing red color in the ledge-forming member. The red, flat-topped butte is the upper slope-forming member. The thin, ledge-forming unit at the color change (white line) can be traced around most of the San Rafael Swell.

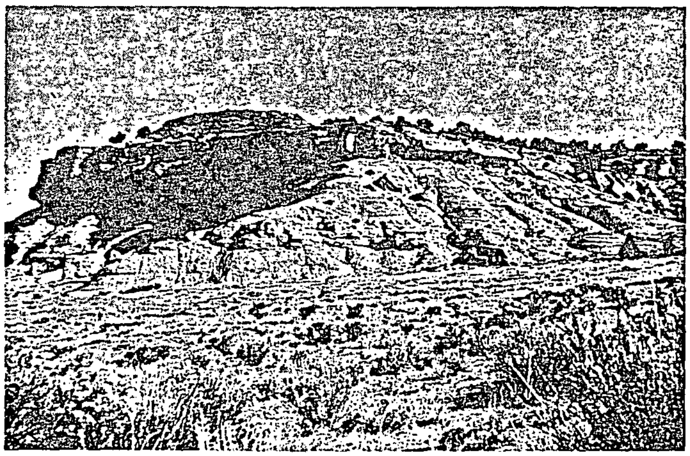


Fig. 12. Photograph 5 mi north of Fig. 11, showing the pinchout of one ledge-forming sandstone and the silty nature of a lower one. All but a few beds are nonred.

has a silty matrix. The third type of sandstone is much less common than the first two and usually is present only east of the Colorado River. It is a fine- to medium-, or rarely coarse-grained, sugary-textured sandstone with angular, colorless quartz grains. This unit locally is conglomeratic and generally occurs as continuous beds less than 2 ft in thickness. Most of the ledge-forming sandstone units display low-angle (less than 10 degrees) cross-stratification, although higher dip angles are common locally. Channels are present at many localities but are very small scale, and basal relief rarely is greater than 2 ft. Bedding in all outcrops is both lenticular and persistent; however, the eastern sections usually contain more lenticular units, and the western sections more persistant units. Ledges range from several in. to 108 ft in thickness, but average 5-30 ft.

The intercalated siltstone, mudstone, and thin sandstone units display a wide variety of sedimentary structures, including ubiquitous ripple marks and mud cracks, load casting, disturbed bedding, intraformational conglomerate, horizontal and ripple-mark stratification, burrowing structures, tracks and trails, feeding marks, and sole markings. Raindrop prints and cubic salt casts also have been reported (McKee, 1954).

The geometry and facies distribution provide strong clues to the origin of the ledge-forming member. The 40-percent line on a plot of the percentage of ledge-forming sandstone at each measured section reveals a distinct bilobed pattern (Fig. 4). The 40-percent line is significant because the ledge-forming sandstone percentage drops off rapidly below this percentage. Field documentation is particularly well displayed in the San Rafael Swell, where the percentage drops from 45 to less than 15 in 30 mi (Figs. 10-13). Where the ledge-forming sandstone percentage drops below approximately 30 percent, it becomes difficult, at some localities, to differentiate the ledge-forming member from the upper slope-forming member (Fig. 13). Accompanying this facies change is a color change from red to nonred, and deposits of tar-impregnated sandstone occur in the nonred strata.

The ledge-forming member displays several important vertical changes. The base everywhere is composed of 10-50 ft of slope-forming siltstone, thin sandstone, or mudstone below the first ledge-forming sandstone. This unit is impossible to separate from the lower slope-forming member where the Sinbad Member is absent; for this reason, the lower slope-forming member is not recognized over much of the Monument upwarp. At many localities, the top of the ledge-forming member contains one or more relatively thin (average 3-10 ft thick), continuous, fine-grained sandstone ledges. One ledge can be traced around most of the San Rafael Swell (Figs. 6, 11, 13); another (possibly the same) ledge can be correlated throughout much of the area around the confluence of the Green and Colorado rivers.

Few diagnostic fossils have been found in the ledge-forming member. The remains of scouring rushes(?) are found in the Elk Ridge area. Numerous trace fossils, including tracks, trails, swim marks, burrows, and feeding marks, are scattered throughout the member; and some questionable mollusks were found in the southwestern San Rafael Swell. Smith and others (1963, p. 13) report *Lingula* specimens from the Teasdale uplift area; Davidson (1967, p. 21) reports fish scales and myalinids characteristic of Lower Triassic strata elsewhere in the world from the Circle Cliffs area; McKee (1954, p. 70, 71) reports trackways from the Capitol Reef area and the Bears Ears on southern Elk Ridge, and fish and amphibian remains from the Bears Ears and Indian Canyon in southeastern Canyonlands National Park. Irwin (1971) essentially correlates the ledge-forming member with the Virgin Member of the Moenkopi Formation in southwestern Utah. This

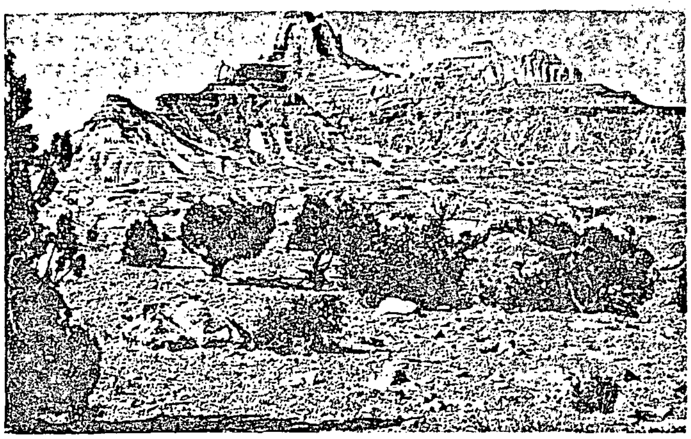


Fig. 13. Photograph of Windowblind Butte, in the extreme northwestern San Rafael Swell. The ledge-forming member (Mlf) is completely nonred and contains only a few ledge-forming units. It is difficult to separate from the nonred upper slope-forming member (Mu). The dashed line marks the contact which is the continuous ledge of Figs. 6 and 11.

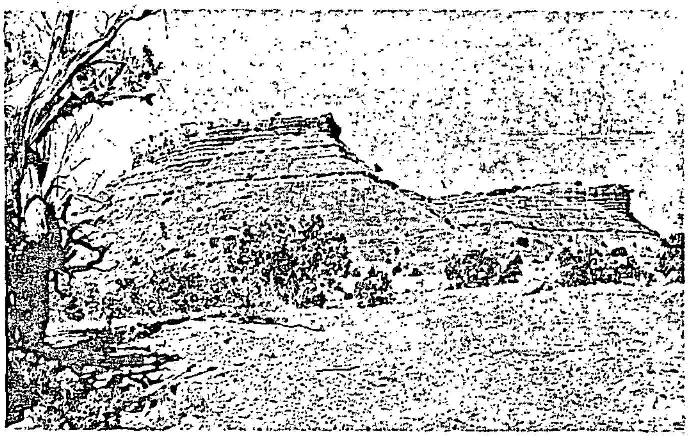


Fig. 14. Photograph of the upper slope-forming member in the southwestern Circle Cliffs showing key beds that can be correlated around entire Circle Cliffs and possibly to the San Rafael Swell. The striped appearance in the lower portion of the member is caused by intercalated thin, nonred ripple-marked siltstone beds. The member here is about 270 ft thick. Light-colored Shinarump Conglomerate (white line) caps the section.

Early

correlation, in conjunction with the Lower Triassic age of the underlying Sinbad Member and the possible Lower Triassic fossils from the Circle Cliffs, place the age of the ledge-forming member as probable Lower Triassic.

Early

Upper slope-forming member

The upper slope-forming member includes all the strata of the Moenkopi Formation between the highest ledge in the ledge-forming member and the base of the overlying Chinle Formation. This division was used by Smith and others (1963), and has been used in modified form by Davidson (1967), and Stewart and others (1972). The latter two authors recognize a cliff-forming member above the upper slope-forming member; however, field recognition of this unit is partly dependent upon the nature of the landforms in the overlying Chinle, making the unit difficult to define. At several localities in the San Rafael Swell, and possibly in Stillwater Canyon, a distinctive unit crops out at the top of the Moenkopi Formation; but because of the limited extent and uncertain relationships, the author prefers to discuss it along with the upper slope-forming member.

Except where removed by pre-Chinle erosion, the upper slope-forming member is present over the entire area of study. The member displays a fairly consistent and uniform west to northwest thickening from a few tens of ft over much of the Monument upwarp to approximately 400 ft in the Teasdale uplift. The member is composed of several distinct lithologies, the most abundant of which is reddish-brown, fissile-weathering, micaceous shale. Because of the fissility, primary sedimentary structures are difficult to study, but the unit appears to be very finely laminated. Interbedded with the mudstone at 4-12 ft intervals are continuous, platy, 0.12-2.0-in.-thick, ripple-marked, micaceous siltstone beds that generally are pale yellowish-gray or grayish-blue in color. They give the slope a distinctive striped appearance (Fig. 14). The upper part of the member contains massive-weathering, silty mudstone and sandy siltstone in beds that average 3-5 ft in thickness. Some of the beds are "structureless"; while others contain "wispy" or faint laminations and, rarely, distinct small-scale cross-stratification. Most of the beds become finer grained upwards and lack channeled bases. Commonly, the top few in. weather to small, thin slabs. These units form obvious ledges in the otherwise smooth slopes and are easily traced for long distances (Fig. 14). Several of these ledges can be traced throughout the San Rafael Swell. The number of ledge-forming beds increases upwards in the member, and this part commonly weathers into a cliff, especially where protected by the overlying Shinarump or Moss Back Members of the Chinle Formation. Gypsum also is common in the upper part of the member, occurring both as beds up to 2 ft in thickness and as cross-cutting veins. Thin beds of fine-grained limestone and dolomite are common at some localities. In parts of the San Rafael Swell, fine-grained sandstone in beds up to 8 ft thick is present at the top of this member.

Several general statements can be made concerning the distribution of the various lithologies within the upper slope-forming member. The fissile mudstone and interbedded thin, ripple-marked siltstone are present throughout the section at all localities. The other lithologies are prevalent in the upper one-third to two-thirds of the member in sections west of the Colorado River. Gypsum and carbonate content increase to the west, as does the number of massive siltstone beds. This, however, may be partially related to the amount of the upper slope-forming member that had been removed by pre-Chinle erosion. For example, in Stillwater Canyon and the Circle Cliffs areas these units locally are absent due to channeling at the base of the Chinle Formation. In the White Canyon and Elk Ridge areas, much of the member probably has been removed by erosion at the base of the Chinle; the nature of the top of the upper slope-forming member in these areas is unknown.

No fossils have been found in the upper slope-forming member. However, it is part of a sequence with few unconformities that contains rocks of Lower Triassic age. It is overlain with erosional unconformity by rocks of Upper Triassic age. Based upon this evidence, the age of this member may be Early or Middle Triassic. The upper slope-forming member may roughly correlate with the Shnabkaib and upper red members of the Moenkopi Formation of southwestern Utah. Because both of these members overlie rocks containing the *Tirolites* fauna, which occurs near the end of the Early Triassic faunal zones (McKee, 1954), many authors have assigned the uppermost units of the Moenkopi Formation a Middle Triassic(?) age. ?

DEPOSITIONAL ENVIRONMENTS

A major goal of this study is to present preliminary ideas concerning the depositional environments of the Moenkopi Formation of southeastern Utah. Most previous papers have dealt with the formation from a limited areal extent and have postulated the depositional environments from evidence dealing primarily with color, continuity of the beds, or presence or absence of marine fossils. According to Hawley and others (1968), color probably is related to the porosity of the units, to structure of the region, and to regional, postdepositional alteration. Stratal continuity, though useful and used extensively as evidence in this report, does not, by itself, indicate depositional environment. Absence of marine fossils does not exclude a marine origin for much of the formation. The main criteria used by the writer in postulating depositional environments are, in order of importance, the following: (1) geometry and horizontal and vertical relationships of the facies and members; (2) sedimentary structures; (3) fossils; (4) known paleogeography; and (5) sediment properties such as grain size, sorting, and mineralogy.

Most workers in this region agree that the Moenkopi Formation was deposited on a nearly planar surface at or near the edge of a sea. Continental conditions prevailed to the east, while marine conditions were dominant to the west. Most of the area of investigation lies within this east-west trending transition zone and, therefore, the sediments are presumed to be in part marine and in part non-marine in origin. The author tentatively concludes that most of the Moenkopi Formation west of the Colorado River is marine and paralic, and that the bulk of it east of the river is paralic and continental in origin, with minor marine deposition.

Because of the low depositional gradients and the relatively stable conditions present throughout much of the study area during Early Triassic time, environments changed slowly; the resulting sedimentary units are gradational and commonly intertongue with adjacent facies. However, several distinct episodes of deposition are recognizable: (1) The Hoskinnini episode, (2) a lower marine and paralic episode, (3) a deltaic episode, and (4) an upper marine and paralic episode. A fifth episode, probably fluvial, corresponds to the few exposures of the fine-grained sandstone sequence at the top of the upper slope-forming member in the San Rafael Swell. The rock sequences representing these depositional episodes cross time lines.

Hoskinnini Episode

The Hoskinnini Member displays no direct evidence to indicate its origin. Paleogeography, however, does provide some useful information. Chert conglomerate in the Hoskinnini in the White Canyon area suggests the presence of a positive area to the west. No time-equivalent rocks occur to the south or southwest, and extensive highlands lay to the east and southeast. This member pinches-out and probably lacks equivalents to the northwest and north (Stewart, 1959), and no known connections to a sea existed to the northeast. Apparently, the Hoskinnini depositional area was rimmed by land. Indications of fluvial conditions, such as channeling and extensive cross-stratification, are absent; continuous beds and indistinct ripple laminations indicate deposition under widespread subaqueous conditions. By definition, such a body of water would be a lake, an inland sea, or a highly restricted bay. The presence of gypsum and carbonate rock units in White Canyon and a deficiency of fossils everywhere in the unit support this hypothesis. A similar conclusion was reached by O'Sullivan (1965, p. 55). He further stated that much of the contorted bedding may be due to subaqueous sliding of unconsolidated sediments. Perhaps the sliding or slumping was caused by earthquakes that may have originated in the salt anticline region to the northeast. A second possibility is that much of the "structureless" bedding was caused by extensive bioturbation. The origin of the coarse "floating" sand grains in the Hoskinnini Member is not well understood. Perhaps alluvial fans at the foot of the Uncompahgre highlands to the east entered the "lake" and became unstable. The resulting turbidity flows and mudflows might have been capable of transporting the coarse sand grains into the center of the basin. Wind action may have transported some of the grains.

Lower Marine and Paralic Episode

Rocks in the lower slope-forming member, Sinbad Member, and possibly lower part of the ledge-forming member probably were deposited in and adjacent to normal marine waters. Marine fossils at the base (Orgill, 1971) and top of the lower slope-forming member in the San Rafael Swell, and marine fossils at most localities in the Sinbad Member provide the best support for this hypothesis. Unfossiliferous, thin-bedded, ripple-marked siltstone was deposited by unrestricted currents, such as are found on tidal flats and on shallow sea bottoms.

Evidence of a prograding shoreline, possibly a delta, is found near the middle of the member in the San Rafael Swell and Stillwater Canyon areas. A continuous fine-grained sandstone unit is present in the northern half of the San Rafael Swell. This unit displays consistent northwest-dipping low- and medium-angle cross-stratification, a gradational base and top, and thicknesses ranging from 11-30 ft, and averaging

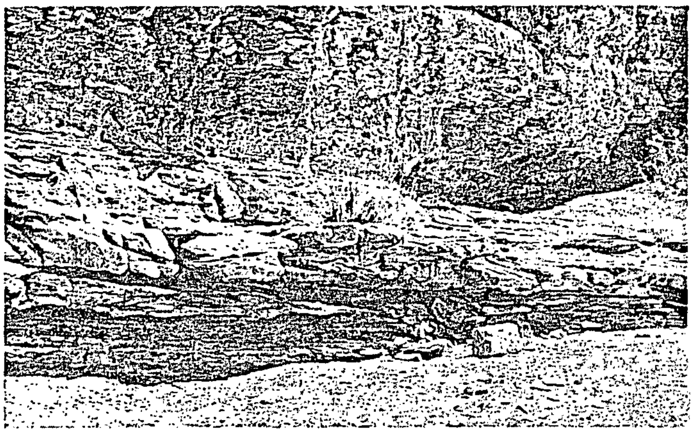


Fig. 15. Photograph in northeast San Rafael Swell of sandstone in the lower slope-forming member. This is the same sandstone shown on Fig. 9. The prominent channel disrupts the otherwise very consistent northwest dip of the cross strata and is believed to be a tidal or inlet channel in a beach or bar sandstone complex. The arrow indicates a geopick used for scale.

about 18 ft. At some localities, the sandstone bed is cut by channels several ft wide and several ft deep that are filled with sandstone similar to that of the main unit (Fig. 15). The main sandstone body is believed to be an offshore bar or beach deposit cut by tidal or inlet channels. This sandstone reservoir contains a large tar sand deposit (Fig. 9). In Stillwater Canyon, several similar sandstone units are present. One can be traced laterally and continuously for over 24 mi, covering an area of over 288 sq mi. This sandstone is coarse- to very fine-grained and displays several types of cross-stratification that show consistent west or northwest dip directions. Immediately below this unit occurs an angular unconformity that overlies eastward-sloping sandstone and siltstone beds (Fig. 7). This sequence of "delta beds", together with the overlying sandstone units, probably were deposited in a complex river-mouth environment, perhaps in a delta or estuary. The angular beds may be true "Gilbert Delta"-type foresets that are characteristic of homopycnal flow which occurs when a river enters a fresh-water body. The extensive sandstone could represent delta-front bar, beach, and shallow marine deposits.

Because the lower slope-forming member thins rapidly and pinches out in the Circle Cliffs, southern Orange Cliffs, and Island in the Sky areas, no widespread equivalent is believed to be present east or south of these areas.

Perhaps due to climatic change in the source area, clastic terrigenous sedimentation waned and permitted widespread carbonate deposition to take place. The sea may not have shifted eastward; only a change in quantity of material being deposited needed to have occurred. Both the Sinbad Member and the lower slope-forming member were deposited in a variety of marine and paralic environments.

Shoreline deposits are present within the Sinbad Member in a band that extends from Stillwater Canyon through the Orange Cliffs and southwestward to the southern Circle Cliffs. In Stillwater Canyon, where the Sinbad Member is less than 5 ft thick, algal stromatolites, thin, laminated algal mats, birdseye structure, and the paucity of fauna (gastropods and a few reported ammonoids) may be indicative of an intertidal or a supratidal environment. Further south, in the Orange Cliffs and Circle Cliffs areas, the edge of the Sinbad Member is very sandy and may represent a nearshore marine or beach deposit.

Elsewhere, the Sinbad Member is thicker and contains both nearshore and offshore deposits. Fossiliferous calcarenite, containing a diverse marine fauna, probably represents normal shallow marine conditions. Similar rock with dwarfed fossils may indicate somewhat restricted marine environments. Oolites, mud cracks, ripple marks, cross-stratification, and bioturbation may indicate shoal areas, such as oolite bars, or tidal mud shoals that formed islands or shallow platforms in the sea. Strongly bimodal, small-scale cross-stratification in the San Rafael Swell is suggestive of tidal flat deposition. The thin, dense, pellet-bearing dolomite that is present at the top of the Sinbad Member at many localities may have been deposited under evaporitic conditions in shallow lagoons.

The overlying siltstone at the base of the ledge-forming member initiated the return to terrigenous clastic deposition. However, this change in lithology does not necessarily indicate a significant change in depositional environment. Rather, this unit probably was deposited under shallow marine and paralic conditions and probably represents a prodelta deposit.

Deltaic Episode

Numerous lines of evidence indicate that a large portion of the ledge-forming member was deposited in a delta complex. The vertical facies indicates that the unit is part of a prograding shoreline. The bilobed distribution of the ledge-forming sandstone unit indicates that it probably is deltaic in origin (Fig. 4). Several facies are recognizable within the delta system: prodelta, delta front, delta slope, delta plain, and fluvial and delta distributary. Within each facies, numerous subenvironments can be recognized; however, the project has not progressed far enough to discuss many of these in detail.

Fluvial and delta-distributary facies

Because of the similarity of the fluvial facies and the delta-distributary facies, they are discussed together. Where the geographic position of the river in relation to the delta is known, the two facies can be separated. Three types of deposits are common in these facies. The most characteristic deposit consists of massive-weathering, ledge-forming sandstone bodies that range up to 108 ft in thickness (averaging 10-20 ft), are broadly lenticular, display erosional bases, and commonly contain a few conglomeratic or coarse sandstone units (Fig. 16). Generally, the sandstone becomes finer grained upward. These sandstone bodies are interpreted as river or distributary channels. Interbedded with the ledge-forming units are

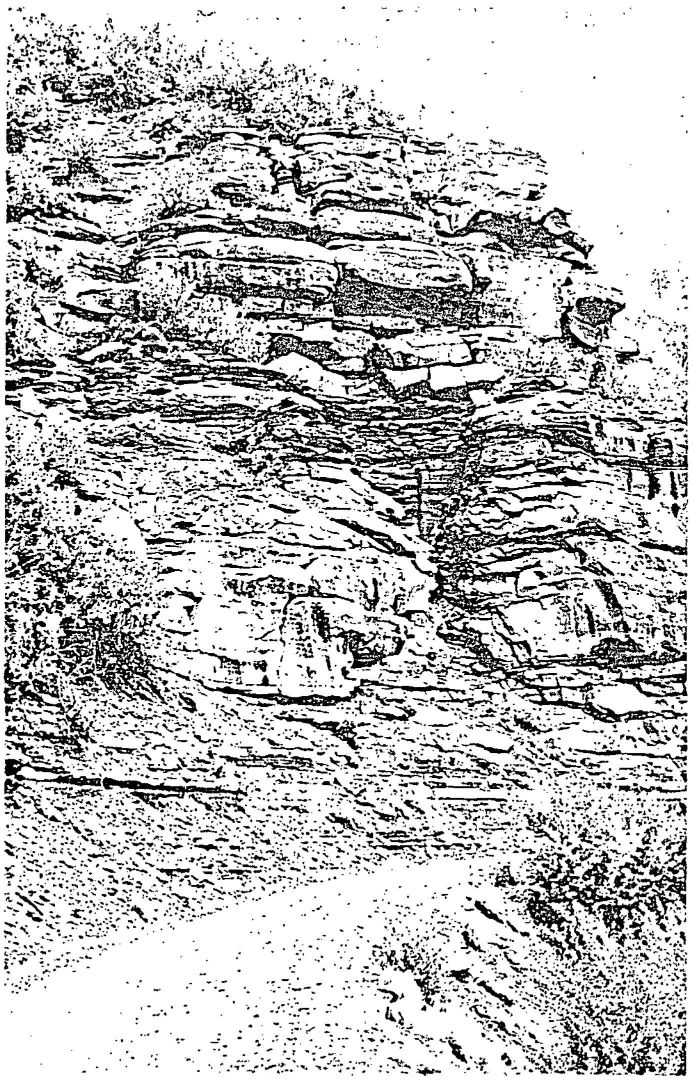


Fig. 16. Photograph of part of the ledge-forming member on Elk Ridge, showing lenticular and channeled sandstone that was probably deposited in a fluvial-delta distributary environment.

two kinds of fine-grained deposits. The first deposit consists of thin, even-bedded siltstone and mudstone, with a few thin intercalated sandstone units. This unit contains a number of sedimentary structures which indicate deposition on flood plains or mud flats; they are interpreted as overbank deposits. Rip-up or intraformational conglomerate is common. The second fine-grained deposit consists of "structureless", knobby-weathering mudstone or sandy siltstone. Two different depositional environments are possible for this second unit if the assumed fluvial origin is correct. It may represent swamp or levee deposits in which the original lamination has been destroyed by plant roots and other organisms, or it may have been deposited very rapidly out of suspension and traction by rapidly waning currents following the breaching of a natural levee. Neither the bases nor the tops of these units are erosional; generally, they grade upward into fissile or platy siltstone or mudstone.

The fluvial and delta distributary facies is most prominent east of the Colorado River. Although distributary sandstone channels probably are present further west, they would be difficult to separate from other sandstone bodies.

Delta-plain facies

Thinner and slightly finer-grained sandstone ledges, commonly 0.5-6 ft thick; and interbedded flaggy sandstone and siltstone, finely laminated siltstone and mudstone, and massive "structureless" mudstone constitute the bulk of the delta plain facies (Fig. 17). Except where they are crossed by a distributary, channels over one ft deep are uncommon. This facies is characterized by an abundance of sedimentary structures that are as numerous and diverse as any other comparable portion of the Moenkopi Formation. The bases of nearly all of the sandstone beds display some form of load casts or flute casts. Ripple marks and mud cracks are ubiquitous; and many kinds of disturbed bedding, sandstone dikes, and pillow weathering are common. Studies of modern deltas have shown that much of the growth of the delta plain is caused by crevassing. The load spreads over the adjacent low-lying area in thin, widespread sheets and is rapidly deposited in crevasse splays. McKee (1939) describes another mechanism of delta plain sedimentation for the arid region at the mouth of the Colorado River. Since the early 1930's, much of the water and most of the sediment of the Colorado River has been retained by man-made dams. Therefore, this river deposits all of its sand-sized load before entering the Gulf of California. On the middle part of the delta, the Colorado River has deposited a number of small, subareal, fan-shaped deltas which are composed of sand that displays a strongly peaked 0.2-mm-size distribution. The deposits are characterized

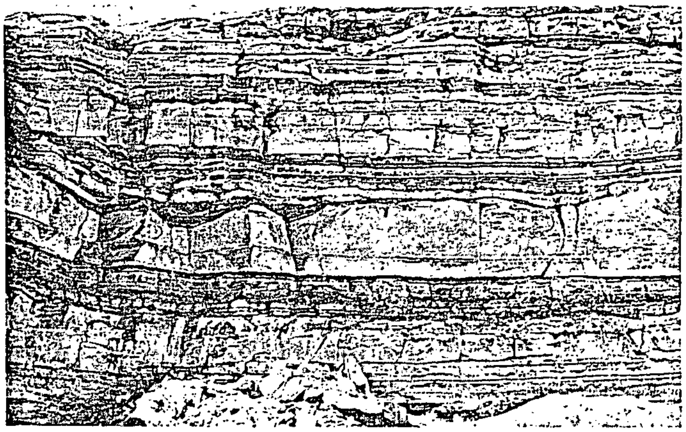


Fig. 17. Photograph taken 14 mi north of Hite on the Dirty Devil River at the mouth of Poison Spring Canyon, showing complexly interbedded siltstone and sandstone of the ledge-forming member thought to be deposited in a delta plain environment. The amount of section shown is about 30 ft.

by delta foresets which dip about 10 degrees downstream in sets that average 10 ft in length. These foresets are deposited on, rather than in front of, the delta topset beds. At a number of localities, especially in the southern San Rafael Swell and eastern Teasdale upwarp, similar deposits occur in the Moenkopi Formation.

A number of factors, including red coloring and beds of primary gypsum, suggest that the Moenkopi Formation may have been deposited under arid conditions. If so, perhaps much of the surface water transporting the sediment evaporated or seeped underground; and much of the sand-sized sediment periodically was deposited on the delta plain. If subsidence was rapid enough to bury these deposits before a major flood or a change in climate took place, the fans could be preserved.

Delta-front facies

The delta front facies comprises sediments thought to be deposited on the edge of the active part of a delta. Included in this complex facies are beach, tidal flat, estuary, bar, and near-shore shallow-water deposits. The nature of the delta front at any one place depends upon whether marine or fluvial processes dominate at that particular point (Scott and Fisher, 1969). Where marine processes dominate, sheet or blanket sand and silt deposits form; and where rivers dominate, elongate channels and bar-finger sand deposits dominate. Using criteria presented by Scott and Fisher (1969), the Moenkopi delta probably was slightly marine dominated. This postulation is based mainly on the sheet-like nature of many of the ledge forming sand bodies of the delta front facies. Other criteria used by Scott and Fisher include the probably medium size of the drainage basin feeding the delta (southwestern Colorado and, possibly, northern New Mexico); the high proportion of sand in the deltaic deposits; the lack of straight, narrow, and deep distributary channels; and the postulated arid climate that presumably reduced the volume of water in the rivers. Units in the ledge-forming member interpreted to have been deposited in the delta-front facies, consist of continuous or broadly lenticular, very fine-grained sandstone and interbedded thin silty sandstone and siltstone. The sandstone ledges average 5-20 ft in thickness and display very low-angle to nearly horizontal cross-stratification, ripple cross-stratification, and trough cross-stratification in sets from several in. to 10 ft thick. Several sequences of deposition occur in the various sandstone ledges, including erosional base fining upward, nonerosional base fining upward, and non-erosional(?) base coarsening upward. The latter probably represents a prograding sand bar deposit. Ripple marks are locally abundant but generally are far less common than in the delta plain facies. Current indicators within the delta front facies are very consistent in any one locality and usually are perpendicular to the edge of the delta lobe (Fig. 4). Some are bimodal and may indicate tidal flat deposition. In many localities, low-angle (5-10 degrees) unconformities are present in the delta front sequence. Commonly, these large-scale features are over 100 ft long and truncate the underlying beds (Fig. 18). These may be foreset beds or, possibly, some type of large-scale submarine channeling. The delta front facies is both well developed and well exposed in the southern Circle Cliffs, western Teasdale uplift, and southern San Rafael Swell areas, but is poorly developed and less extensive in the Orange Cliffs area.

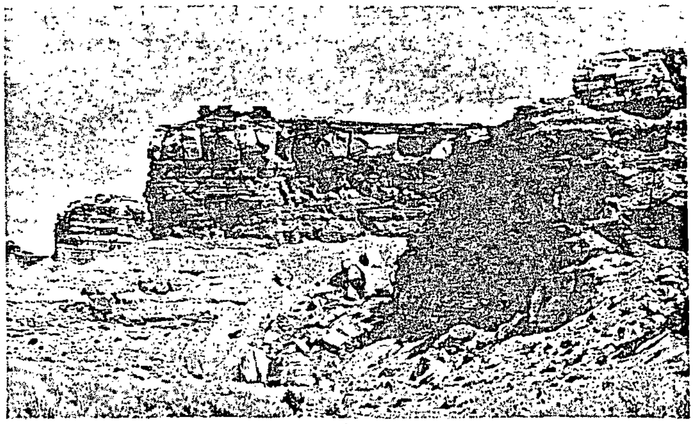


Fig. 18. Photograph of the ledge-forming member in the southeastern San Rafael Swell, showing lenticular and continuous sandstone ledges and angular bedding. This type of deposit is probably characteristic of the delta front facies. Faulting has offset the outcrops. The cliff and slope in the center of the photograph is 70-100 ft high.

Delta slope facies

The delta slope facies includes those sediments deposited farther off shore on the subaqueous slope of the delta. Essentially, it is a transition between the delta front and prodelta deposits and consists of interbedded units of each of these facies. There is a sharp reduction in the number of ledge-forming sandstone units in a distal direction (Figs. 10-13). The few sandstone ledges present are continuous for miles and probably have been reworked a number of times (Fig. 19). The bases of these units generally do not channel into the underlying beds. The sandstone is very fine-grained and silty and, in places, displays low-angle planar cross-stratification or ripple lamination. In the northern San Rafael Swell, parts of one continuous ledge contain slump and channel features similar to those described in the presumed off-shore bar deposit in the lower slope-forming member. Parts of the delta slope facies may contain off-shore bars that locally projected above the surface of the sea. However, the bulk of the deposits in the delta slope facies consists of thin-bedded or platy, silty sandstone and siltstone, and fissile mudstone. From the description of the localities and the rock units, the fish scales and mayalinids reported by Davidson (1967) probably came from the delta slope or delta front facies. The probable marine origin of these fossils supports the hypothesis for the origin of the facies.

The area of interfingering between the delta front and the delta slope facies contains considerable petroliferous sandstone deposits. In addition, the formation is generally nonred in these areas. The updip gradation of more porous sandstone into less porous siltstone or mudstone may have trapped the petroleum and associated natural gas and water. These fluids then reduced or hydrated the red iron oxide (hematite) to nonred iron oxides and pyrite. The color change does not seem related directly to marine versus nonmarine environments, but it can be explained by the "bleaching" of redbeds by migrating fluids trapped at permeability barriers. The secondary origin of the color is supported by the fact that in many localities, red-nonred boundaries cross bedding planes and other sedimentary structures.

The delta slope facies is present in the northwestern and central Circle Cliffs, west-central San Rafael Swell, and northwest Monument upwarp areas; and probably is present at, and west of, the westernmost exposures of the Moenkopi in the Teasdale uplift area.

Prodelta facies

Fine silt and mud deposited at the distal margins of the delta by dominantly suspension processes comprise the prodelta facies. Because of the probable shallowness of the Moenkopi sea, wind- and tide-induced currents were able to rework some of the deposits and create many ripple marks and small-scale cross-stratification. In most places, the prodelta facies is a monotonous sequence of platy- to fissile-weathering siltstone and mudstone. In some of the areas in the eastern part of the study area, the prodelta facies contains thin sandstone beds. The prodelta is present at all localities at the base of the ledge-forming member, and in most places forms a conspicuous slope between the Sinbad Member (where present) and the lowest ledge in the ledge-forming member. The prodelta deposits thicken westward; and in the northwest San Rafael Swell, they dominate the deltaic episode and enclose most of the other facies (Fig. 20). This is characteristic of prodelta facies in most modern and many ancient delta systems.

Close of deltaic deposition

Deposits at the top of the ledge-forming member suggest that the forces of marine erosion reworked the foundering delta system. Sheets of sand and silt were spread over very large areas, perhaps like the St. Bernard area of the Mississippi Delta. One silty sandstone at the top of the ledge-forming member can be traced over most of the San Rafael Swell (Figs. 6, 11, & 13). Similar units are present in the Orange Cliffs and probably elsewhere in southeastern Utah. Following deltaic deposition, a broad, flat plain extended over most of the area of study. Upon this plain, the upper slope-forming member was deposited.

Upper Marine and Paralic Episode

The high degree of continuity and the thin, even bedding of the upper slope-forming member indicate that the upper marine and paralic sequence was deposited under widespread, uniform, low-energy conditions. The overall deposit indicates a lack of any appreciable paleo-relief, and, probably, the topography of the region was very similar to that proposed by Irwin (1965) for the theoretical epicontinental sea. He suggested that very gentle slopes, less than one ft per mi, dampen wave and tidal energy and produce extensive near-shore shallow-marine mud deposits and supratidal flats. In the Moenkopi Formation, two mechanisms may have produced the somewhat rhythmic alternation of fissile mudstone, ripple-marked siltstone, and "massive" siltstone and mudstone. First, slight changes in relative sea level would cause the migration of slightly different environments for many miles across the very gently dipping sea bottom. For example, a

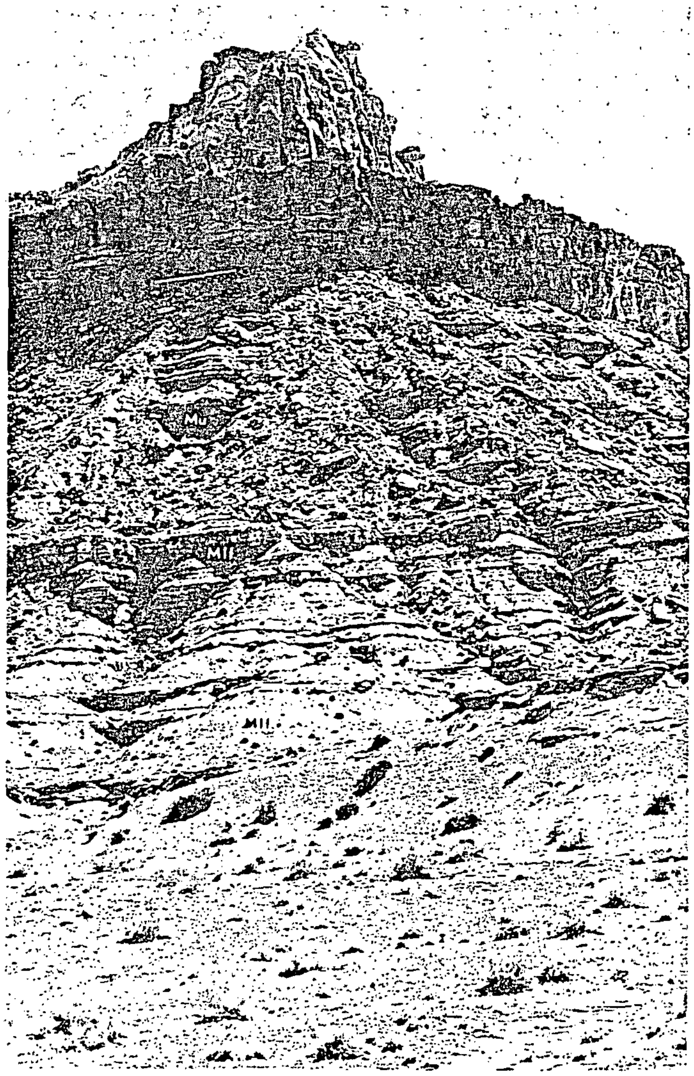


Fig. 19. Photograph in the northern San Rafael Swell of the ledge-forming (Mlf) and upper slope-forming members (Mu). The relatively few, thin, continuous silty ledges in the ledge-forming member are characteristic of the delta slope and prodelta facies. Several sandstone units are present at the top of the upper slope-forming member. The massive cliff of the Moss Back Member of the Chinle Formation rests unconformably on the upper slope-forming member of the Moenkopi Formation. The unit that divides the two members of the Moenkopi can be traced around the San Rafael Swell (Figs. 6, 11, and 13). This picture displays over 400 ft of Moenkopi.

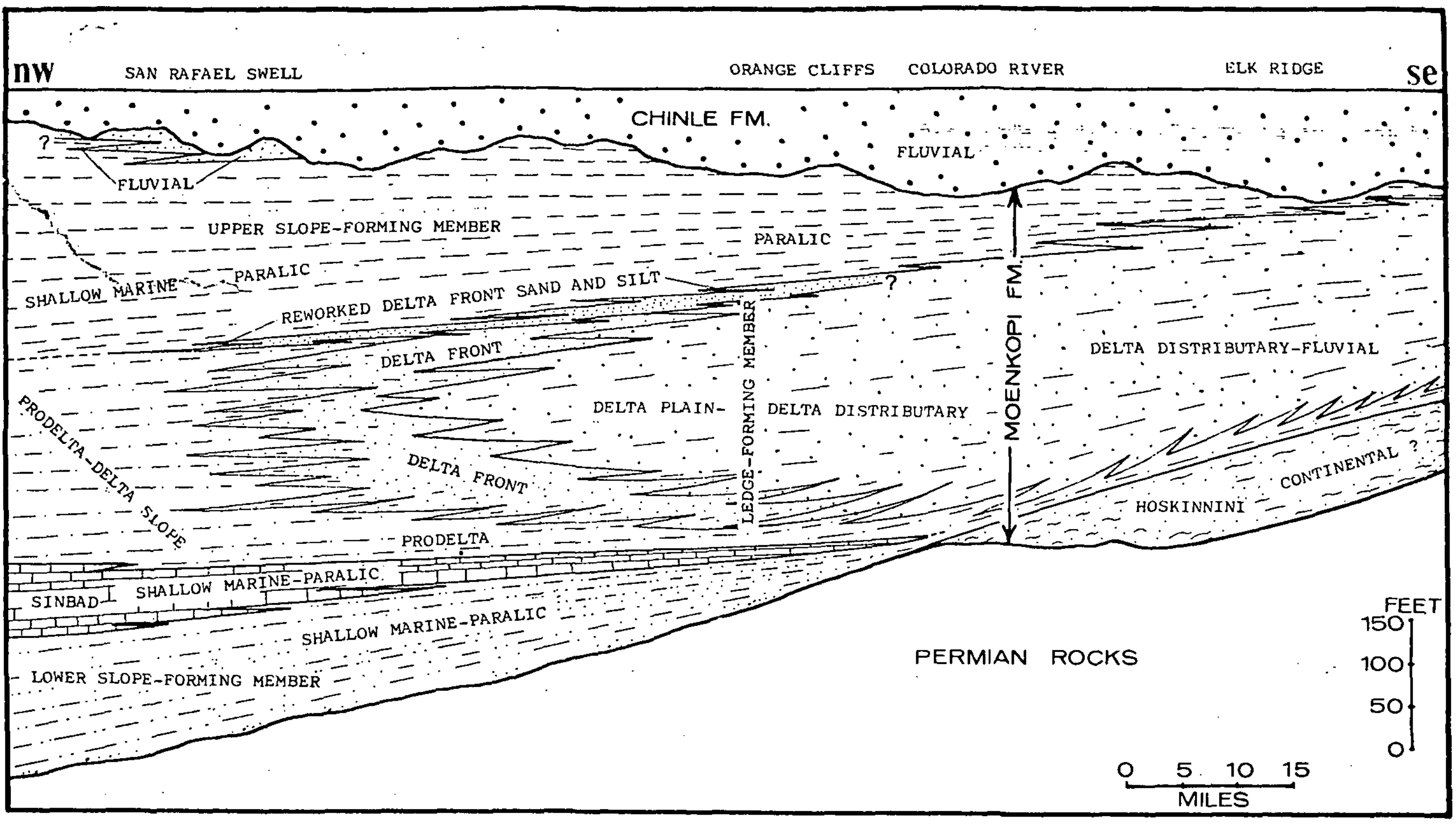


Fig. 20. Idealized sketch of the facies and members of the Moenkopi Formation of southeastern Utah from southeast to northwest. The location of the tongues is diagrammatic.

change of sea level of 5 ft on a slope of 0.5 ft/mi would cause the shoreline to migrate 10 mi. Second, external forces or changes in sedimentation applied to an extensive, uniform environment would cause differences in sediment type. These external changes include periodic intense storms, changes in amount of sediment in the system, and changes in climate. The intercalated fissile mudstone and ripple-marked siltstone may reflect the migrations of environments of slightly different energy levels caused by slight changes in sea level. However, the continuous (for more than 25 mi) "massive" siltstone and mudstone units probably indicate rapid deposition in widespread, nearly identical environments. In areas of low relief, these conditions exist for a very short time during storms: widespread, shallow, turbid water inundates several normally different environments and leaves a rather uniform extensive deposit (Ball and others, 1967). Commonly, these beds grade upward or horizontally into current-bedded siltstone that displays current-parting lineation and poorly preserved ripple marks. Intraformational conglomerate, present at some localities, also may characterize storm deposits (Ball and others, 1967).

Bedded gypsum, common throughout the sequence, suggests the presence of lowlands adjacent to a sea and an arid climate. Some of the gypsum may have been deposited in shallow lagoons or other bodies of water that had only periodic or restricted connections with the sea. Lucia (1972) postulated evaporite deposition on supratidal flats that may have been periodically flooded perhaps every 20 years; the balance of the time, the source of gypsum and other salts can be from ground water or sea-water springs. The intercalated clastics, which generally dominate the cycles, can be derived from the land by wind and periodic sheetwash, and from the sea by storms or periodic rises in sea level.

In parts of the San Rafael Swell (especially the eastern portion), siltstone and sandy siltstone are conspicuously abundant; and in Stillwater Canyon, good field evidence of intertonguing between the ledge-forming member and the upper slope-forming member can be shown. These two observations probably indicate that the deltaic and the upper marine and paralic episodes are partly diachronous and that, at times, the waning delta to the east provided coarser sediment to the upper slope-forming member.

In the northeastern San Rafael Swell, about 270 ft above the ledge-forming member, the upper slope-forming member contains several ledge-forming sandstone units up to 8 ft thick (Fig. 19). The base of the basal sandstone may be unconformable, and it contains coarse quartz detritus. These sandstone units are believed to have been deposited over a larger area and then later removed by pre-Chinle erosion. Perhaps they represent a change in depositional regime from low-energy paralic and shallow marine environments to higher energy fluvial environments, similar to those represented by the overlying Chinle Formation. The fact that these ledge-forming sandstones are interbedded with normal units of the upper slope-forming member indicates that this change took place gradually. The original extent of these sandstone units is not known.

Pre-Chinle Erosion

The amount of material in the Moenkopi Formation that was removed by pre-Chinle erosion probably was considerable. Because of the lateral continuity of beds observed in the even-bedded fine clastics in the upper slope-forming member, local thickness variations of more than a few ft are probably related to post-depositional erosion. In the San Rafael Swell, marker beds that can be traced long distances and, thereby, provide horizontal reference planes, exhibit erosional relief of over 240 ft (Fig. 3). In the northeast and southwest Circle Cliffs, the Shinarump Member of the Chinle Formation locally rests on the ledge-forming member. The maximum measured thickness of the upper slope-forming member in the Circle Cliffs is 295 ft (Davidson, 1967), which demonstrates that at least that much erosion occurred prior to deposition of the Chinle Formation. Relief between 30 and 120 ft can be documented at other locations in southeastern Utah. With the exception of the San Rafael Swell, where the basal Chinle unit consists of the Moss Back Member or the basal mudstone, the greatest erosional relief occurs where the basal unit is the Shinarump Member.

CONCLUSIONS

A high degree of continuity, a key fossil-bearing unit, and generally excellent exposures allow the Moenkopi Formation to be correlated within and between the four major uplifts of southeastern Utah. This northwestward-thickening, predominantly non-fossiliferous clastic sequence represents several episodes of marine, paralic, and fluvial deposition. The following statements summarize the sequence of events during Moenkopi deposition:

1. In the eastern part of the study area, the Hoskinnini Member was deposited under subaqueous, but probably non-marine, conditions.
2. To the west, possibly at about the same time, scattered chert-pebble conglomerate and sandstone were deposited, possibly under both continental and marine conditions.
3. Marine and paralic conditions developed on a slowly subsiding, westward-sloping plain. This culminated in the deposition of a fossiliferous carbonate sequence.
4. An influx of clastic sediment from the southeast terminated carbonate deposition and slowly forced marine conditions to the northwest, as a complex deltaic system prograded westward across the area.
5. Sedimentation waned with respect to subsidence, and the latest deltaic sediments were reworked by marine and paralic processes.
6. A widespread, low-energy paralic and shallow-marine environment developed on a surface of low relief.
7. Subsidence ceased, and the sea was forced from the area by uplift and nonmarine sedimentation. Fluvial conditions and erosion preceded Chinle deposition.

Although this investigation did not emphasize the petroleum potential of the Moenkopi Formation, nevertheless a sizeable portion of the field work was spent mapping the extensive tar sand deposits of the San Rafael Swell and other areas. The following preliminary conclusions summarize the petroleum potential of the Moenkopi Formation in southeastern Utah.

1. The tar sands of the San Rafael Swell and Circle Cliffs areas consistently occur within delta front sheet sands, and beach and offshore bar sandstones.
2. These deposits are not feasible to mine at present, due to economic limitations and environmental restrictions.
3. If sufficient permeability is present, subsurface stratigraphic traps located in delta front and other sandstone units may contain commercial petroleum accumulations recoverable by primary techniques. Buried traps such as these may constitute a significant economic potential.

ACKNOWLEDGMENTS

The author acknowledges the assistance of the following persons in the preparation of this report. The Utah Geological and Mineralogical Survey provided field vehicles and defrayed expenses; Mr. Howard R. Ritzma of that organization supervised field work. Doctors W. F. Furnish and P. H. Heckel of the Department of Geology, University of Iowa, criticized the manuscript and made numerous helpful suggestions. Sam Quigley and David Bernini of the Utah Geological and Mineralogical Survey, and my wife, Dee, assisted in the field at various stages of the study.

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STRUCTURAL SIGNIFICANCE OF TERTIARY VOLCANIC ROCKS IN SOUTHWESTERN UTAH

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ABSTRACT. Most of the silicic volcanic rocks of the Great Basin are ignimbrites rather than lava flows. The more common types were probably formed by nuées ardentes which spread laterally as density currents of very high fluidity, but there are aberrant types that may be in some manner transitional between ignimbrites and lava flows, and the whole problem of mechanism of origin is as yet little understood. Uncertainty on this score is of no concern here; mapping of many of the units indicates that, whatever their origin, they assumed a distribution approaching that of an equal volume of water, filling valleys to a common level and forming sheets of substantially uniform thickness where the relief of the pre-existing surface was low. Some of the individual ignimbrites are many hundreds of feet thick and have an areal extent of as much as 10,000 square miles. Because each of these extensive and initially flat sheets were formed everywhere at the same instant of time, they are very nearly ideal stratigraphic units. They occur in most parts of the Great Basin and range in age through most of the Tertiary.

Eleven ignimbrites which are widespread in southeastern Utah are described and given formal stratigraphic names. The fact that the oldest of them lies unconformably across the beveled edges of thrusts and folds involving late Cretaceous strata indicates that the beginning of volcanic activity post-dates the Laramide orogeny. As planar units which provide a record of Tertiary crustal movements, the ignimbrites confirm the Gilbert theory, based originally on physiographic evidence, that block faulting has been the characteristic type of post-Laramide deformation in the Great Basin. The stratigraphic-structural approach makes it possible (1) to work out the geometry of the block faulting with a precision not obtainable by use of displaced erosion surfaces; (2) to deal with episodes of block faulting that occurred during the early Tertiary and are not expressed by the present topography; and (3) to crossdate these and other geologic events on a regional scale.

On the basis of detailed work in southwestern Utah, and reconnaissance elsewhere, it is stated as a deliberately provocative working hypothesis that block faulting has been the only type of regional tectonism in the Great Basin in post-orogenic time. The first requirement in testing this hypothesis is the recognition, as such, of flexures and thrust faults developed (1) by emplacement of hypabyssal intrusions, and (2) by gravity sliding from primary relief features raised by intrusion and block faulting. These two classes of structures are of much interest in their own right; their significance for present purposes is merely that they may be readily mistaken as evidences of regional tectonism. Equally critical is the need for distinguishing post-orogenic deformational effects from those produced during the orogeny. Examples are given of use of the ignimbrites in making these distinctions.

INTRODUCTION

It is now generally recognized that the silicic volcanic rocks of the Great Basin, commonly considered to be lava flows in early geologic reports, are nearly all ignimbrites; that is, as this term is used here, depositional units formed by eruptions of the nuée ardente type. Attention has been called by C. S. Ross (1955) to the widespread occurrence of these special kinds of pyroclastic rocks in the Cordilleran region, and individual units or sequences of units have been described in many places in the Great Basin and neighboring provinces in recent years (e.g. Mansfield and Ross, 1935; Gilbert, 1938; Callaghan, 1939; Enlows, 1955; Sabins, 1957).

My acquaintance with Great Basin volcanic rocks dates from the field seasons of 1950-52, which were spent largely in mapping a thick and varied sequence of them in the Iron Springs district in southwestern Utah for the U. S. Geological Survey (Mackin and Nelson, 1959). Mapping of adjoining areas (fig. 1) by University of Washington graduate students, R. L. Threet (1952) in the Red Hills to the northeast, E. F. Cook (1952, 1957) in the Pine Valley Mountains and W. R. McCarthy (in progress) in the Gunlock area to the south, H. R. Black (in progress) in the Bull Valley district to the southwest, G. M. Miller (1958) in the Wah Wah Range to the northwest, and E. H. East (1956) in the San Francisco Range to the north, has greatly broadened our knowledge of the stratigraphic succession worked out in Iron Springs, and has added many new units. An investigation of the basin-range problem in eastern Nevada in 1955, for the Gulf Oil Company, quickly resolved itself into a regional reconnaissance of the volcanic rocks because it was apparent that there, as in Iron Springs, the stratigraphy of these rocks is an indispensable key to an understanding of basin-range structure and topography. An unexpected dividend was the discovery that some of the Nevada units are definitely correlatable with units in southwestern Utah. E. F. Cook worked with me in Nevada early in the 1955 season, and has subsequently continued the stratigraphic study of the Nevada volcanics independently, paralleling similar work by me in the Great Basin in west central Utah during the 1955 and 1956 seasons. Threet (1952, 1956) has spent parts of several seasons extending his mapping eastward from the Red Hills into the Colorado Plateau. A tour to examine relationships between uranium ore deposits and igneous rocks in the Great Basin during 1957, in company with Atomic Energy Commission personnel familiar with geology in the vicinity of the ore bodies, provided an opportunity to observe, in many new places, volcanic sequences which for the most part conform with, or are instructive variations of, stratigraphic and structural patterns that have been determined in southwestern Utah over the past eight years.

The theme of this paper is a combination of two points suggested above: (1) that as depositional units that were deposited as essentially horizontal sheets, the Great Basin ignimbrites serve as ideal reference planes for measurement of Tertiary deformation, and (2), that as layers of great areal extent they provide a means of cross-dating Tertiary episodes of deformation, intrusion, metallization, and other geologic events, from place to place throughout much of the province. The concepts developed are based primarily on studies in southwestern Utah, but they are advanced here as working hypotheses applicable to the Great Basin as a whole. The hypotheses are outlined briefly, without the detailed statement of evidence and reasoning, the formal maps and sections, and the careful qualifications, that would be needed in presentation of a specific conclusion regarding a particular place. The treatment of a given hypothesis is intended, not to prove that it holds true in the area used as an example, but merely to establish its claim to consideration as a possible explanation of relationships of the type stated, in any area. When a point is set forth as a definite conclusion, this is a promise that it will be adequately documented in later reports. References to the literature are intended, not so much

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The regional stratigraphic study of the Tertiary volcanics indicates that some individual ignimbrites are hundreds of feet in thickness over an area measured in many thousands of square miles. These great sheets represent the frothing eruption of many hundreds of cubic miles of magma, perhaps within a period measured in weeks or months. The total volume of Tertiary silicic volcanic rocks in the Great Basin is of the order of magnitude of 50,000 cubic miles. It seems reasonable to suppose that the transfer of so enormous a quantity of material from depth to the surface, in eruptive episodes that occurred from place to place and from time to time during the Tertiary, must be in some manner genetically related to episodes of block faulting that were in general similarly distributed in space and time (Longwell, 1950, p. 427-428). An early draft of this article called attention to the striking similarity in pattern relationships between basin-range structure and the sets of antithetically tilted slump blocks formed in clay which fails by reason of withdrawal of lateral support, and suggested that Great Basin block faulting is an expression of a comparable slump-creep movement of segments of the crust toward a "free side" created by the rapid expulsion of very large volumes of magma formed by fusion of crustal rock. But this "eruptive-tectonic" hypothesis for origin of basin-range structure ramifies persuasively in many directions—starting as an innocuous after-thought, it quickly became a Part II, equal in size to the original article. This overgrowth of an appendage wholly different in substance and approach from the body of the paper called for surgery—the present article, which treats the structural significance of the volcanic rocks in a descriptive sense, will be followed in a forthcoming issue of this journal by a sequel dealing with some possible genetic relationships between eruptive activity and deformation during the post-orogenic period in the Great Basin and neighboring provinces. The fact that there will be a sequel needs to be noted here because reference is made to it at a number of places in this article, and because discussion of some aspects of the timing and geometry of basin-range movements is deferred to it.

Both articles are bundles of working hypotheses, the first at the field relations level and the second at the level of underlying causes. Some of the interpretations that seem to fit the "facts" in southwestern Utah may be incorrect, and it is quite likely that concepts which are valid in that area may not hold true for the remainder of the Great Basin. But these are not serious defects in articles such as these; it is more important that a working hypothesis be provocative than that it be right. The merit of the articles depends on the extent to which, by giving new meanings to familiar relationships, and sharpening the perception for inter-connections that might otherwise be missed, they tend to accelerate the gathering and analysis of the data needed for an eventual understanding of the post-orogenic history of the Great Basin.

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IGNIMBRITES AS STRATIGRAPHIC UNITS

Terminology.—Discussion of volcanic rocks as stratigraphic units requires sets of terms which apply to and distinguish between (a) the depositional unit formed by a single eruptive episode, this being the basic stratigraphic element observed in the field, (b) the rock type or types comprising this unit, and (c) the eruptive mechanism. Terms are available to fit these needs, but because some of them have been applied in different and overlapping senses, it is necessary to state the manner in which they are used here. A review and discussion of the terminology of volcanic rocks is now in preparation by E. F. Cook.

The term "nuée ardente" was proposed by Lacroix (1908), and later modified by Perret (1935), for a special type of eruptive mechanism observed at Mount Pelée and La Soufrière. It is the general consensus that the nuée ardente originates by frothing of the magma and bursting of the bubbles of the froth to give rise to a mass of hot gas so charged with comminuted pumice as to be heavier than air; this mass "boils" from the vent, and moves downslope under the influence of gravity (see for example, Anderson and Flett, 1903, p. 394; Bell, 1942, p. 525-528; Fenner, 1923, p. 72; Finch, 1935; Williams, 1957, p. 59-65). In this respect the nuée ardente contrasts sharply with the genetically related Plinian eruptive mechanism, in which the fragmented pumice is violently propelled upward from the vent and spread laterally by winds, losing all or most of its heat before settling to the ground. The nuée ardente spreads laterally, on the ground, as a density current of very high mobility—it may attain hurricane velocity in a short distance and its charge of solid particles may be glowing hot when it comes to rest. Cauliflower clouds of ash and gas which rise from the surface of the density current phase are an integral part of the nuée; the contrasted deposits of the two phases are usually gradational.

"Nuée ardente" is widely used by students of modern volcanism for this general type of eruption, readily qualified as Peléean, Katmaian, and so on, to designate nuées with the particular habits of those observed at those places. If we may judge by the thickness, lateral extent, degree of welding, and other features of their deposits, the Tertiary eruptions of the Great Basin would compare with those of modern times as the explosion of a hydrogen bomb with the bursting of a firecracker. Because they are of an altogether different order of magnitude, there is no reason to believe that the observed eruptions are

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good models of those of the past. It is probably true, as pointed out by Howel Williams (oral communication) that most of the Tertiary nuées issued from fissures rather than from central vents, but to call them "nuées ardentes of the fissure eruption type" would be to beg a very important question. "Nuée ardente of the Great Basin type" has some advantages, but anyone familiar with the rocks in question is aware that they represent a wide variety of mechanisms of eruption and spreading, which are not well understood. In this paper "nuée ardente" without qualifiers merely means that the characteristics of the ancient pyroclastic deposits indicate an eruptive mechanism, the closest approach to which in modern times is that to which this term was applied by Lacroix and Perret. The alternative is to invent a new word, and the only justification for so doing is the argument that "nuée ardente" should be restricted to the small scale eruptions to which it was first applied. This pious thought is not realistic. As indicated above, the term has been used loosely, generally for the type of eruption which operates as a density current, by many workers for many years; its virginity could not be restored, even if it were desirable to do so.

An understanding of the mechanism of origin of the volcanic rocks of the Great Basin depends primarily on accumulation of data regarding such factual matters as the areal extent of individual units constituting the Tertiary succession; the principal types of units represented; and lateral and vertical variations in degree of welding, size of rock fragments and crystals, and the many other lithologic features that characterize each type—until these things are known we do not even know what a theory of origin must account for. The first essential step in this direction is the working out of the regional stratigraphy of the volcanic rocks; we are now in this stage of the investigation. Origin is not an issue in this article—the concept stated above in oversimplified form, that the ignimbrites were spread laterally as density currents of very high fluidity, is significant only in that it provides a rational explanation for their observed habits of form and distribution. These rhyolitic and latitic units nowhere exhibit the bulbous forms that are characteristic of silicic lava flows, but show instead a distribution approaching that which would be assumed by sheets of water, surrounding hills and filling lowlands and valleys to a common level.

Zirkel used "welded" and "fused" at a number of places in his descriptions of silicic rocks of the Fortieth Parallel collections, for example, "a pumice-breccia which the microscope discovers to be composed of numerous fragments welded or cemented closely together" (1876, p. 267). It is clear that he was aware of the unusual nature of these rocks, but his meaning of "welded" seems to have been quite different from its present meaning as applied to volcanics. The term was first used in the modern sense by Iddings in discussion of the microscopic features of a volcanic rock occurring in Yellowstone Park; he described the structure as "a confusedly twisted arrangement of glass fibres and films," and suggested that the rock might have been formed "by exploded fragments of molten material . . . which fall together in a heated condition, plastic enough to weld together in a compact mass" (p. 404-406). The concept of welding is now usually associated with the nuée ardente type of eruption, and "welded tuff" is sometimes used for the depositional unit, to express the idea that it was formed by that type of eruption. But use of the term in this sense, that is, for the depositional unit, will almost always give rise to statements to the effect that a given welded tuff is nonwelded in the upper part, or, perhaps, shows no welding whatsoever. This nonsensical wording is the consequence of an unwarranted extension of a descriptive term, referring to a special manner of lithification, to a depositional unit that may be lithified by different processes and in different degrees from level to level and from place to place. "Welded tuff" will be used here in Idding's sense as a rock term, applicable to a hand specimen or a ledge, usually with qualifiers to indicate the degree of welding.

The term ignimbrite—"fire cloud rock"—was first defined by Marshall as the rock comprising a nuée ardente deposit, without regard for the degree of welding (1932, p. 200). In a later paper (1935) the term is used in this sense and also to mean the nuée ardente depositional unit, as such. It has come to be used widely in the first sense. But the pressing need, in any discussion of the stratigraphy of ancient volcanics, is for a term with Marshall's second meaning; that is, for the depositional unit formed by the nuée ardente type of eruption without regard for degree or method of lithification from level to level or from place to place. Ignimbrite is used in this sense in this paper. Actually there is no serious conflict between the two meanings, because the context usually makes it clear which is intended. "Ignimbrite" in any sense is anathema to a number of outstanding students of volcanic rocks, but it is firmly fixed in the literature, is better than any alternative term that has been proposed, and is a great deal better than a new term—like "nuée ardente" it will irritate some readers, but will confuse none.

Lateral extent.—The proposition that certain individual ignimbrites and ignimbrite sequences are regional in extent will seem to many geologists familiar with the Great Basin so patently true as to be scarcely worth stating, and to others, incredible.

Perhaps the latter attitude stems in part from the fact that our conceptions of Great Basin volcanic rocks have been based largely on studies in mining districts, where the volcanics are commonly so intensely deformed and altered by intrusions that district-wide mapping of individual depositional units is difficult or impossible (see, for example, Westgate, 1932, p. 27). Moreover, in many mining districts the volcanic section consists of lava flows, breccias and agglomerates, interlensing in disorderly fashion and laced by dikes and sills, the whole clearly an ancient volcanic pile in which many of the units change drastically in thickness and pinch out entirely within short distances. Such areas of strong deformation and alteration, and/or initial stratigraphic complexity, are the worst possible places for working out stratigraphic relationships, particularly in a suite of volcanics which did not conform to any concept of origin available at the time when most of the mining districts were mapped. Now that it is known that many ignimbrites have very great lateral extent, it is evident that the stratigraphic relationships of the volcanics can best be worked out in areas of simple structure remote from centers of intrusion and vulcanism. In many instances the firm stratigraphy thus established can then be carried

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back into the areas of complexity, where the ignimbrites serve as keys to geologic problems that could not be solved locally.

Probably a much more important explanation of the general failure to recognize the usefulness of ignimbrites as regional stratigraphic units is the fact that most workers in the Great Basin have been preoccupied with other aspects of the geology, and have been inclined to dispose of the volcanics with a single map color or, if something more is required by obvious differences in lithology or structure, to lump them in the fewest possible cartographic units. An attitude that is very common in the present generation was expressed by Spurr in 1901 (p. 225):

> Our knowledge of the ranges . . . is comparatively slight, since . . . the volcanic rocks are so abundant *that nearly everywhere they mask the structure.*

The italics are mine. It goes without saying that this dim view of the volcanics is not conducive to rapid strides in the understanding of their stratigraphy. Individual depositional units are not apt to be mapped separately if it is taken to be a certainty, without looking, that they have no continuity; and the fact that many of the units are readily correlatable from range to range is not apt to be recognized if such correlation is considered to be impossible.

The literature provides some noteworthy exceptions to these generalizations. Studies by Ransome (1909) in the Goldfield district, Nevada; Ransome, Emmons, and Garrey (1910) in the Bullfrog district, Nevada; and Callaghan (1939) and Kerr and others (1957) at Marysvale, Utah, are examples of the use of Tertiary volcanic units in working out structure in mining districts of extraordinary complexity. Anderson and Russell (1939, p. 243-247) identified the Nomlaki tuff of Pliocene age in the northern Sacramento Valley as a nuée ardente deposit, and used it as a key bed in stratigraphic studies over an area of about 2000 square miles. The Rattlesnake tuff is now recognized as a single ignimbrite (Wilkinson, 1950) that may have covered as much as 5000 square miles in eastern Oregon in Pliocene time (Campbell and others, 1958). Van Houten's (1956) "vitric tuff" is a distinctive suite of Mio-Pliocene tuffaceous deposits rather than an individual depositional unit, but it is said to be recognizable and usable as a stratigraphic datum throughout most of Nevada and in neighboring parts of the Great Basin.

It is literally true that some of the volcanic units of the Iron Springs district are so distinctive lithologically, so well exposed, and so obviously continuous, that they very nearly map themselves—seven "flows" were distinguished in a reconnaissance study in 1908 (Leith and Harder, plate 1). Moreover, the volcanics are readily separable into unconformable sequences which predate and postdate the ore-bringing intrusions, and a knowledge of the detailed stratigraphy of the pre-intrusive and post-intrusive sequence is essential to any understanding of the localization of the ore bodies and virtually every other aspect of Tertiary structure and physiography. In other words, in Iron Springs it was both practicable and necessary to work with the individual depositional units comprising the volcanic section, and this work quickly changed my attitude from one close to Spurr's to the diametrically opposed position of this paper, which lumps the pre-Cambrian, Paleozoic and Mesozoic rocks as a pre-Tertiary basement complex, of interest chiefly as the underpinning of the volcanics.

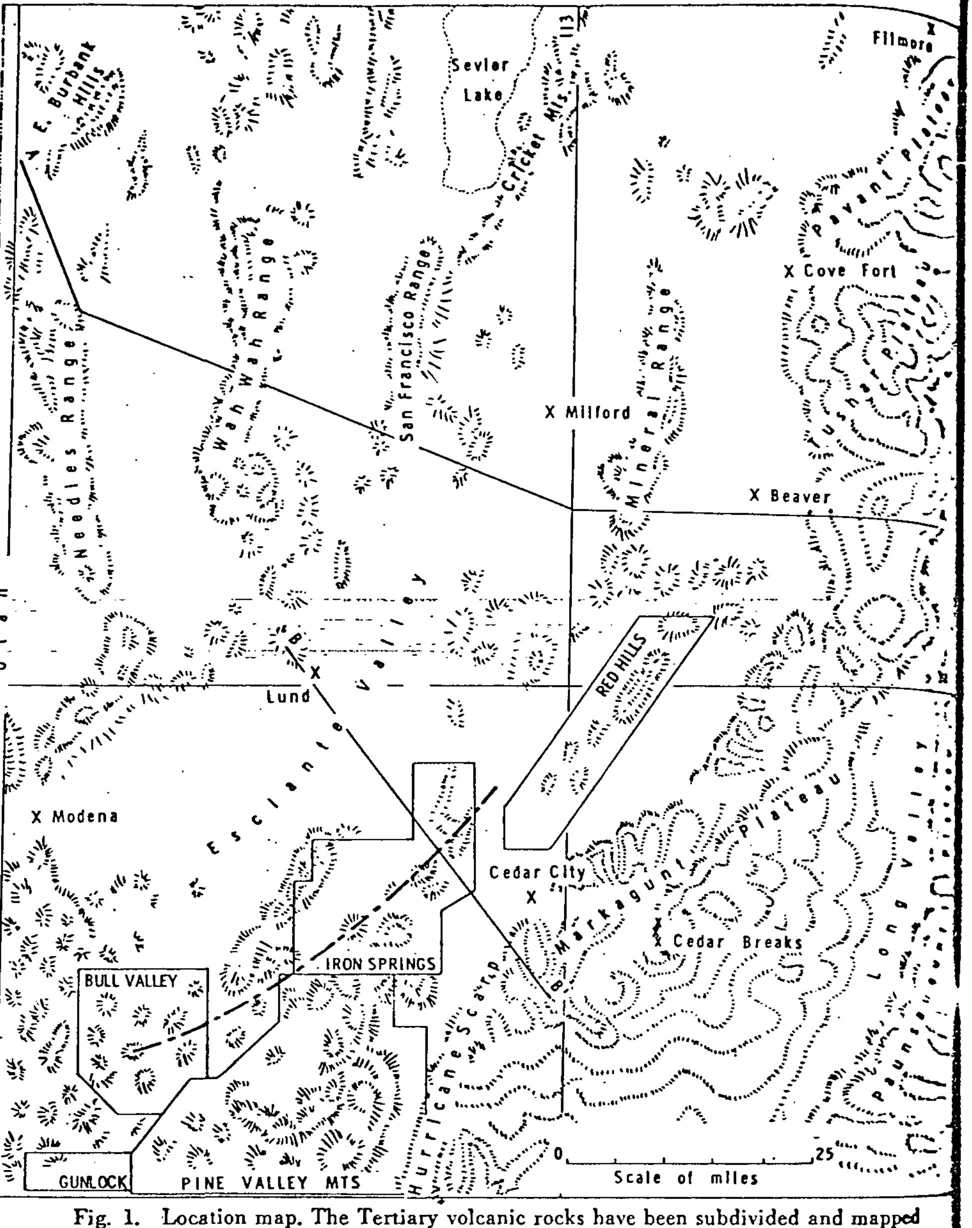

Fig. 1. Location map. The Tertiary volcanic rocks have been subdivided and mapped on a scale or 1/62,500 or larger in the districts defined by solid lines. A-A′ and B-B′ indicate the approximate location of the sketch section in figure 5 and the restored section in figure 3, respectively. The general trend of the Iron Springs Gap structure is shown by the heavy dash-dot line; this structure is greatly distorted by six intrusive bodies which are aligned along it.

An area of about 3,000 square miles centering around Iron Springs has been mapped on a scale of 1/62,500 or larger by members of the University of Washington group named earlier. With this substantial area as a proving

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ground for principles of ignimbrite stratigraphy, regional reconnaissance by me indicates that an area of about 10,000 square miles in the Great Basin and the High Plateaus in southwestern Utah can be tied together by one or more groups of ignimbrites. Cook has independently developed a correlation network for an area of comparable size in eastern Nevada.

Identification of individual ignimbrites in these reconnaissance studies is based in the field on conventional lithologic characteristics and, of course, as in all correlation of stratified rocks, on similarity in sequence. A laboratory method that has proved very useful in testing tentative field correlations is outlined in an accompanying paper by Paul L. Williams. Briefly, the method involves binocular study of "thick sections", etched and stained to aid in distinguishing the minerals; ratios of crystals to ground mass, percentages of the principal rock-forming minerals, and other properties are expressed by histograms. Individually (fig. 2) or arranged in columnar sections in a correlation chart as in William's paper, the histograms provide an effective means of conveying a large amount of mineralogic data at a glance.

QUICHAPA FORMATION

General statement.—Discussion of systematic stratigraphy is beyond the scope of this article, but an understanding of the general nature of the volcanic succession and the approximate age relationships are essential for what follows. For ease of reference in this article, in the companion paper by Williams, and in other papers now in preparation by the University of Washington group, certain volcanic units that are known to be regional in extent are assigned formal stratigraphic names.

The Quichapa formation[1] is not at the base of the volcanic section in southwestern Utah, but it is in several respects well suited to introduce and illustrate the concept of a regional stratigraphy based on ignimbrites. The three or four ignimbrites comprising the formation were spread over a surface of low relief throughout most of the area where they have been mapped, and there was no roughening of any of the units by erosion prior to emplacement of the next unit. These circumstances mean (1) that the Quichapa ignimbrites show none of several sorts of internal complexities associated with strong relief on the underlying surface, and (2) that they tend to be substantially uniform in thickness and to be in the same orderly sequence over very large areas. Moreover, the Quichapa units are characterized by unique sets of lithologic features and complements of minerals that make them rather readily and positively identifiable. Finally, it so happens that the Quichapa sequence includes the three principal types of ignimbrites which occur in the Great Basin, so that most other ignimbrites can be succintly described as variants of one or another of the Quichapa units, as types.

The various makeshift names that have been used in the past for the

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[1] Cook's designation of the Quichapa as a group (1957, p. 53) corresponded with my usage at that time. But in addition to the regional ignimbrites which make up most of the Quichapa, which need formal stratigraphic names, there are in many places lava flows and other local intercalations which are best referred to in lithologic terms. It is a well established rule that a formation may include undesignated units of member rank, but that all of the formations comprising a group should carry formal stratigraphic names (Ashley, 1933). Chiefly for this reason, I now favor a formational rank for the Quichapa.

TABLE 1

Comparative Nomenclature of the Volcanic Succession in Southwestern Utah

Leith and Harder, 1908		Mackin, 1954		Cook, 1957		This paper	
				Page Ranch formation		Page Ranch formation	Kane Point tuff
							Irontown member
				Rencher formation		Rencher formation	
Succession of flows	No. 7 Biotite dacite	Volcanic rocks	Member E	Quichapa group	Tv 3	Quichapa formation	Harmony Hills tuff
	No. 6 Latest trachyte		Member D		Tv 2		Bauers tuff
	No. 5 Later trachyte						Swett tuff
	No. 2 Early tuffaceous rhyolite		Member C		Tv 1		Leach Canyon tuff
			Member B	—		Isom formation	Hole-in-the-Wall member
	No. 1 Early trachyte		Member A				Baldhills member
						Needles Range formation	Minersville tuff
							Wah Wah Springs tuff
Claron formation		Claron formation		Claron formation		Claron formation	

Quichapa units, and the formal stratigraphic names that are proposed for them here and used in William's paper, are shown in table 1. The type localities, all in the Iron Springs district, are as follows: Leach Canyon tuff, the south side of Leach Canyon, Desert Mount quadrangle; Swett tuff, the west-facing scarp of the Swett Hills, Desert Mound quadrangle; Bauers tuff, Bauers Knoll, Cedar City, N. W. quadrangle; Harmony Hills tuff, the Harmony Hills, specifically, the south side of Right Quichapa Canyon, Mount Stoddard quadrangle. At these places the units are in the order of superposition shown in the table. Elsewhere in the district there are lava flows or other volcanic rocks, local in origin and extent, at every contact.

Routine descriptions of the units are given in the reports cited in table 1, and the percentages of the principal rock-forming minerals are shown by histograms in William's paper and in figure 2 of this paper. Descriptions at the type localities, given below, stress certain features of the units which bear on problems of origin.

Leach Canyon tuff.—As seen in cliff exposures in the vicinity of Leach Canyon, the Leach Canyon tuff is a single depositional unit, remarkably uniform in lithology through a thickness of 450-500 feet. Except at the base and near the top the rock consists of a matrix with the texture of unglazed porcelain, gray to flesh in color, enclosing fragments of dark red felsite, light gray pumice, and other rocks, and crystals of quartz, feldspar, biotite, and other pyrogenic minerals, mostly broken. A square foot of exposure commonly shows five to ten readily visible lithic fragments. The fragments make up as much as 10 percent of the rock, and the pyrogenic minerals range from 15 to 25 percent. There is no suggestion of grain-size stratification, but some favorably situated faces exhibit a poorly developed foliation paralleling the base of the unit, brought out by a preferred orientation of lenticules of pumice and other rock fragments and mineral grains. The foliation plane shows no lineation; there is no alignment of inequidimensional fragments or grains, and the pumice lenticules are shapeless blotches. The absence of lineation indicates that the foliation is a compaction structure, not a flow structure in the conventional sense.

The stony-textured material grades downward uniformly or through a zone of interlensing into black, gray, or salmon silky-lustred vitrophyre which ranges from zero to several tens of feet in thickness. The proportions and types of rock fragments and mineral grains in the vitrophyre are substantially the same as in the stony-textured material. There may or may not be a layer of pulverulant ash as much as ten feet thick at the base.

In the upper 50 to 75 feet of the unit there is a gradual decrease in the number and size of the rock fragments, and in the degree of induration. In some places the uppermost few feet consist of distinctly bedded tuff, rich in pumice granules; this part of the deposit is evidently air-fall ash. The slightly indurated upper phases are preserved only under special circumstances, to be outlined below.

The conspicuous rock fragments, the general absence of sorting, the complete gradation from basal vitrophyre to ashy top, and other characteristics of the Leach Canyon tuff indicate, on the basis of the field relations alone (without recourse to the microscope), that the unit as a whole cannot be a lava flow nor an ordinarily air fall tuff nor any combination of these; it is clearly the sort of unit for which the term "ignimbrite" was proposed by Marshall. It is in all respects closely similar to the Bishop tuff of California (Gilbert, 1938).

Bauers tuff.—The Bauers tuff differs from the Leach Canyon tuff in three ways that are of petrogenetic interest: (a) the content of pyrogenic mineral grains is appreciably lower (10 to 15 percent as compared with 15 to 25 percent); (b) foreign rock fragments are rare or absent; and (c) it is much more strongly indurated. At Bauers Knoll and in about 95 percent of its outcrop area in the Iron Springs district it consists of three intergrading but sharply contrasted phases: a basal vitrophyre about 10 feet thick; a middle lithoidal phase characterized by a conspicuous compaction foliation, 150 to 200 feet thick; and an upper non-foliated lithoidal phase, 10 to 40 feet thick.

The basal vitrophyre is black and has the glassy luster and conchoidal fracture of obsidian. Toward the top it is flecked with red spherulites. The transition to the overlying lithoidal phase is generally deeply weathered, a fact that suggests that the vitrophyre was predisposed to rapid weathering by al-

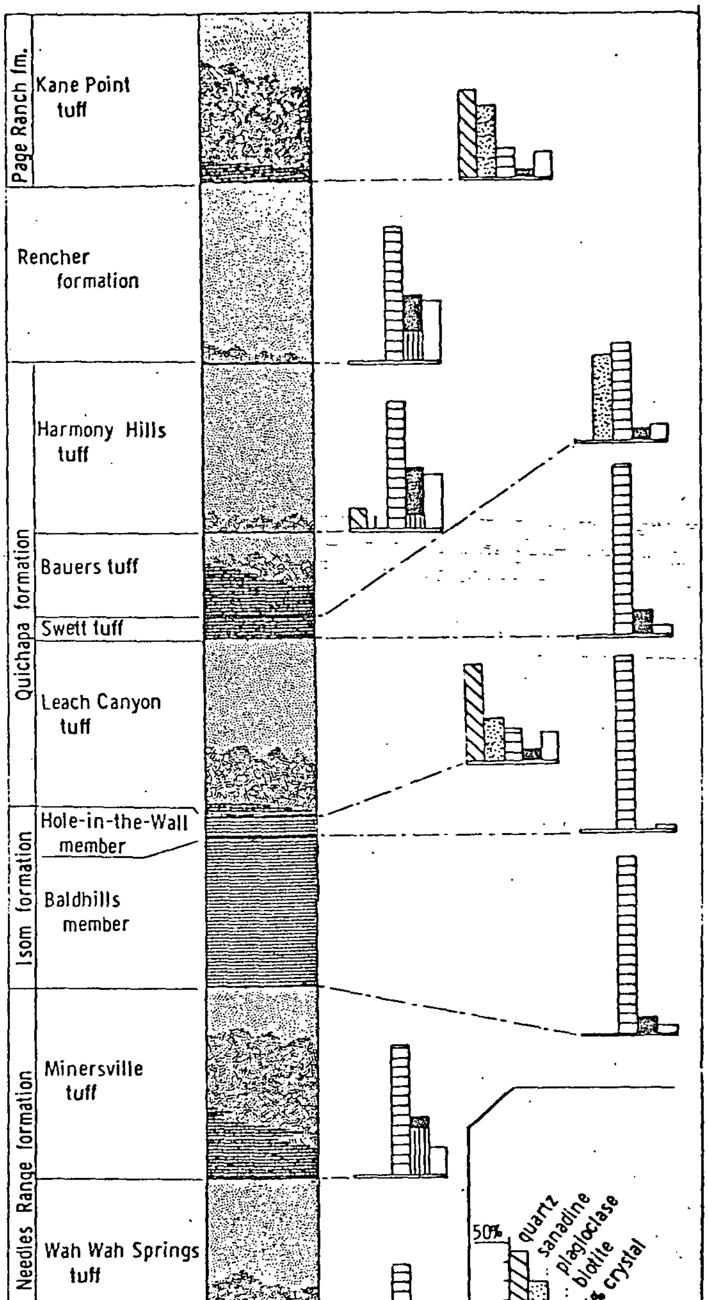

Fig. 2. Phenocryst composition of certain volcanic units.

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The foliated lithoidal phase is pale red to deep red-brown in color. The foliation is made apparent by a parallelism of light gray lenticules that make up as much as 10 percent of the rock. The lenticules range in size from barely visible wisps to 5 inches in thickness and many feet in length—the ratio of thickness to length is extremely variable, ranging from 1:2 to 1:25. The foliation tends to conform with the base of the unit and there is no lineation in the foliation plane—"length" of the lenticules, seen in a face normal to the foliation, is actually the diameter of irregular discoids. The lenticules terminate by wedging out or feathering out, or in angular faces that are suggestive of fracture but are raggedly gradational when viewed with a lens. They are in some respects superficially similar to the flattened pumice inclusions in the Leach Canyon tuff, but there is reason to believe that they were formed primarily by recrystallization of gas-rich portions of the consolidating and compacting ignimbrite material. The field and laboratory evidence bearing on this matter, and views expressed in the literature, are too involved for discussion here; it suffices to say that the gray lenticules are earmarks of the middle foliated phase of the Bauers tuff throughout its known area of distribution.

The foliated phase grades upward, usually with a decrease in depth of color, into the massive lithoidal phase which contains no lenticules. In most places the massive lithoidal phase is overlain directly by the Harmony Hills tuff; it rings to the hammer up to the contact, and the contact is knife-blade sharp, so that a specimen can be taken across it.

This relationship is anomalous. If an ignimbrite is defined as the deposit

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The vertical dimension of the columnar section is about 4000 feet; no scale is given because the section is composite, intended to convey only the general order of magnitude of the thickness of the units. All are not present in any one place. Most of the contacts are erosional disconformities and some are angular unconformities. Sedimentary and volcanic rock units of local extent, which are intercalated at every contact, are not shown.

Degree of induration is indicated schematically in the columnar section by three patterns: a light stipple for slightly indurated, friable rock; a heavy stipple for moderately indurated rock with a firm lithoidal matrix; and a heavy stipple combined with horizontal lines for vitrophyre and lithoidal rock of lava-like hardness.

The histograms are arranged in three rows corresponding with the general types of ignimbrites discussed in the text. The left column includes histograms for units of the Harmony Hills type, characterized by a relatively high percentage of crystals and a low degree of induration. The Minersville tuff, which has a very thick vitrophyre at or near the base where it is best known, is an exception to this rule. The column on the right includes the Bauers tuff and three other units of the same type, characterized by a low content of crystals and an assemblage of lithological properties indicative of high temperature at the time of emplacement; the Hole-in-the-Wall and Baldhills members may be in some manner transitional between ignimbrites and lava flows.

It should be noted that the percentages of crystals shown in the histograms includes only grains large enough for identification by binocular study of stained slices. This percentage may be considerably lower than the percentage of crystals based on study of thin sections with a petrographic microscope.

Particularly in the volcanic units with a low percentage of crystals, the phenocryst composition as shown by the histograms has little significance with regard to the rock name. For example, as noted in the text, a chemical analysis of the Baldhills member indicated that it is in the latite-quartz latite compositional range.

formed by a nuée ardente type of eruption, an ashy top should be as much a part of it as a vesicular top is a part of a lava flow. Actually the massive lithoidal phase of the Bauers tuff, only a few tens of feet thick at most, is everywhere present throughout an area of about 50 square miles mapped in detail in the Iron Springs district; there are neither erosional channels cut into or through it, nor any of the remnants of the ashy material that might be expected to survive for a long time on a flat surface in places remote from water courses. These facts count heavily against stripping away of a non-resistant top of the unit by ordinary erosional processes as an explanation of its absence.

A part of the answer is supplied by the fact that in one part of the district (the Antelope Hills) where the next overlying rock is an andesite flow, there is a complete gradation from the massive stony phase into light gray moderately indurated ash, 30 to 50 feet thick, at the top of the unit. The suggestion is that the ashy phase was elsewhere removed, not by ordinary erosion, but by hurricane sand-blasting by the nuée by which the Harmony Hills ignimbrite was formed; it was preserved only where protected by an armor of andesite flow rock. This hypothesis is supported by the fact that where the massive lithoidal phase of the Bauers ignimbrite is overlain directly by the Harmony Hills ignimbrite the knife-blade contact is itself "welded"—it is described by R. A. Christman in our field notes for 1950 as a "blow-torch contact". If the idea expressed by "blow-torch" is correct, the difference between the nature of the contact where the overlying rock is, (a) another ignimbrite and (b) a lava flow, is yet another example of the contrast that is to be anticipated between contacts in which the covering material was formed by a process (a) capable or (b) incapable of erosion (Mackin, 1950, p. 62).

The rarity of fragmental inclusions in the Bauers tuff, its conspicuous foliation, and especially its lava-like hardness from base to top where the ashy phase is missing, mean that this unit poses the field problem—lava flow or ignimbrite? The absence of lineation, implying that the foliation is a compaction structure; and the fact that this silicic rock unit is a tabular sheet of enormous areal extent, are the most obvious field criteria. Under the microscope the shard structure, and the fact that most of the mineral grains are angular fragments of crystals, are diagnostic.

Swett tuff.—The Swett tuff which underlies the Bauers tuff in the Iron Springs district (table 1) can be concisely described as a Bauers type of ignimbrite, that is, it is characterized by the same low content of mineral grains, rarity of foreign rock fragments, and a very high degree of induration. The basal vitrophyres and lithoidal phases of the two units differ in detail, but isolated specimens can be distinguished only on the basis of a mineralogic contrast (fig. 2). The Swett tuff ranges from 30 to 45 feet in thickness in the Swett Hills. Whether its absence from the section in some places in southwestern Utah is due to nondeposition or erosion is a special stratigraphic problem that needs no discussion here.

Harmony Hills tuff.—The rock composing the greater part of the Harmony Hills member is tan to light red brown in color. Grains of biotite, plagioclase, and other pyrogenic minerals make up 30 to 45 percent of the rock.

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The biotite grains are cleavage flakes which tend to be oriented subparallel with the base of the unit; the resulting foliation makes it possible to obtain an attitude in most ledge outcrops. The thickness ranges from 300 to 350 feet in the Harmony Hills. It is for the most part only moderately indurated; except as noted below, there is no sign of welding. In contrast with the Bauers member, the Harmony Hills member poses the field question, ignimbrite or airfall tuff?

Perhaps the most compelling evidence bearing on this question is presence near the base of the unit of schlieren of black vitrophyre which grade into the surrounding rock, forming the "wilsonite" of the New Zealand writers (for example, Marshall, 1935, p. 330). In some places the schlieren coalesce to make a massive vitrophyre layer comparable with that of the Bauers tuff. It is significant also that most of the Harmony Hills member shows no grain size stratification—in so thick a deposit, covering an area of several thousand square miles, an absence of sorting indicates a method of spreading other than dispersal by winds.

Pock marks or nodes on some exposures of the basal part of the Harmony Hills tuff call attention to the presence of inclusions, etched out by differential weathering, which might readily escape notice on a fresh break because the lithology is similar to that of the enclosing rock. The inclusions are rounded to subangular discoids, commonly a few inches in greater diameter, oriented parallel with the base of the unit. They are clearly cognate in that they are certainly in some manner consanguineous with the rock unit in which they lie, but their mechanism of origin is uncertain and the problems are much too involved for discussion here; for the moment, the point made is that inclusions characterize the lower part of the Harmony Hills tuff in some places, and that they are autoliths rather than xenoliths.

Lateral extent of the Quichapa units.—It is a good general principle that, in the measure that an hypothesis is inherently unlikely, the evidence required to endow it with a given degree of validity must be strong in the same measure. Certainly it will seem in the highest degree unlikely to nearly everyone, perhaps "impossible" to some, that individual ignimbrites are correlatable from Brian Head (Cedar Breaks) in the Colorado Plateau for a distance of about 100 miles westward to the Upper Narrows of the White River near Hiko, Nevada. But the evidence supporting the correlation *is* very strong. We deal with three or four units, each more or less unique in mineralogy, in the same sequence in each of the histogram columnar sections in Williams' chart and in many other measured sections as well. Identity of the units is further checked by suites of heavy accessories and by special "index minerals"; for example, pan concentrates of material weathered from the Leach Canyon tuff show an amount of sphene of an altogether different order of magnitude than the content of this mineral in other ignimbrites studied to date in the Great Basin. And it should be noted that the laboratory work merely confirms correlations tentatively established in the field on the basis of general lithology, types and proportions of inclusions, jointing habits, and weathering and erosion forms of the individual ignimbrites.

The best field check of the correctness of correlation is success in prediction of the physical properties of the units next overlying and underlying the one in sight on the basis of the known succession. The Quichapa units have met this test so consistently in so many places that it is no longer surprising to find the sequence in proper order in an area examined for the first time—it is any flaw in the order that is anomalous. The explanation, if it can be worked out, is usually in terms of topographic features, residual or formed by concomitant deformation or local volcanism, which prevented the spreading of the missing unit to the place in question, or caused it to be unusually thin or thick.

The areal extent of the Quichapa formation in southwestern Utah only, that is, not including its extension in southeastern Nevada, is about 2500 square miles. A conservative average thickness of 1000 feet makes the volume about 500 cubic miles.

The Quichapa units as lithologic types.—As stated earlier, the Quichapa sequence includes representatives of the three principal types of ignimbrites which make up the Tertiary volcanic sequences in the Great Basin. Ignimbrites of the Harmony Hills type are characterized by a large percentage of pyrogenic crystals and a low degree of welding. Inclusions are typically cognate; they may be about or may make up a large share of the rock. Ignimbrites of the Bauers type are characterized by a low content of pyrogenic crystals and a high degree of welding. Inclusions are usually rare or absent. Where the vertical section is complete ignimbrites of this type commonly show the four gradational but distinct lithologic phases described above. Ignimbrites of the Leach Canyon type are intermediate between the Harmony Hills and Bauers types in content of crystals and degree of welding. Angular fragments of other rocks are usually abundant.

The foregoing paragraph fairly bristles with questions. What is meant by "degree of welding"? How can this and other properties of ignimbrites be quantified as lines of evidence bearing on such petrogenetic questions as temperature at time of emplacement? Is it a valid generalization that there is an inverse relationship between crystal content and degree of welding in the Tertiary ignimbrites, and between either or both of these properties and the nature and percentage of inclusions? If there are such relationships are the several so-called types of ignimbrite merely arbitrary divisions of one or more completely gradational sets of properties, or do the ignimbrites fall into natural groups corresponding with genetic classes? How do the sets of properties vary with differences in chemical composition? There must surely be changes in a single ignimbrite, from the vicinity of the vent to the distal margin, in temperature at the time of consolidation and also in the nature and percentages of mineral grains and inclusions; is it proper to attempt to evaluate the petrogenetic significance of differences in these properties in different ignimbrites without taking into account lateral variations in the same ignimbrite? Is there, in single eruptive episodes such as that represented by the Quichapa formation, a consistent order of occurrence of the same ignimbrite types? Do the same rules apply to sequences of ignimbrites in different parts of the Great Basin, and of different ages during the Tertiary?

These questions are worth asking because they bring out the full meaning of a point suggested earlier. We are not "drowning in data" relating to ignimbrites: we have as yet only a small fraction of the data needed for an analysis of the origin of these rock units. Work with single vertical sections, and mapping in limited areas, are good starts, but because many of the units are regional in extent, any comprehensive study of them must be on the same scale. The first step must be the restoration, as of the time of their origin, of a representative number and variety of the Tertiary ignimbrites; the evidence that is basic to such restorations can be obtained only by regional stratigraphic studies.

POST-QUICHAPA VOLCANICS

General statement.—Spreading of the Quichapa ignimbrites as flattish sheets over a tolerably level plain was followed by a protracted period during which continued or recurrent volcanism was accompanied by emplacement of laccolithic intrusions in the Iron Springs district. The intrusions produced dome mountains as much as several thousand feet high. The lowlands between and adjacent to the intrusive domes were the site of deposition of (a) direct volcanic products, as lava flows, ignimbrites and lahars, and (b) detrital materials supplied by erosion of the domes. The detrital materials consist mainly of fragments of the Quichapa and older volcanic rocks, but in some places include Tertiary and Mesozoic sedimentary rock types and fragments of intrusive rock—the sequence clearly represents the erosional deroofing of the intrusive domes. The record is complex because the direct volcanic products and the detrital materials interfinger irregularly, and especially because additional intrusions were emplaced from time to time during the period, deforming the older interintrusion trough deposits and radically changing patterns of erosion and deposition.

Rencher formation.—The Rencher formation (Cook, 1957, p. 57-59) consists predominantly of crystal ignimbrites and other volcanic rocks which may rest directly on the Harmony Hills member of the Quichapa formation, or on aprons of detritus bordering the intrusive domes, or unconformably across the truncated edges of all the older strata on the flanks of some of the domes.

Page Ranch formation.—The Rencher formation is overlain by the Page Ranch formation (Cook, 1957, p. 61-63), a composite unit typically exposed in an east-facing scarp two miles northwest of Page Ranch and one mile southwest of Old Irontown Historic Site (see Page Ranch quadrangle). The lower part of the scarp consists of crudely bedded fanglomerate, made up chiefly of subangular blocks of the Harmony Hills tuff and other Quichapa ignimbrites, here designated the Irontown member of the Page Ranch formation. The upper part of the scarp consists of a vitric ignimbrite of rhyolitic composition, here designated the Kane Point tuff for a peak of that name several miles to the southwest on the same scarp. These two members of the Page Ranch formation clearly represent the filling of a synclinal trough between the Iron Mountain and Mount Stoddard intrusions. There has been little or no deformation of the Page Ranch formation at the type locality, but elsewhere in the Iron Springs district (for example, on the east side of an intrusion that underlies parts of the Antelope Hills) it has been sharply flexed.

Age relationships.—The Leach Canyon tuff, the lowest ignimbrite of the Quichapa formation, has a zircon age of 28 m.y. (Jaffee, written communication). One of the Iron Springs intrusions (Three Peaks) is 22 m.y., and the Kane Point tuff is 19 m.y. on the same basis. These figures suggest that the Quichapa formation is Oligocene and that the Rencher-Page Ranch period of extrusive-intrusive igneous activity is late Oligocene or early Miocene.

Younger volcanics.—In the Bull Valley district a sequence of volcanics which is equivalent in part to the Page Ranch formation is overlain unconformably by a younger sequence consisting of lava flows, ignimbrites, and volcanic-derived sediments, dominantly rhyolitic in composition (oral communication, H. R. Blank). Rocks of the same lithology and position in the section are present in a number of other places in southwestern Utah (for example, the Mount Belknap rhyolite of Marysvale, Callaghan, 1939). As far as is now known, these young rhyolitic rocks postdate the emplacement of all the larger laccolithic intrusions. They differ from the older volcanics in that they are commonly associated with small plugs that were probably local feeders. While there has been as yet no attempt to work out the unit-by-unit stratigraphy of these rocks on a regional scale, there is no reason for believing that they were spread as sheets of great lateral extent, as were the older volcanics—the available evidence indicates rather that their present limited distribution corresponds approximately with their original extent. They are commonly regarded as Mio-Pliocene of Pliocene in age.

Local volcanism, chiefly the spreading of basalt flows and the building of small volcanoes, has continued through the Pleistocene into Recent time (see Gardner, 1941; Threet, 1952; Cook, 1957).

PRE-QUICHAPA VOLCANICS

Isom formation.—The Quichapa formation is underlain by a sequence of volcanics made up chiefly of ignimbrites and lava flows, with intercalations of sedimentary rocks, collectively designated the Isom formation (table 1). The type locality is the southern slope of an east-west ridge just north of Isom Creek in the northwestern part of the Iron Springs district (Three Peaks quadrangle, Sec. 5, T. 35 S., R. 12 W.). At the type locality and generally in southwestern Utah the Isom formation rests on the volcanics of the Needles Range formation (see below), but in some places it lies on the Claron formation or on older volcanic rocks of local origin. The Isom formation is as yet the least known of the volcanic sequences of southwestern Utah, both as regards its internal stratigraphy and the origin of the anomalous porphyries which characterize it; it is a complex of problems that cannot be profitably attacked until after the stratigraphy and origin of the overlying and underlying sequences have been worked out.

At the type locality the lower part of the Isom formation consists of an ignimbrite of the Leach Canyon type, a few tens of feet thick, which has not been definitely identified elsewhere and needs no formal stratigraphic name. The principal member is a sheet of porphyry of latitic composition (Leith and Harder, 1908, p. 58, analysis C), glassy to lithoidal in texture, black to dark red-brown in color, with a strong platy parting and an unusual blocky fracture which causes it to break into roughly cubic granules. It is here designated the Baldhills member for its occurrence in a ridge of that name (see Three Peaks quadrangle) which trends northward from the type locality of the Isom formation. The uppermost member of the Isom formation at the type locality is a sheet of latite porphyry, lithoidal in texture and purplish gray in color, with light gray lenticules similar to those of the Bauers tuff. This unit is rarely more than 40 feet thick, but it is very widespread and is here named the Hole-in-the-Wall member for its occurrence at the east end of a pass of that name, two miles north of the type locality of the Isom formation.

The Baldhills and Hole-in-the-Wall members exhibit some of the features of ignimbrites of the very highly welded type represented by the Bauers tuff, but they have internal structural features indicative of viscous flow, and other features, as vesicules, which mark them as aberrant types. The fact that their mechnism of origin is not known does not detract from their value as stratigraphic units.

The Isom formation is at most only about 500 feet thick in the Great Basin in southwestern Utah. It thickens greatly and is widespread in the High Plateaus, but not enough is yet known of its distribution to justify an estimate of areal extent and volume.

Needles Range formation.—The Needles Range formation consists primarily of crystal-rich ignimbrites of the Harmony Hills type. Colors are commonly pink to dark red brown, but range widely from black in the solidly-welded vitrophyre phases that occur near the base of some of the units to light gray in their almost incoherent uppermost parts. The type locality is the east side of the Needles Range at and south of the Garrison-Milford Highway. In this vicinity the Needles Range ignimbrites rest on an erosion surface with a local relief of as much as 500 feet cut in Paleozoic rocks, or on early Tertiary (?) fluvial and lacustrine sediments or older volcanics which lie in erosional and tectonic depressions in that surface. There is in most places no evidence of any considerable lapse of time between the deposition of these rocks and the spreading of the first ignimbrite of the Needles Range formation—the subjacent volcanics are arbitrarily excluded from the formation on the basis of lithology. In most places the Needles Range formation is sharply defined at the top by the glassy latitic rocks of the Isom formation.

Many sections of the Needles Range formation include two, and some sections include three separate ignimbrites. The lower of the two members at the type locality is here designated the Wah Wah Springs tuff, for its occurrence just south of Wah Wah Springs, fifteen miles west of the abandoned mining town of Frisco. At this place the unit is 700-800 feet thick and is probably substantially complete—it shows a complete gradation upward from a black vitrophyre at the base to a light gray nonwelded ashy top. The upper member at the type locality is designated the Minersville tuff for its occurrence in the Minersville Canyon of the Beaver River, where it is represented chiefly by dark gray to black devitrified tuff several hundred feet thick, underlain by the Wah Wah Springs tuff and overlain by the Isom formation.

Lateral variations of these and other as yet undesignated members of the Needles Range formation need no discussion here. It may be stated briefly that crystal-rich ignimbrites believed to be parts of the Needles Range formation have been measured in many places from the Paunsaugunt Plateau north of Bryce Canyon westward 110 miles to the Nevada line; Cook (oral communication) finds that one or more of the same units are widespread in eastern Nevada. The north-south dimension is about 125 miles from the latitude of Levan to that of Cedar City. The areal extent is at least 10,000 square miles. A conservative estimate of average thickness of about 500 feet makes the volume well over 1000 cubic miles.

Stratigraphic problems.—Because the Needles Range ignimbrites are the oldest of the regional ignimbrite sheets in southwestern Utah, and because they seem to be approximately contemporaneous with the first major breakdown of the Great Basin relative to the High Plateaus, the age of the Needles Range formation is a matter of special interest. It is certainly Eocene or Oligocene, but it cannot be dated closely in this long span of time on the basis of any evidence now available to me. The following discussion is intended, not so much to establish the time range of the Needles Range formation, as to bring out the nature of certain stratigraphic problems in the Great Basin-Colorado Plateau transition zone (see caption to fig. 3), and to indicate the role of ignimbrites in the eventual solution of these problems. The discussion starts with the sedimentary Claron formation, which generally underlies the Needles Range formation in the transition zone and in the Plateau.

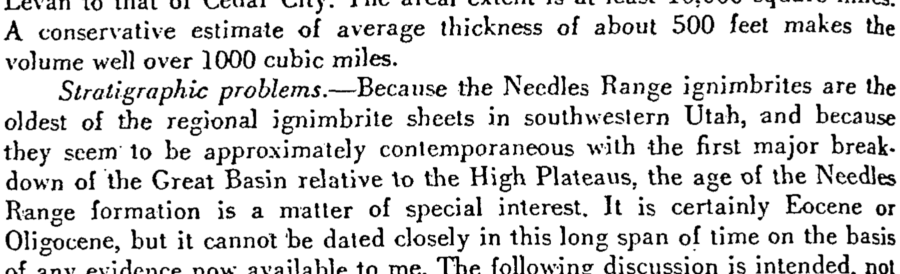

Fig. 3. Diagrammatic restored section prior to the beginning of eruptive activity.

The section trends southeastward from the southeastern part of the Wah Wah Range to the Colorado Plateau in the vicinity of Cedar City, Utah. The over-all length is about 50 miles, but the section is not to scale. WW is in the present position of the southeastern part of the Wah Wah Range; EV, Escalante Valley; IS, Iron Springs district; CV, Cedar Valley; CP, Colorado Plateau.

The major thrust which brings Paleozoic rocks over Navajo sandstone in the Wah Wah Range has been mapped by G. M. Miller (1958). It corresponds approximately in position with the so-called Wasatch Line (WL), shown by Eardley (1951, fig. 178, p. 316) as the "front of major thrust sheets" (see also Spieker, 1946, fig. 20). The principal Laramide structure in the Iron Springs district is the Iron Springs Gap structure (ISGS), a foreland décollement thrust which brings the Jurassic Carmel limestone over the Cretaceous Iron Springs sandstone; the zone of gliding is a gypsiferous horizon in the lower part of the Carmel (Mackin, 1954). At K-H the K refers to the Laramide Kanarra fold (Gregory and Williams, 1947); the H refers to the late Tertiary Hurricane fault (not shown), which follows the trend of the Kanarra fold in part of its course.

The Hurricane fault zone is the western boundary of the Colorado Plateau. The broad belt between it and the southeastern Wah Wah Range has the Mesozoic and early Tertiary stratigraphy of the Plateau, and the antithetic block fault structure of the Great Basin—it is referred to in the text as the Great Basin-Colorado Plateau transition zone. The Claron sediments were derived chiefly from Laramide thrust ranges in what is now the Wah Wah area, but were furnished in part by ridges formed by the foreland structures. The Needles Range ignimbrites were spread across the upper surface of the drawing while Claron sedimentation was still in progress in some places. The ignimbrites cannot be shown without drastic modification of the base of the drawing because the eruptions were immediately preceded or accompanied by foundering of the western part of the section.

The Claron formation consists of as much as 1500 feet of fluvial and lacustrine sediments, first described by Leith and Harder in the Iron Springs district (1908, p. 43). It is not complete at Mount Claron, but the intended rock content is clear from the Leith and Harder mapping and text treatment. In detailed remapping it is possible to carry four to seven lithologic members throughout the district (Mackin, 1954). These members need no discussion here, but are worth mention because at least three of them have exact equivalents in the Pink Cliffs at Cedar Breaks, 20 miles to the east and 5,000 feet higher, near the crest of the Markagunt Plateau. In general, both in the Iron Springs district and at Cedar Breaks the formation consists of a lower part made up chiefly of freshwater limestone, sandstone, and conglomerate, characteristically red in color, and an upper part made up chiefly of sandstone and conglomerate, characteristically light gray in color, with one or more interbedded layers of white limestone. The gray unit is increasingly tuffaceous toward the top. Gregory called the Cedar Breaks strata Wasatch or "Pink Cliffs Wasatch" and considered them to be Eocene on the basis of fresh-water shell material (1949; 1951, p. 50-52). But Claron is preferable to Wasatch as a formation name (Spieker, 1946, p. 137-139), and is used hereafter in this paper both for the Great Basin and the Plateau occurrences; "red Claron" and "gray Claron" are used informally, in much the same sense as Gregory's "red Wasatch" and "white Wasatch," for ease in reference to the lower and upper parts of the formation.[2]

In the Iron Springs and Red Hills districts the Claron formation rests on an erosion surface which truncates Cretaceous and Jurassic strata locally overturned in Laramide foreland folds (Mackin, 1954, fig. 4; Threet, 1952, p. 76-79)—the Claron is clearly post-Laramide (see fig. 3). The "red Claron" contains no igneous detritus; shards and other pyroclastic materials first appear in the "gray Claron."

Ignimbrites of the Needles Range formation rest concordantly on the "gray Claron" in an area of many hundreds of square miles in the transition zone and the Plateau. In some places, as in the northern part of the Iron Springs district, there is a lag mantle of quartzite pebbles at the contact and/or bentonitic weathering of the tuffaceous Claron sediments just below the contact. In the Red Hills and the Bull Valley districts ignimbrites that are quite certainly members of the Needles Range formation seem to be interbedded at the top of the Claron, that is, there are Claron-type sediments above, as well as below, the first Needles ignimbrites. And it may be noted that, in some places in the transition zone, volcanics similar to those which underlie the Needles Range formation at its type locality lie between the Claron formation and the Needles Range formation. The over-all relationships suggest that the explosive eruptions represented by the pre-Needles volcanics and the tuffaceous materials in the upper part of the "gray Claron" culminated in the paroxysmal nuées which spread the Needles ignimbrites across a Claron fluvial and lacustrine plain which was in some places still the site of deposition of Claron-type

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[2] A paper now in preparation by Threet will explain why it is not practicable to use Gregory's "Brian Head formation" in a discussion of the detailed stratigraphy of the volcanic rocks of the High Plateaus.

sediments. This would imply that if the "gray Claron" is Eocene, the Needles Range formation is also Eocene or earliest Oligocene.

Where the Needles Range formation rests on the Claron formation in the Iron Springs district it is generally less than 100 feet thick, but in the Wah Wah Range and generally to the west, where it lies on a mature erosion surface cut in older rocks, the thickness is 1000 to 1500 feet. Because much of the nonvolcanic sediments comprising the Claron were derived from the west, it is believed that the erosional topography in the Wah Wah area must have stood above the level of the Claron depositional plain, and that it subsided immediately prior to or during the spreading of the Needles ignimbrites (fig. 3).

As shown by Threet's mapping in the Markagunt Plateau (paper in preparation) and reconnaissance by me in the Tushar and Paunsaugunt Plateaus, two or more of the *units of the Claron-Needles-Isom-Quichapa sequence are seen in many sections in this* southern part of the High Plateaus. These widespread units are essentially concordant in a regional sense, but they are intercalated with volcanics of local origin in many places, and where the local "volcanic piles" attained considerable height, the regional units tend to wedge out by overlap on their flanks. The stratigraphy is further complicated by erosional removal and non-deposition of some of the units as a result of local deformation. The relationships are particularly complex in the vicinity of centers of eruptive activity; in the Tushar-Marysvale eruptive area, for example, the Needles Range formation is equivalent in part of Callaghan's Bullion Canyon group (1939), and the Isom formation is equivalent in part to his Dry Hollow latite. Many unsolved stratigraphic problems need no discussion here. The point is simply that what are now the Great Basin in southwestern Utah and the southern High Plateaus were parts of a single fluvial and lacustrine depositional plain during Claron time, and continued through Needles, Isom, and part of Quichapa time to be a single volcanic field consisting chiefly of regional ignimbrites, surmounted in places by volcanoes and perhaps intrusive dome mountains. The "breakdown" along the Hurricane and related faults which made the transition zone a part of the Great Basin in topography and altitude seems to have started during Quichapa time (fig. 3).

The youngest Cretaceous sedimentary unit (the Kaiparowits formation) cut by the regional unconformity beneath the Claron is said to be Laramie in age on the basis of invertebrate and plant fossils (Gregory, 1950, p. 55-56). As indicated above, the Leach Canyon tuff has been zircon dated at 28 m.y., which tentatively places it close to the Oligocene-Miocene line of the time scale. The order of occurrence of major geologic events in southwestern Utah between these dates is reasonably well known, but the timing of the events in this long interval is not at all known. For example, it is established that the beginning of igneous activity post-dates the close of Laramide orogenic deformation in this area by a period of time long enough for erosional beveling of Laramide structures and deposition of 400 to 600 feet of nonvolcanic sediments comprising the "red Claron." The hypothesis for origin of the eruptive magmas to be presented in the sequel to this article makes the absolute length of the time interval between the main orogenic event in an area and the beginning of volcanism in the same area a matter of special interest, but because the "red Claron" is dated loosely only as Eocene, the overlying tuffaceous "gray Claron" may range from lower Eocene to middle or late Oligocene—that is, the time span between the orogeny and the eruptive activity may be a few million to as much as 30 million years. If the "gray Claron" is Green River (see below), then the question arises as to how the 20 to 30 million years that separate "gray Claron" time from Leach Canyon time should be apportioned within the Needles Range and the Isom formations, and to the "gray Claron"-Needles, Needles-Isom, and Isom-Quichapa interformational contacts. The difficulty lies in the fact that these units are regionally concordant. If the tentative dates suggested above are even approximately correct, erosional processes on the volcanic plain must have been for most of the time in a state of suspended animation which bespeaks a low altitude relative to base level.

Correlation of the Claron formation of the Pink Cliffs and southwestern Utah with the section in central Utah, where the detailed history of orogenic and early post-orogenic events has been worked out by Spieker and his Ohio State group, has long been uncertain because the intervening Marysvale-Tushar volcanic pile makes it impossible to "walk out" the sedimentary units. Spieker (1949, p. 35) and others have noted the presence of interbeds of tuff in the Green River formation of central Utah, and Muessig (1959) has presented evidence indicating that volcanism which started in Green River time culminated in the spreading of a thick pyroclastic unit which is exposed in highway cuts just south of Chicken Creek reservoir, eight miles southwest of Levan. This unit is an ignimbrite, generally similar in lithology to those of the Needles Range formation. It is overlain concordantly by Muessig's Golden Ranch formation, consisting of volcanic boulder con-

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glomerate and tuffaceous sediments said to have been spread southward from the Tintic eruptive center (Muessig, 1951; Morris, 1957, p. 30). The Sage Valley limestone member of the Golden Ranch formation has yielded fossil plants regarded by R. W. Brown as upper Middle Eocene in age (Muessig, 1951). Morris states that two intrusive bodies of the Tintic eruptive center have been zircon dated as 46.5 and 38 m.y. (1957, p. 30).

Chicken Creek reservoir is several tens of miles beyond the northeastern border of the area within which the Needles Range formation is well enough known to be correlated with confidence. If the ignimbrite there is a Needles Range member then Muessig's Green River, which is gray in color and increasingly tuffaceous and bentonitic toward the top, may be equivalent in part to the "gray Claron" of southwestern Utah, which is also increasingly tuffaceous and bentonitic toward the top. The underlying Flagstaff formation, which is red in color and non-volcanic, may be equivalent to the non-volcanic "red Claron".

This general view has been held for some time by Spieker on the basis of regional stratigraphic relationships and lithologic similarities (1946, p. 136; 1949, p. 32; see also Hunt, 1956, p. 18, figs. 55 and 56). It implies that the major change from non-volcanic conditions of sedimentation to dominantly volcanic conditions occurred at about the same time in central and southwestern Utah, and that the first regional ignimbrite, a member of the Needles Range formation, spread over both areas late in Green River time.

Work by Donald P. McGookey near Richfield, in central Utah about 50 miles south of Muessig's area, indicates a different history. His section includes two volcanic units, seen in the field by me under his guidance and in company with Spieker, which are probably Needles Range and Isom members. But McGookey's Needles Range member (?) overlies a thick sequence of fluvial and lacustrine sediments, the Crazy Hollow and Gray Gulch formations, which is said to rest unconformably on the Green River formation. For this reason McGookey thinks that the Needles Range member (?) which is the first regional ignimbrite of his area is considerably younger than the ignimbrite which rests on the Green River at Chicken Creek reservoir. He suggests further, in a paper now in preparation, that the central Utah equivalents of the "red Claron" and the "gray Claron" are respectively the Crazy Hollow, which is dominantly red and non-volcanic, and the Gray Gulch, which is gray and increasingly tuffaceous toward the top. According to this view the Needles Range formation is perhaps early Oligocene in age.

It is only necessary to visualize a restored section including the sedimentary and volcanic units in question to make clear how widely varied are the possible arrangements of time lines connecting the different places, for example, the Tintic, Marysvale, and southwestern Utah eruptive centers. Analysis of the conflicting and inconclusive evidence known to me bearing on the general problem, and particularly on the age of the Needles Range formation, would not be worth the space it would occupy and it is in any case beyond the scope of this paper. The point made here is simply that (1) as emphasized by Spieker, correlation of complexly intertonguing fluvial and lacustrine sedimentary units of the type that characterize the late-orogenic and early post-orogenic period in the Colorado Plateau-Great Basin transition zone is uncertain at best and (2), when the regional stratigraphy of the volcanics has been worked out the ignimbrites will provide a means of cross-dating geologic events with a precision not obtainable by any other method.

Cross-dating establishes only the relative order of events. As indicated earlier, the ignimbrites contain enough radioactive substances to allow "absolute" age determinations within certain limits of error, which will surely be reduced as the methods are perfected.

It is interesting, after arriving laboriously at the ideas stated above, to find that Dutton's studies in the High Plateaus north and south of the Tushar volcanic pile led him to state, in 1880:

> These tufas . . . rest everywhere upon beds which are either of Bitter Creek or Green River age . . . and must have been deposited before the final dessication of the Great Eocene lake, which appears to have taken place throughout that part of its expanse now covered by the High Plateaus after the middle and before the

> close of the local Eocene. They are widely distributed and could not very probably be supposed to have accumulated in local temporary lakelets. Thus, then, the opening of the eruptive activity goes back into Eocene time (1880, p. 57).

In most places Dutton's "tufas" are ignimbrites or water-laid ash deposits belonging to the Needles Range formation.

Those interested in historical aspects of the ignimbrite concept will find delightful reading in Dutton's troubled discussion of the origin of the Needles rocks. He points out first that they could not be ordinary airfall pyroclastics because the trajectories required to explain the distance of movement of the fragments would be fantastic. More or less by default, he regards them as having been derived from erosion of older volcanics. Some well-bedded deposits in the East Fork Canyon in the Sevier Plateau are in fact stream-laid—Dutton's difficulty was with the manner of origin of intercalated units more than 100 feet thick which show no bedding or sorting. He remarks again and again the lava-like hardness of these rocks (see, for example, 1880, p. 56, 79, 244-245), and their close resemblance to lavas even under the microscope (p. 80). The hardness is credited to metamorphism (p. 245). But it is noted on the next page that they are underlain by sedimentary rocks which show "no trace of alteration." The conclusion is that the "tufas" must have been especially susceptible to metamorphism, of a type of which little is known (p. 247-248).

Summary.—The silicic volcanic rocks of the Great Basin are predominantly ignimbrites rather than lava flows. Some of the individual ignimbrites are many thousands of square miles in areal extent. They are very nearly ideal stratigraphic units in that (1) each was formed everywhere at the same instant of geologic time, (2) their upper surfaces were essentially flat when formed, and (3) they exhibit a wide variety of distinctive physical properties useful in correlation.

The eruptive activity began in southwestern Utah after the close of the Laramide orogeny, being separated from it by a period of time sufficient for (1) erosional beveling of orogenic structures developed in late Cretaceous rocks, and (2) deposition of fluvial and lacustrine sediments comprising the lower part of the Claron formation. Volcanism started late in Claron time. The same ignimbrites which overlie the Claron conformably in the Colorado Plateau are widespread in the Great Basin, where they rest directly on an erosion surface of considerable local relief cut chiefly in Paleozoic rocks. The Claron and the associated ignimbrites are considered to be post-orogenic rather than late orogenic because the deformation structures seen in these rocks are different in kind from those that characterize the orogeny.

The volcanic section in southwestern Utah consists of (1) a Needles-Isom sequence, perhaps Eocene or early Oligocene in age, (2) a Quichapa-Page Ranch sequence, of perhaps Oligo-Miocene age, and (3) an unnamed sequence of late Tertiary rhyolite flows and pyroclastic units. Correlation with other parts of the Great Basin and the Colorado Plateau is as yet uncertain, but enough is known to make it evident that it will be possible to establish an ignimbrite stratigraphy for the Tertiary on a regional scale.

Questions that will be automatically resolved by the regional stratigraphic approach are (1) location of vent areas and (2) whether episodes of eruptive activity in the various parts of the Great Basin were contemporaneous, or were otherwise systematically or randomly placed in time. The ignimbrite stratigraphy will provide a much-needed basis for working out the post-orogenic deformational history of the Great Basin, to be considered in the next section. Finally, a well-established regional stratigraphy is a prerequisite for obtaining data on lateral and vertical variations in thickness, degree of welding, sizes of crystals and clasts, and other original features of ignimbrites, that are essential to any understanding of the origin of these extraordinary volcanic units.

THE BASIN-RANGE PROBLEM

The physiographic approach.—The history of thought regarding the origin of basin-range topography has been summarized by Davis (1903, 1905), Gilbert (1928), and most comprehensively, with respect to its stratigraphic and structural aspects, by Nolan (1943); the high points that are significant for present purposes can be stated very briefly:

King stated (1870) that the present topography was formed by erosion of highlands produced initially by the deformation recorded by structures of the pre-Tertiary rocks comprising the ranges. This view is representative of the habits of thought current at that time, as exemplified by the theory held by the Rogers brothers and Lesley for the origin of the Appalachian Mountains. The deformational history of an area was interpreted solely on the basis of the structures of the rocks—landforms entered into the thinking only as indicating the recency or antiquity of the orogeny.

Gilbert (1874, 1875) saw a difference in kind between the narrow, V-shaped erosional valleys that dissect the ranges and the broad alluvium-floored basins that lie between them. He noted, moreover, that the trend of the ranges commonly differs from the trend of their internal structures, and that at many range fronts the structures are truncated by straight baselines not adequately explained by erosion alone. He concluded from these and other physiographic relationships that the ranges must correspond with blocks raised relative to the adjoining basin blocks by movement on range-front faults. Powell (1877), and at about the same time King (1878), recognized the possibility of two distinctly different types of crustal movements in the Great Basin, and Powell especially made the point that the folds and other strongly compressional structures within the ranges pre-date and must have been deeply eroded prior to the block faulting. Dutton (1880, p. 48) stated this view succinctly:

> These flexures are not, so far as can be discerned, associated with the building of the existing mountains in such a manner as to justify the inference that the flexing and the rearing of the ranges are correlatively associated. On the contrary, the flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion.

In opposition to these views, Spurr (1901) pointed out (1) that many high-angle faults within the ranges have no topographic expression, and (2) that there are no faults at many range fronts, where the alluvial deposits of the valleys overlap on the range-forming rocks. He made it clear that he depended on the solid geology that could be seen in a ledge and beaten with a hammer, not on landforms; on this basis he insisted that the existing topography could be accounted for by erosion of folds, without benefit of later block faulting.

In reply to Spurr, Davis (1903, 1905) defended the Gilbert concept and developed the physiographic criteria for block faulting in the form now found in most geologic textbooks. With his usual perception for essentials he outlined the geologic history of the Great Basin in terms of (a) growth of an ancestral range of *King Mountains* during the Laramide orogeny, (b) reduction of these mountains to the *Powell Plain* in early Tertiary time, and (c) subsequent formation of the *Gilbert Ranges* by block faulting (Davis, 1930).

If to the many oversimplifications of the last two paragraphs one more is added to the effect that block faulting began or occurred chiefly in late Cenozoic time, then we have the version of the basin-range theory expressed by the familiar Davis diagram showing a tilted block consisting of folded strata, bounded on one or both sides by faults, in process of burial by upbuilding basin fills of its own detritus. This picture may be thought of as representing the general consensus at the end of the heroic period—the Gilbert-Powell-Dutton period—of development of the basin-range concept. It is difficult, looking back over the years, to grasp fully the impact of the new, much needed, and obviously good idea which was the crux of that concept, i.e., that the origin of a range as a topographic feature may be an entirely different matter from the origin of its internal structures.

The development of the concept in this century is marked by an increasing awareness that the first-cycle block-fault range is only one of a variety of range types that occur in the Great Basin. Marked contrast in the stages of erosional development of different ranges was recognized early by Davis (1905, see also 1925) as indicating differences in the date of faulting from place to place. The graded slopes extending basinward from many ranges were definitely identified as pediments rather than alluvial fans; that is, as erosion surfaces cut in the range-forming rock or in Tertiary fluvial and lacustrine deposits which accumulated under topographic conditions wholly different from those of the present. Blackwelder (1928) led the way in constructive criticism of the one-cycle version of the concept, emphasizing the need for discriminating between fault scarps and fault-line scarps which, while superficially similar to each other in form, are wholly different in geologic meaning. Representative of the attainment of maturity in our understanding of the significance of landforms with regard to the Tertiary deformational history are Nolan's review of the literature (1943) and many recent papers dealing with individual ranges (for example, Sharp, 1939).

The structural approach.—The physiographic criteria for block faulting apply to best advantage in ranges in an early stage of erosional development—the morphologic features indicative of faulting are quickly blurred and may be lost altogether in ranges that have advanced beyond early maturity. This means that, insofar as topographic form is concerned, the more deeply eroded ranges might as well be Tertiary anticlines as Tertiary fault blocks. It means, also, if commonly held rates of erosion are accepted as true, that there can be no topographic evidence of early Tertiary deformation—perhaps this point lies behind the idea that Great Basin block faulting occurred chiefly during the late Tertiary.

Even in those ranges where it is well preserved, the "pre-faulting" erosion surface can be used for measurement of block-tilting and fault displacement only in very general terms because it was in most places a surface of considerable local relief (see, for example, Eardley, 1933). And there is always a question as to whether the "pre-faulting" surface is a "Powell Surface" in the sense of Davis' meaning, that is, an erosion surface which pre-dates the beginning of block faulting, or whether it may have been developed during a period of relative crustal quiet between two episodes of block faulting. The difficulty in dealing with the deformational and erosional history of a Great Basin range in quantitative terms on the basis of a restoration of the "pre-faulting" erosion surface is brought out clearly by Gilluly's sensitive handling of the problem in the Oquirrh Range (1928, p. 120-122).

Structural and stratigraphic evidences of block faulting which are at least in principle free from these limitations were described by Russell (1884) in southern Oregon, where Steens Mountain and other ranges consist mainly of mid-Tertiary basalt. The ranges are sharply asymmetric in form. The gentle "back-slopes" correspond approximately with the homoclinal dip of the basalt, and the scarp slopes in many places show complex structures, generally credited to step faulting, drag effects, or superficial slides. There has been question as to whether the main faulting is reverse or normal (Smith, 1927; Fuller and Waters, 1929) and there is a possibility that some of the ranges are asymmetric anticlines (personal communication, Harry Wheeler). Definite answers await detailed mapping based on unit by unit stratigraphy of the volcanics.

Figure 4, a section of Umtanum Ridge in Central Washington, brings out the point that asymmetry of form coupled with homoclinal structure in a ridge formed by uplift does not necessarily mean that the ridge is a fault block. The structure of the north side of Umtanum Ridge is excellently exposed where the

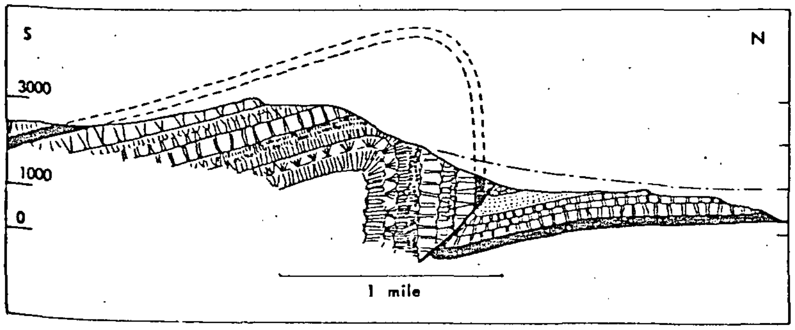

Fig. 4. Diagrammatic structure section of Umtanum Ridge.
The section is located just west of the Columbia River near Priest Rapids, Washington. The flows are part of the Yakima Basalt, of late Miocene age. The section includes twelve stratigraphic units that are rapidly mappable throughout this part of the Columbia Basin. The unit shown in solid black below the surface and restored by dotted lines above the surface is a widespread porphyritic flow, distinguished in the drawing to bring out the structural relationships. The dash-dot line indicates the approximate level and form of a pediment which bevels the steep limb of the fold in places remote from the main drainage lines. Where the pediment is covered by alluvium, the ridge simulates a tilted fault block.

Columbia River cuts across it diagonally. The flows and interbeds shown are good cartographic units (Mackin, 1955). The structure is a fold, overturned and overthrust to the north. Where this and other similar structures in Central Washington are *remote from main* streams the shattered basalt of the steep limb is commonly truncated by a pediment (Waters, 1955, p. 676-679) and the topographic high is on the gently dipping limb as much as a mile from the surface trace of the axial plane of the fold. The nature of the structure is apparent in most places because the pediments are in various stages of dissection, but if the lowlands were completely veneered by alluvium, the topographic from and homoclinal structure of the ridge might well be taken to mean that it is a tilted fault block. The Columbia Basin is, of course, an altogether different structural *province from* the Great Basin, but an image of Umtanum Ridge, as it *would appear if the drainage happened to be internal*, is a salutary item in the mental equipment of anyone dealing with the basin-range problem in the Great Basin.

Louderback (1904, 1923) is *properly* credited with bringing structural evidence afforded by Tertiary rocks, chiefly volcanics, to bear on the origin of typical Great Basin ranges in northwestern Nevada. Davis (1930, p. 299) made "louderback" a specific name for an erosion remnant of a lava flow on the back slope of a *tilted fault block consisting* primarily of complexly-structured pre-Tertiary rocks. The advantage of the tilted flow (the structural approach) relative to the tilted erosion surface (the physiographic approach) lies in the fact that it is planar—if the "louderback" flow is exposed at a low altitude adjacent to the range front it *provides* a means, not only of proving the general nature of the deformation, but of measuring it very closely (fig. 6). Moreover remnants of the flow may remain as structural evidence of block faulting long after the range has been beveled by erosion. The particular points made here are (1) that ignimbrites are *available throughout* much of the Great Basin to serve in the role of louderbacks, and (2) that they are wide-spread sheets susceptible to the regional stratigraphic approach.

Illustrations of basin-range structure.—Figure 5A is a diagrammatic section across several ranges in southwestern Utah, not along any straight line, but offset to transect the ranges where the structural relationships of the volcanic rocks are most clearly seen. The approximate latitude of the section was determined by the fact that the volcanics thicken markedly southward in each of the ranges until the pre-Tertiary rocks are lost to sight, *and thin northward* until erosion remnants of this sequence of volcanics are so scattered that they do not provide a structural picture. The relationships shown in the section are based on stratigraphic reconnaissance in which the principal concern was with measurement of sections rather *than with areal or structural geology as such.* Much remains to be learned about the structure, and the stratigraphy as well, but the essential relationships in figure 5 are well established.

The first of these is that the Needles Range formation was originally continuous throughout the area of the section. This conclusion is based on the fact that the two principal members of the formation (the Wah Wah Springs tuff and the Minersville tuff), and certain members of the overlying Isom formation, are definitely correlatable from range to range. Residual peaks of older

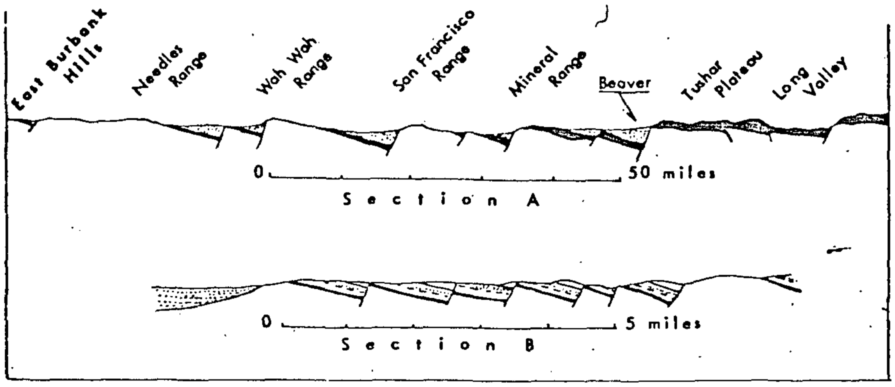

Fig. 5. Diagrammatic structure sections in southwestern Utah.

Section A extends southeastward from Garrison near the Nevada line to Beaver, Utah, and thence eastward into the Colorado Plateau. The Tertiary volcanic rocks, shown in solid black, rest mainly on Paleozoic rocks in the western half of the section, and mainly on the Claron formation in the eastern half (see fig. 3). In the Needles and Wah Wah ranges the Needles Range formation is 0-500 feet thick and makes up most of the volcanic sequence. It thickens eastward to 1000-1500 feet in the Tushar Plateau, but the marked increase in thickness shown diagramatically in the section is due chiefly to the fact that, in the Tushar area, it is overlain by thick Isom units and by several thousand feet of post-Isom flows and pyroclastics. The east-dipping homoclinal structure that characterizes the volcanic rocks in the Needles, Wah Wah, San Francisco, and Mineral ranges is greatly distorted in parts of the San Francisco and Mineral ranges by Tertiary intrusions; the intrusions, and their structural effects, are not shown. Faulting began in Needles time or earlier, but most of the faulting that controls the topography is middle or late Tertiary.

Section B passes east-west through the southern part of the Mineral Range, three to five miles south of the Beaver River. The sequence consists of Needles, Isom, and lower Quichapa ignimbrites, interbedded with lava flows and lahars from the Tushar eruptive center. The unit shown in solid black is a member of the Isom formation.

rock may have protruded through the volcanics, and there is reason to believe that block faulting was in progress in some places during Needles time, but the similarity in the volcanic sequence from range to range indicates that the Needles nuées ardentes swept across the entire span of the section.

The interpretation shown in the section, which makes each range a tilted fault block bounded by normal faults, is the traditional basin-range theory, clearly exemplified by Butler's sections of the San Francisco Mountains and the adjoining ranges (1913; 1920, figs. 2 and 53). It could be argued, because not a single range-front fault is exposed, that the faults might just as well be reverse as normal, or for that matter, that the Tertiary structure might be drawn as a series of asymmetric folds of the Umtanum Ridge type, with the steep western limbs of the anticlines nowhere exposed.

Perhaps the most direct objection to the fold hypothesis is simply that, if there were in fact western limbs consisting of volcanic rocks, these *should* be exposed somewhere, in so many ranges, at, or north or south of, the line of section. Circumstantial evidence bearing on the question is as follows:

Section B in figure 5 is an east-west section through the South Mineral Range (the Mineral Range south of the Beaver River). The volcanic strata dip eastward in a belt four to six miles wide. If the faults were not recognized, the section could be taken to mean a thickness of the order of 10,000 feet. Actually it includes distinctive units that are repeated as many as five times—the thickness is less than 2,000 feet. The faults branch and rejoin, so that their number, and the stratigraphy of the fault blocks, varies considerably along the strike. This pattern relationship, the stratigraphy of the volcanic rocks, and the fact that there are generally no reversals in dip in these rocks, prove that the structure within this range cannot be a system of asymmetric folds. Gilbert's conclusion, based primarily on morphology, that basin-range deformation was by fault displacement of "comparatively rigid bodies of strata" (1874, p. 48) is borne out by the fact that the characteristic structure in the Tertiary volcanic rocks, whatever the scale, is the homocline—the tilted slab bounded by faults.

The dip of only a small percentage of the faults in the South Mineral Range is ascertainable. Of these, most are high angle normal and a few are high angle reverse. If structures due to intrusion and other non-tectonic causes are for the moment left out of account, normal faulting is the rule and reverse faulting the exception in the Tertiary volcanic rocks within the ranges in southwestern Utah. Gilbert's generalization that range-front faults probably have the same geometry as faults within the ranges, and are therefore probably normal holds true for the few range front faults in southwestern Utah for which attitudes have been determined, and for other places in the Great Basin where special attention has been directed to this problem (see, for example, Gilluly, 1928, p. 1113-1116).

If one word expresses the habit of basin-range faulting more completely than any other, it is "antithetic," in the sense that, regardless of the direction of the dip of the faults, their throws tend to be opposite to, and to counteract the effect of, the dip of the faulted strata (fig. 5). Perhaps the best way to grasp how firmly fixed is this habit is the hard way, by being repeatedly rebuffed by repetition of the same units, again and again, in measurement of a great many sections of homoclinally dipping volcanics; antithetic faulting is so common that in measuring sections it should be assumed to be present unless proven to be absent. The ranges themselves tend to form antithetic groups; that is, the direction of tilt is commonly not reversed from range to range, but tends to remain the same for a small number of ranges, and then to be in the opposite direction for the next small number. This relationship is seen in nearly every traverse across the range trends. Any theory of origin of basin-range structure must take it into account.

A generalized east-west section from the Toquima Range in central Nevada to the House Range in Utah, in a paper by John Osmond (in press) came to my attention after this article was substantially completed. Osmond's section is similar to those in figure 5 in that the direction of tilt of each of the thirteen ranges shown in it is indicated diagrammatically by a thick black dash representing a sheet of "early Tertiary" volcanic rock; it differs in that the direction of tilt is more frequently reversed. The tilt directions can be expressed by a formula in which E and W, meaning eastward and westward, are coupled with integers for the number of ranges inclined in each direction. For Osmond's section this is, from west to east: 2W, 3E, 2W, 1E, 2E, 1W, 1E.

There is, of course, no *a priori* reason why some of the ranges of the Great Basin should not be Tertiary anticlinal folds rather than fault blocks.

The chief reason for thinking that none were formed by folding is simply that no unequivocal cases have been described. Unequivocal means after elimination of (1) dragfolds and other structures formed by draping of Tertiary strata over fault blocks, (2) local folding due to jamming between blocks, and (3) arching and compressional folding around intrusions, and other pseudotectonic effects to be considered later.

It goes without saying that Tertiary strata are needed to demonstrate a Tertiary fold. The fact that a range corresponds with an anticlinal structure in Paleozoic rocks cannot be taken as proof that the range as a topographic feature is a Tertiary anticline unless it can be demonstrated that the Paleozoic strata remained flat until folded during the Tertiary. If the anticlinal structure is defined by a thrust plane it must be demonstrated, in addition (1) that the thrust was initially flat when it was formed, and (2) that it was not folded during the waning stages of the orogeny in which it was formed or during subsequent periods of pre-Tertiary compressive deformation. In attempting to show that the ranges of the Great Basin were formed by erosion (not by faulting), Spurr (1901, p. 219-240) proved that the structure of the pre-Tertiary rocks has no direct bearing on the origin of the ranges by simply pointing out that the number of ranges showing anticlinal structure in pre-Tertiary rocks is equaled or exceeded by the number in which the structure is synclinal. What is more compelling, most ranges are neither anticlinal nor synclinal but, to the extent that they consist of folded strata, *are both from place to place* because the trend of the fold axes is diagonal to the trend of the ranges. Finally, and most compelling, is the line of evidence mentioned earlier; namely, that Tertiary volcanic rocks, characterized by simple homoclinal structure, commonly rest on an unconformity which bevels the edges of compressional structures developed in the pre-Tertiary *rocks. Some of the ranges in Osmond's* section bring out this point very clearly, and the list of examples could be greatly extended if there were any point in so doing. The most recently described and most striking example known to me is the case of the Stansbury Mountains in Utah; the structure of the pre-Tertiary rocks is anticlinal, but the range is shown by Rigby (1958) to be a Tertiary fault block on the basis of physiographic relationships and the structure of scattered erosion remnants of Tertiary volcanics.

Spurr credits the homoclinal structure of Tertiary rocks to folding unless there is conclusive evidence that it was formed by faulting. It is of course true that, *if the intervening basin floor* is concealed by alluvium, adjacent ranges in which Tertiary rocks dip in opposite directions can be interpreted either as limbs of a single fold, or as a pair of oppositely tilted fault blocks, *provided* (a) *that attention is limited to a single cross-section, not to the arrangement of the ranges in plan and* (b) *that this cross-section is viewed out of the context of its regional setting.*

Opposed dips in adjacent ridges in the Pennsylvania Appalachians can be confidently interpreted as limbs of a fold even though the structure of the intervening valley is concealed, because (1) the axial parts of the many folds are excellently exposed throughout the Pennsylvania Ridge and Valley province; (2) the two ridges and the valley in question are elements of a systematic map pattern that is uniquely associated with plunging folds; and (3) drag folds, fracture cleavage, and other internal structures in both ridges indicate strain relationships known to be characteristic of the limbs of folds. But in the Great Basin all three lines of evidence indicate that block faulting, not folding, was the general habit of deformation during the Tertiary.

This is *not* to say that there was no folding anywhere, nor at any time. It means, rather, that evidence of folding merits special attention; a question certain to be encountered very early in any inquiry into the origin of basin-range structure is whether the kind of stress condition manifested by dip-slip movements on faults inclined 60° to 70°, which was surely the "normal" stress condition in the Great Basin, was reversed by one or more episodes of apparent crustal shortening during the Tertiary. But it means also that the "burden of proof" is on Tertiary folding as an interpretation of geologic elements that are equally well explained by Tertiary block faulting and/or pre-Tertiary folding —something more than opposed dips is needed to prove a Tertiary fold in the Great Basin.

Structure and topographic form.—Figure 6 serves as a basis for discussion of the timing of basin-range movements in southwestern Utah. The volcanic unit shown in solid black in diagram A is supposed to have been spread over the area just prior to the block faulting. The basins are occupied by playa lakes and are in process of filling by detritus washed in from first-cycle ranges. That the ranges are tilted fault blocks would be suspected on the basis of topographic form alone even if there were no volcanic rocks, but as indicated earlier the presence of the volcanics, and especially the knowledge that the several occurrences are parts of an originally continuous sheet, make it possible to work out the erosional and deformational histories in a degree of refinement that could not otherwise be attained.

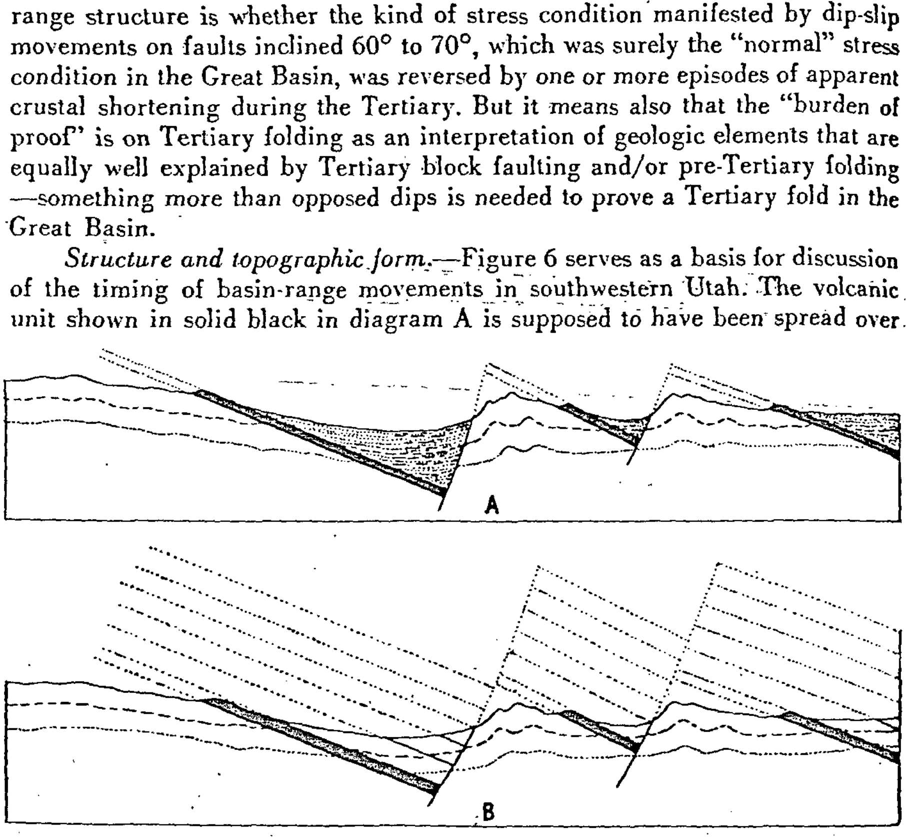

Fig. 6. Relationships between structure and topographic form.

The dashed line indicates a later stage of erosional development, produced with respect to baselevel at some remote place, such as a lower playa or

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the sea. The basin floors are pediments cut in the earlier fill, and the range front in the center of the drawing is a resurrected fault scarp. The dotted line indicates a still later erosional stage, with the ranges reduced to low relief. In the stages represented by the dashed and dotted lines the principal, and perhaps the only evidence of the episode of block faulting is the structure of the volcanic rocks.

Diagram B is similar to A except that the volcanic unit is overlain by a thick sequence of weak sediments deposited prior to the faulting. All the profiles, solid, dashed, and dotted, are entirely erosional. There are probably no simple, large-scale examples of this case as such, but tilted sedimentary sequences deposited under conditions wholly different from those of the present time are common in some parts of the Great Basin.

A common variant of these histories is the spreading of a younger sequence of volcanics across the erosion surface in any erosional stage in either diagram followed by a second episode of block faulting, on the same faults or new ones, and with the same or the opposite direction of block tilting.

The precipitous Hurricane scarp in the latitude of Kanarraville, Utah (Gardner, 1941), is analogous to the fault scarp in figure 6. The fact that the Eocene (?) Claron formation and the Oligocene (?) Leach Canyon tuff are substantially conformable in the Plateau and the Great Basin indicates that probably no major movement on the Hurricane fault occurred during the early Tertiary. Movement started during the mid-Tertiary and continues to the present. The same conclusion applies to many other scarps in the Great Basin.

At the other extreme are extensive areas where there is basin-range structure but no basin-range topography. In the East Burbank Hills, for example, wide-spaced erosion remnants of the Needles Range formation represent the deeply inset edges of tilted fault blocks, preserved in what is now a late mature landscape (fig. 5A). The relationships are analogous to those shown by dashed and dotted lines in figure 6. The faulting is certainly much older than that in the Hurricane zone—the advanced erosional stage suggests that it probably occurred during the early Tertiary, with little or no reactivation during the late Tertiary. And the subdued erosional topography of the East Burbank Hills, which passes beneath the surrounding alluvium with a contact that is irregular in plan and generally shows no break in slope, is overlooked on the west by the rugged and straight-based front of the Snake Range, credited by Drewes (1958, p. 237-238) to normal faulting of as much as 7,000 feet during middle and late Tertiary time.

Two or more episodes of normal faulting are demonstrated by structure, stratigraphy, and relationships of the faults to intrusions and metallization in many places in the Great Basin (see, for example, Ferguson, 1924; Hewett, 1931; Gianella, 1936).

Finally, some areas, for example, the greater part of the Iron Springs district show little or no evidence of block faulting even though there are volcanic rocks of several ages to record such movements.

The fact that Great Basin block faulting may have no topographic expression raises a question as to whether "basin-range structure" should be restricted to what seems to have been its original meaning, i.e., the block fault structure that produced the present ranges,[8] or whether it should be explicitly broadened to conform with what it means to most people working in the Great Basin, i.e., Cenozoic block faulting without regard for the relationship of the faulting to topographic form. It is used in the latter sense throughout this paper.

Summary.—Gilbert and his colleagues concluded on physiographic grounds that the relief features formed by orogenic deformation in what is now the Great Basin area were reduced by erosion to a surface of moderate relief, and that the present Basin ranges were formed by block faulting. This fundamental distinction between orogenic and post-orogenic stages of deformation was established early in the investigation of the geology of the Colorado Plateau, where the early Tertiary Claron is clearly unconformable across the great east-throwing Laramide monoclines but is displaced by the west-throwing Tertiary faults. In the Plateau-Great Basin transition zone in southwestern Utah the Claron lies on an erosion surface which bevels foreland folds and thrusts developed in late Cretaceous and older rocks, and is itself involved in typical Great Basin antithetic block faulting. In the Great Basin to the west, the Claron is not present as a continuous sedimentary deposit, but the ignimbrites which are conformable with it in the Plateau and the transition zone serve the same critical role, namely, as stratigraphic units that were spread as flat sheets across the stumps of the orogenic structures, and therefore provide a record of post-orogenic deformation. The ignimbrites confirm the Gilbert-Davis view that the Basin ranges were formed by block faulting.

More specifically, the ignimbrites permit a working out of the geometry of the Great Basin block-fault type of deformation with a precision that would not otherwise be possible. And because they range in age throughout much of the Tertiary and are virtually ideal time-stratigraphic units, they provide a key (a) to such problems as whether the block faulting has been episodic in a regional sense or random in distribution in space and time, (b) to the relationship of the block faulting to eruptive activity, and (c) to many other elements of the geologic history that are essential to any understanding of the mechanism of deformation.

INTRUSIONS AS "STRUCTURE-MAKERS"

Antithetic faulting associated with intrusions of low structural relief.—The topography and exposed geology in figure 7, if encountered in the field in the Great Basin—without benefit of the subsurface relationships shown in the section—might well be taken to mean that the alluvium-floored basin is under-

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[8] It is interesting to note that "basin-range" was not, to Gilbert, a contraction of *ranges* and the intervening alluviated *basins*, but a designation of a member of the system of the Ranges of the (Great) Basin. Basin-range structure is the fault block structure believed by Gilbert to be characteristic of the Great Basin. He states (1928, p. 1):

> If with the advance of knowledge geologists shall conclude the fault block structure is not the dominant structure of the Basin Range, the term Basin Range structure can no longer be used in its original sense and may properly be abandoned.

For use as an adjective it is preferable to reduce the capital letter to lower case, and it makes for clarity if the words are hyphenated, i.e., basin-range topography.

lain by a down-faulted block consisting of the same volcanic rock units which form the ranges on either side. The fact that the volcanic rocks stand highest along the borders of the basin, and dip away from it, might be construed as evidence that the faulting is of the ramp type—that is, that the major faults are thrusts which curve back under the ranges (Willis, 1928, p. 510-537). The minor normal faults exposed along the scarps would then be regarded as superficial slips. But if the same relationships were viewed through glasses of a different color, the normal faults might be seen as the principal structural elements or symptomatic of them, and the ranges might appear as tilted blocks in a setting of regional "tension."

How little the topography and exposed geology justify either of these views can be brought out by considering some elementary physiographic reasoning, and by additional items of information as to the subsurface geology of the basin floor.

If throughout its course each of the paired scarps corresponds with a resistant-over-weak-rock relationship, and if the graded slopes are everywhere alluvium-veneered pediments rather than aggradational surfaces, then the topography is fully accounted for by differential erosion and cannot be considered evidence of block faulting. The point is worth making because this topographic relationship—the broad, flattish-floored basin flanked by rugged ranges with straight base lines—tends to be associated with basin-range structure even though both Gilbert and Davis were careful to point out that the physiographic criteria for block faulting do *not* apply to the case shown in figure 7. But the association is so strong that the step faults along the range-fronts tend to clinch the case for block faulting.

It would take only a few strategically located exposures, revealing that the sub-alluvium floor across the entire width of the basin consists of the weak sedimentary rock which underlies the scarp-forming strata, to eliminate block faulting as an essential element in the geologic history. These exposures would indicate that the structure is an arch, deroofed by erosion, with inversion of relief because the axial area at this level is composed of weak rock.

Depending on the color of the glasses through which the arch is viewed, it may be seen as a compressional anticline, proof positive of crustal shortening subsequent to the spreading of the Tertiary volcanics. It might seem that the normal faults in both limbs would give pause to this view. But if the coloring of the glasses is deep enough the faults are seen, not as anomalous structures, but as evidence of a period of relaxation after the period of compression, or as evidence that there have been periods of crustal shortening and lengthening from time to time during the Tertiary.

Because he can look deeper than the floor of the basin, the reader has been aware all along that the structure in figure 7 is an intrusive arch. The model for the drawing is the Neck of the Desert, an alluvium-floored lowland in the Iron Springs district. The lowland and the bordering ranges are superficially similar to basin-range topography, but the scarps are actually cuesta faces, kept steep and straight by sapping—they are clearly in Dutton's department, rather than Gilbert's. The presence of a concordant intrusion at depth is proved

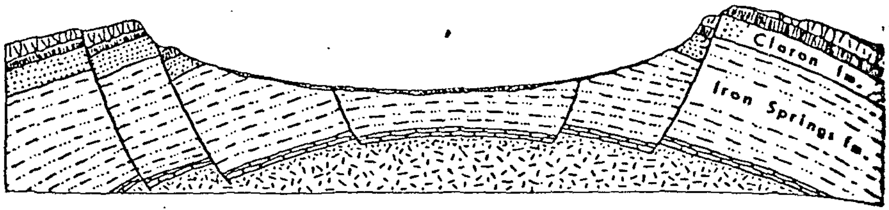

Fig. 7. Diagrammatic section across "The Neck of the Desert," Iron Springs district, Utah. The vertical scale is exaggerated—the valley floor is four to six miles wide and the total relief is only about 1000 feet. The fact that the graded slopes at the base of the scarps are pediments, rather than the surfaces of thick alluvial fills occupying a graben, indicates that the step faults in the vicinity of the scarps could not have been formed by "gravity sliding" from faces oversteepened by rapid uplifting movements on major faults which are now concealed. *The possibility that some of the tilted blocks at the base of the* scarps may be Toreva-type blocks, slumped from faces oversteepened by sapping, cannot be eliminated by field evidence in every instance. But the fact that the same types of antithetic faults occur in many places remote from scarps indicates that this type of "lengthening fault" is indigenous in the stretched roofs of intrusions of low structural relief.

by drilling for iron ore which occurs as replacement pods at the intrusive contact.

This type of structure—the intrusive arch or dome—is seen in southwestern Utah in every stage of erosional development from (1) the unbreached arch of volcanics; through (2) the first topographic reversal, the erosional lowland on the Cretaceous; to (3) the second topographic reversal, the mountain mass formed by the resistant intrusive rock. Excellent exposures at all erosional levels make it evident that antithetic normal faults of the type shown in figure 7, which have been variously misinterpreted in the foregoing discussion, are in fact commonplace structures in the stretched roofs of the Iron Springs intrusions (Mackin, 1954, fig. 4). They are members of the family of "roof-lengthening" faults (streckflächen) of the Cloos school, observed in many intrusions (see, for examples, Balk, 1937; Robinson, 1913, fig. 23) and beautifully developed in the model studies of Hans Cloos (1939). Their arrangement in the intrusive arches and domes of Iron Springs is strikingly similar to that developed above salt domes on the Gulf Coast (Wallace, 1944) and "salt anticlines" of the Colorado Plateau.

It is evident from this that antithetic normal faulting cannot be taken to mean that the range in which it occurs is a basin-range fault block. Antithetic normal faulting is a symptom of local lengthening, and this may occur in a basin-range fault block, in a dome or arch caused by intrusion, in the outer parts of compressional folds of the concentric type, and in any other situation involving horizontal elongation.

Compressional structures associated with intrusions of high structural relief.—Figure 8 brings out the familiar point (see, for example, Balk, 1937, p. 101-106) that intrusions of high structural relief commonly make room for themselves in part by shouldering aside the confining rocks. Most intrusive faults around the structurally steep sides of the Iron Springs intrusions are near-vertical, but some have dips as low as 45° into the intrusions. Some intrusive thrusts have throws exceeding 1000 feet (Mackin, 1954, sections C and D).

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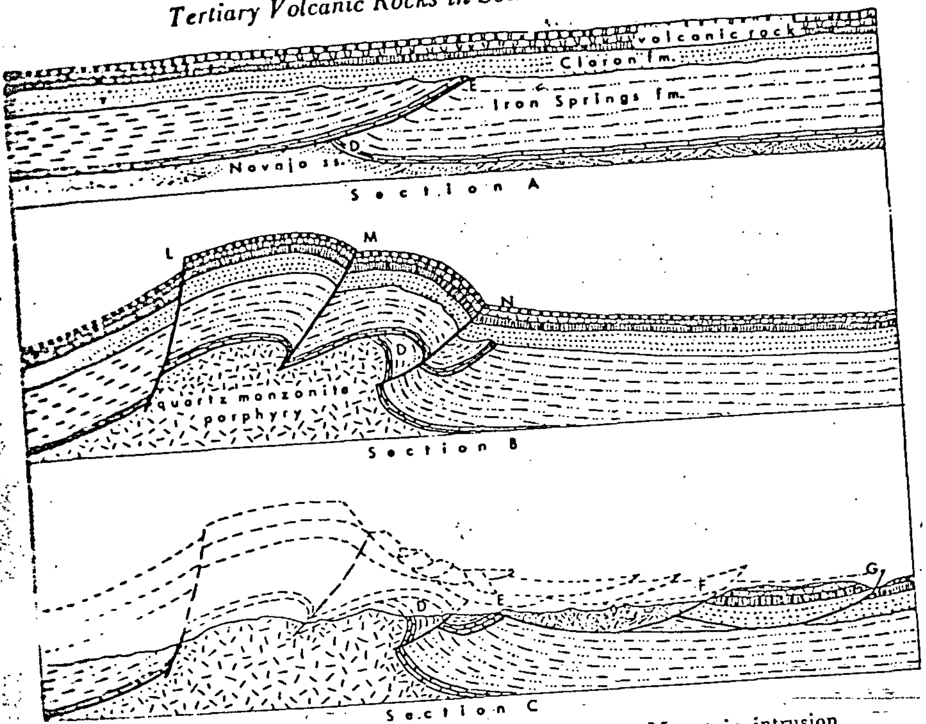

Fig. 8. Structural features associated with the Iron Mountain intrusion.

Section A. Restoration of pre-intrusive structure. A plate consisting of the Jurassic Carmel limestone and the Cretaceous Iron Springs formation moved eastward at least one mile and was beveled by erosion prior to deposition of the Eocene Claron formation and the volcanic rocks. West of D the movement was décollement over the Navajo sandstone. From D to E the thrust broke across the bedding of the Iron Springs formation (see USGS, fig. 3).

Section B. Restoration after emplacement of the Iron Mountain intrusion, showing structures formed directly by the intrusion, but excluding the gravity slides. West of D the magma inserted itself at the horizon of the Laramide décollement zone. East of D it followed the Carmel-Navajo contact rather than the thrust where the fault plane broke across the bedding. L, M, and N are intrusive faults, normal, high angle reverse, and low angle thrust, respectively.

Section C. Same as B, but showing the gravity slides. A traverse outward from the intrusive contact near D would cross Carmel and Iron Springs autochthonous strata to the surface trace of the Laramide thrust. The allochthonous sequence east of the Laramide thrust is involved in a syncline, the east limb of which has substantially the dip imparted by Laramide deformation (compare with drawing A), while the west limb was faulted and overturned in process of emplacement of the intrusion. The axis of this syncline marks the approximate outer limit of the direct structural influence of the intrusion. Between E and F incompetent Claron and Iron Springs strata have been churned into a chaotic jumble; the stippled wedges are strike ridges of near-vertical Claron conglomerate and limestone in a matrix of Cretaceous shale and sandstone. The imbricate thrusts in the overriding volcanics are above the surface in the vicinity of this section, and the deep slide planes are far below the surface, but both of these important elements of the structure are at the surface elsewhere along the strike.

Monoclinal flexures serve the same function in the room-making process as the intrusive faults, and have the same distribution in the roofs and around the borders of the intrusions—these structures grade into each other along the strike and down the dip (Mackin, 1950, p. 65-68). The intrusive monocline may occur as a minor structure interrupting the uniformity of the outward dip on the flank of an intrusive arch or dome, or it may stand alone as the principal border structure of an intrusive body.

Implications.—A number of workers in the basin-range province (e.g., Lasky, 1947; Nolan, 1950) have made the good point (1) that the Tertiary intrusions exposed at all levels from tops to floors make it reasonable to suppose that there must be many more not yet deroofed by erosion, and (2) that future production of metallic ores will probably come from blind ore bodies around these intrusions. The concern here is with the buried intrusions, not as "ore-bringers," but as "structure-makers."

Structures formed by intrusion can be most readily identified as such (1) where the intrusive rock is exposed, and (2) where the structures are developed in strata that are otherwise undisturbed (Baker, 1935). And it does not require much imagination to consider the possibility that the same types of structures, observed nearby in the same rocks, may have been formed by intrusions which do not crop out. This is the situation in the Iron Springs district, where four exposed intrusions, with a total area of about thirty-four square miles, have subsurface extensions or companion bodies that are at least equal to the outcropping bodies in areal extent. Throughout the district, in places many miles from the exposed intrusions, deformation structures which include thrusts and overturned monoclines in Tertiary strata are intrusive rather than tectonic.

The literature, and discussions with many geologists with diverse special fields of interest, indicate that there is a tendency to regard Tertiary intrusions in the Great Basin as stocks or plugs, rather than laccolithic bodies, unless there is compelling evidence to the contrary. This prejudice is significant for present purposes because it carries the connotation that the area of structural influence of an intrusion is apt to be limited to the immediate vicinity of its area of exposure. When the evidence is viewed through glasses colored by use in southwestern Utah, there is reason to believe (1) that many of the Tertiary intrusions were emplaced along low-dipping planes of easy parting—bedding planes in areas of simple structure and flat thrusts in areas of complex structure, (2) that they made room for themselves largely by upflexing and upfaulting their roofs rather than assimilation or stoping, and (3) that their lateral extent and hence their areas of structural influence are in many cases very much greater than their areas of outcrop.

There is, of course, no formula for distinguishing between intrusive structures and tectonic structures. The dome, the arch, and the monocline, indeed, flexures in general as opposed to homoclines, are suggestive of intrusive origin. Intrusive faults may be normal or reverse, and they may throw away from or toward the structural high—the only common denominator of intrusive structures is that all must be parts of "enlargement" patterns, expressing the upward and outward growth of the intrusive bodies.

Dikes, sills and hydrothermal alteration effects suggest the presence of a subjacent intrusion, but the reverse is not true. These elements of the "metamorphic halo" are so remarkably limited in extent around many of the exposed Tertiary intrusions that their absence in a given structure, for example, a dome, does not mean that the structure is not intrusive.

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As stated above, deformation structures formed by intrusions are most readily identified as such in strata that are otherwise flat. The difficulty of interpretation is greater (1) where the intrusive structures are superposed on one or more older generations of tectonic structures, or (2) where they have been broken and tilted by post-intrusive tectonism. Recent papers describing the deformation of flat overthrusts by exposed intrusions and further distortion of the resulting compound structures by normal faulting (e.g., Gilluly, 1956; Drewes, 1958), suggest the difficulties that may be anticipated in the diagnosis of the same types of polygenetic structures where the intrusions are concealed. A good approach to the complexities of Great Basin relationships is via Hunt's exposition of the rich variety of intrusive structures in the Colorado Plateau and his analysis of the mechanism of origin of these structures (Hunt, 1953; 1958).

It is my impression that intrusions have been greatly underrated as "structure-makers" in the Great Basin. This prejudice is helpful, not harmful—it means merely that before structural features seen in the field or described in the literature are accepted as evidence of a type of post-orogenic regional tectonism other than block faulting, due consideration should be given the possibility that they are intrusive.

STRUCTURES FORMED BY GRAVITY SLIDING FROM PRIMARY RELIEF FEATURES

The Iron Mountain slide.—Figure 8 is modeled after the Iron Mountain intrusion in the Iron Springs district. The lower drawing (section C) is a diagrammatic section through the intrusion, showing an interpretation of the present geologic relationships. The restorations in sections A and B are helpful in distinguishing three different generations of structures that are combined in section C.

Section A includes the essential elements of the pre-intrusive geology. The thrust fault is a part of the Iron Springs Gap structure (see fig. 3). It is not directly involved in the topic under consideration here, but is shown for later reference.

The second generation of structures, in Section B, belongs to the class just discussed; that is, they are structures formed directly by emplacement of the intrusion. L, M, and N are intrusive faults, normal, high angle reverse, and low angle reverse, respectively.

Section C shows a third generation of structures, formed by the sliding of huge masses of rock from the flanks of the growing intrusive dome—these structures are associated indirectly, rather than directly, with the room-making process. For what it may be worth by way of introduction to the problem, the deductive approach is as follows:

Strata known to have been substantially flat prior to the emplacement of the Iron Mountain intrusion are now near-vertical in the border zone. The structural relief of the intrusion is at least 3000 feet—the same order of magnitude as the thickness of the cover at the time of intrusion. The rate of emplacement is not known, but it is clear that there was only one episode of intrusion rather than a succession of episodes—there is no cross-cutting of solidified or partly solidified porphyry by apophyses of later porphyry. The emplacement may have occurred during a period of a few years or a few tens or hundreds of years—the period was probably not measured in thousands or millions of years. The rate of growth of the intrusive dome as a topographic feature therefore probably greatly exceeded the rate of lowering by normal erosional processes, the more so because the uppermost of the updomed strata were massive ignimbrites of lava-like hardness. These considerations indicate that the flanks of the growing intrusive dome may well have been greatly oversteepened, and that there is nothing inherently improbable in the idea of sliding of parts of the roof on a grand scale. Burbank's analysis of stress relationships in the roofs of laccolithic domes led him to the same conclusion (1932, p. 49).

Slides from relief features produced by various types of tectonic deformation have been described in many parts of the world (for a brief analysis, see De Sitter, 1956, p. 266-292). The concept of sliding from igneous intrusive domes is less familiar, perhaps in part because only a small percentage of intrusions form topographic features steep enough to cause sliding, in part because most intrusions of pre-Tertiary age have been so deeply eroded that such slides as may have occurred have been removed, and in part because slides from intrusive domes have been interpreted as thrusts due directly to the intrusive room-making process or to regional tectonism.

To explain shallow faulting in the plains area adjacent to the Bearpaw Mountains, Montana, Reeves (1946) suggested that a load of volcanic rocks on the flanks of a low arch of probable intrusive origin was relieved plainsward by wholesale sliding along beds of bentonitic shale. Reeves' hypothesis may have to be modified because Pecora (written communication) finds that the earliest volcanic rocks of the uplift rest with angular unconformity on extensively block-faulted sedimentary formations. Evaluation of the slide hypothesis is being made by Pecora and co-workers who are currently mapping the Bearpaw Mountains uplift in detail.

Sears (1953) has recently suggested that the famous Amargosa Chaos of the Death Valley area, ascribed by Noble (1941) to Tertiary thrusting, may be in part a superficial slide associated with emplacement of an intrusion exposed nearby.

A mass of brecciated rock that clearly overlies faulted and slickensided "Tertiary lake beds," in the Contact mining district in northeastern Nevada, was regarded by Schrader as a result of a thrust fault or a landslide (1912, p. 143-145; 1935, p. 38). Schrader described the anomalous relationships competently, but he was concerned primarily with the economic geology of the district, and he did not discuss the relative merits of his two explanations. In a paper dealing with the possibility of mistaking Tertiary or Quaternary fanglomerate-mudflow breccia for evidence of Tertiary flat thrusting in the Great Basin, Hazzard and Moran favor the view that Schrader's breccia mass was formed by landsliding "related to a previous erosion cycle" (1952, p. 855). Its location about two miles south of the southern contact of a large intrusive body suggests that the sliding may have occurred at the time of emplacement of the intrusion, as at Iron Mountain, but this hypothesis does not comport with Schrader's view that the intrusion predates the "Tertiary lake beds." I have

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not seen the field relations. The structure is mentioned here merely as an example of a type of anomaly—brecciated pre-Tertiary rock resting on Tertiary rock—encountered in many places in the Great Basin; the possible explanations always are (1) ordinary landslide, precipitated from a relief feature formed by erosion, (2) "gravity slide," precipitated from a relief feature formed by tectonism or intrusion, and (3) low-angle thrust.

The deductive considerations outlined above, and the other possible cases of slides from growing intrusive domes, are of interest only as background and to make it clear that the idea is not new. Field relations indicating that the crescent of complex structure southeast of Iron Mountain was formed by sliding are spelled out in detail in a report now in preparation, which includes the colored maps and sections on which a demonstration must depend. What follows is an outline of several lines of evidence intended to *explain* the slide theory, not to prove it.

Most exposures in the slide area can be mapped as consisting of one or another of eleven well-defined members of the Claron formation and the volcanic sequence. Were it not for this firm stratigraphy, which can be carried into the slide zone from the bordering areas, nothing could be done with the internal structure of the slide mass. The upper and outer part of the mass consists of a pile of imbricate plates made up chiefly of volcanic rocks in older-over-younger relationship (fig. 8, section C). The lower and inner part consists of a chaotic jumble of Claron and Iron Springs sedimentary rocks, with as many as four repetitions of the same Claron members, all nearly vertical and all with the stratigraphic tops outward. Certain individual stratigraphic units within the chaotic mass have strike lengths of as much as two miles. These "solid" slabs lie in a breccia consisting of one or several rock types. Slickensides pass from block to block through the matrix, and the breccia is so highly indurated, particularly where it is composed of volcanics, that it stands as ledges in bold relief. Clearly it is not in any sense a mudflow-fanglomerate deposit, but a crush breccia. Restoration of the structure indicates that it was formed as much as 2000 feet below the surface of the ground (fig. 8). The relationships are taken to mean that the slide consisted of two dynamically contrasted parts, an upper plate consisting of forward-riding sheets of competent volcanic rocks, and a lower chaotic mass of crushed and rotated slabs of the relatively incompetent Claron and Cretaceous sedimentary rocks.

The possibility that the structure might have been caused by Tertiary thrusting is eliminated by the fact that it occurs only adjacent to that part of the borders of the Iron Mountain and other intrusions where the intrusive contact is nearly vertical—elsewhere in the 3000 square miles that have been mapped in detail by the University of Washington group the Tertiary sedimentary and volcanic rocks show no suggestion of this type of structure, or other evidence of strong regional compression. Moreover, the pattern of the deformation, both with regard to gross distribution and the orientation of internal structures, proves that the movement was not in any one compass direction but was radially outward from Iron Mountain to the south, southeast, and east.

The possibility that the structure could have been formed directly by the intrusion, as part of the room-making process, is eliminated because it starts half a mile to a mile out from the intrusive contact, on the far side of a normal intrusive border zone (fig. 8) and by other relationships that can be shown adequately only on detailed maps and sections.

Slides from tectonic features.—Some Great Basin fault scarps stand at angles considerably exceeding the angle of repose, and it is likely that block faulting was more active at some places and times during the Tertiary than it is now. There is, therefore, nothing inherently improbable in the proposition that slides, of the same order of magnitude as those on the east side of Iron Mountain, may have been shed from oversteepened fault scarps. The possibility that the "turtle-back complexes" of Death Valley were formed in part by sliding was not eliminated by evidence outlined in Curry's preliminary statement (1954) of his theory that the "turtlebacks" are folded parts of flat thrusts of Tertiary age. No attempt to evaluate sliding (Bucher, 1956, p. 1310-1311) versus Tertiary thrusting as an explanation of the features of the Death Valley area is needed here. It may be stated simply that sliding is a possible or even likely alternative to Tertiary thrusting in the Great Basin as an explanation of structural complexities involving Tertiary rocks, particularly if these complexities are localized near major structural features, whether intrusive or tectonic. The slide concept is easy to grasp where the structural anomalies are in the shadow of a high range; it is not so obvious, but no less likely, where erosional reversal of topography has reduced to a lowland the elevated place from which the slides might have been shed.

Earl Cook suggested in the field that erosion remnants of slides should be called, not klippen, but slippen. This term certainly does not belong in our new glossary, but it is a good catchword, well suited to keep in mind an hypothesis that is an essential part of the mental field equipment of geologists working in the Great Basin.

POST-OROGENIC VS OROGENIC STRUCTURES

Introduction.—To this point the focus has been on ignimbrites as reference planes for measurement of post-Laramide deformation; Laramide orogenic structures have been considered simply as elements of a pre-Tertiary "basement complex." Here the emphasis shifts to use of the ignimbrites in distinguishing between the effects of orogenic and post-orogenic deformation. There are two points of view:

To the geologist concerned primarily with the orogenic deformation, the structure of the Tertiary volcanics may be of interest only as a measure of a distortion that must be removed from the structures of the subjacent rocks as a first step in analysis of these older structures. The student of Tertiary deformation is concerned with the opposite side of the same coin; if he mistakenly considers certain structures, actually formed during the Laramide orogeny, to be post-orogenic, this error is certain to vitiate his analysis of post-orogenic deformation.

The discussion to follow proceeds from the simple case of removing the distorting effects of block tilting from orogenic structures, to the somewhat more complicated case in which a major basin-range fault corresponds in position with an overturned Laramide fold, and to the complexities caused by superposition of Tertiary intrusive structures on a Laramide thrust.

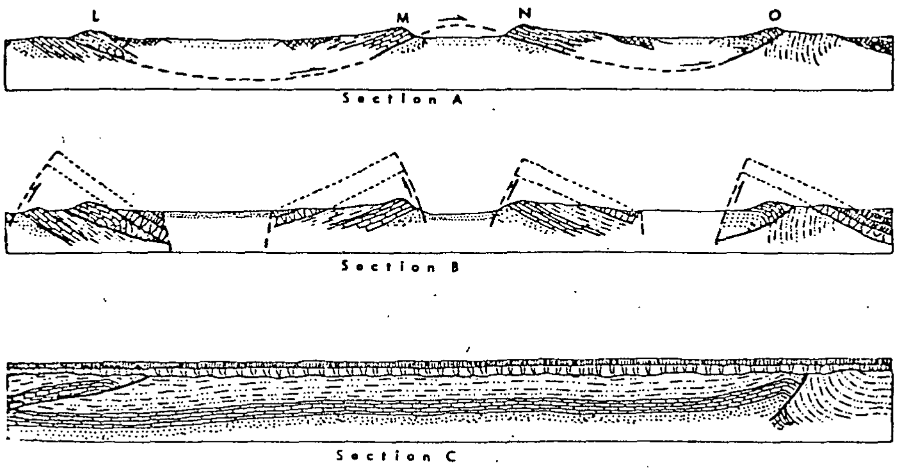

Fig. 9. Distortion of an orogenic structure by Tertiary deformation.

Sections A and B show contrasted interpretations of two different issues: (1) whether there is or is not a single thrust of regional extent; and (2) whether deformation after the main orogeny was by folding or block faulting. These issues are entirely independent of each other; the regional thrust might as well have been combined with post-orogenic block faulting in Section B as with late- or post-orogenic folding in Section A.

Section C is a restoration prior to the beginning of Tertiary deformation, based on the attitudes of the older rocks after the volcanics are rotated back to the horizontal.

Effects of simple rotation.—Section A in figure 9 shows three sedimentary rock units, a sandstone, a limestone, and a shale, exposed in four ranges, L, M, N, and O, separated by volcanic rock and alluvium. In ranges L and O low angle thrusts bring the limestone over the younger shale. In ranges M and N the sedimentary rocks are in the normal order of superposition, but there is a zone of gliding at the contact of the sandstone and the limestone.

The heavy dashed line in Section A shows an interpretation of the structure based on the attitudes of faults and bedding in the pre-Tertiary rocks only, that is, on the basis of geologic observations in the Spurr tradition which lumps the Tertiary volcanic rock with the alluvium as part of a superficial blanket, and leaves the landforms to the physiographers. According to this interpretation, the older-over-younger thrusts in ranges L and O, and the planes of younger-over-older décollement gliding in ranges M and N, are at the base of the same far-traveled thrust plate. Folding of the thrust may be assigned to a waning stage of the orogeny or, if the attitudes of the volcanics are taken into account, the folding may be considered to be Tertiary. If the implication that the flat-floored basin between ranges M and N was developed by erosion in resistant sandstone is disturbing, minor range-front faults can be postulated, but these are incidental to the bed rock structure.

Figure 9 B is an alternative interpretation of the same observational data, but with the attitudes of the volcanics credited to block faulting.

Figure 9 C is a restoration of the Laramide structure, drawn to conform with the attitudes in the older rocks corrected by rotating the volcanics back to horizontality. The thrust in range L was formed with a westerly dip of 15°, not an easterly dip of 17°. The thrust in range O is an entirely different structure; the original dip was 65°. The amount of décollement movement in ranges M and N is not known but may be only a few tens of feet or hundreds of feet. Bedding-plane gliding is to be expected at contacts of rock units of different competence even in areas of mild deformation; the zones of gliding in ranges M and N are not evidence that the thrust faults in ranges L and O are parts of a single flat thrust of regional dimensions.

The restored section of figure 9 C is modeled after relationships in the Great Basin-Colorado Plateau *transition zone* in southwestern Utah. The western of the two structures is the Iron Springs Gap thrust seen on the east side of the Iron Mountain intrusion (fig. 8). The eastern structure is the Kanarra fold of Gregory and Williams (1947). The unconformable cover, shown in the sections as consisting entirely of volcanics, actually is made up of the Eocene Claron formation overlain concordantly by the volcanics (compare with fig. 3).

The Iron Springs Gap thrust and the Kanarra fold are about 15 miles apart. The Claron is substantially conformable with the Cretaceous between these structures, and east and west of them. The Iron Springs Gap thrust is clearly a foreland structure, similar in all essential respects to the Pine Mountain thrust of the Cumberland Plateau (Rich, 1934; King, 1951, p. 128-130). The counterpart of the Chattanooga shale as a widespread zone of décollement gliding in the southeastern Great Basin is a zone of shaly and gypsiferous limestone near the base of the Carmel limestone, just above the top of the Navajo sandstone. The Kanarra fold cannot be considered a "break through" from this décollement horizon because the fold involves the Navajo and subjacent rocks at least as old as Kaibab. It exhibits the strongly compressional features of the Iron Springs Gap thrust but in other respects is more closely akin to the east-throwing Laramide monoclines of the Colorado Plateau. The relationships shown in figure 9 C are not easily seen in the field or on a geologic map because both the Laramide structures are obscured, not only by simple block tilting of the type shown in figure 9, but also by strong and sharply localized Tertiary deformation (Threet, paper in preparation).

A basin-range fault superposed on an orogenic structure.—The Kanarra fold, overturned and overthrust to the east, was beveled by erosion and the stump was covered by the Eocene Claron formation and silicic volcanic rocks of probable Oligocene age prior to the beginning of Hurricane faulting (fig. 10A). Hurricane faulting began in mid-Tertiary time and has continued to the present (fig. 10B). Two surficial elements which further complicate the field relations but have been omitted from the diagrammatic sections are: massive rock slumps of the Toreva type (Reiche, 1937), which clutter parts of the fault scarp; and basalt flows of several ages, broken and tilted by jogs of movement in the fault zone (Gardner, 1941).

In a segment of the Hurricane scarp south of Cedar City, Utah, the Claron formation and the silicic volcanics have been entirely removed by erosion except for remnants at the base, as shown in figure 10B. Rocks of Permian to

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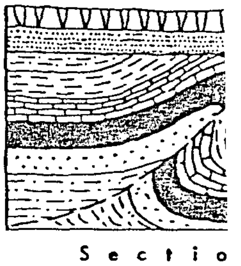

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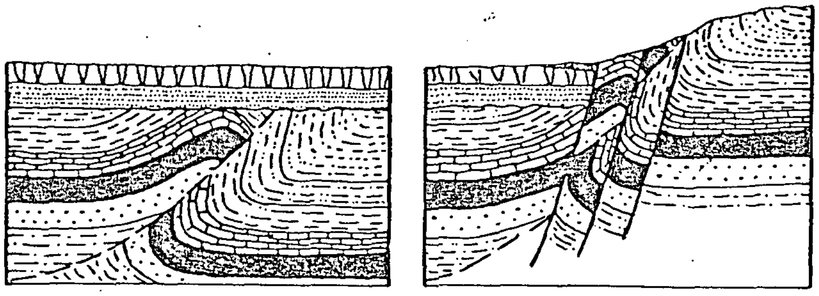

Section A Section B

Fig. 10. Structure of the Hurricane fault zone.

The rock units shown diagramatically in the Kanarra fold in Section A do not correspond with the actual stratigraphic succession, which ranges in age from Permian to Cretaceous. The unconformable cover consists of the Claron formation overlain by volcanic rocks.

As indicated in Section B, the Claron and the volcanics have been entirely removed by erosion from the upthrown side of the Tertiary Hurricane fault. The compressional structures that characterize the fault zone long predate the movement that formed the scarp.

Cretaceous age composing the fault zone are in many places vertical or overturned, and are involved in eastward thrusts. The scarp is clearly due to late Tertiary and Quaternary faulting. These relationships might well be taken to mean that the compressional structures in the fault zone were formed by the crustal movement that made the scarp; that is, that the Hurricane fault is a complexly shattered thrust of late Cenozoic age. That the compressional structures predate the beginning of movement on the Hurricane fault, and that the history is that shown in the diagrams, must be pieced together: (1) from the work of Cook to the south, where a part of the west limb of the Kanarra fold is capped by Claron and volcanic rocks on the down-thrown side of the Hurricane fault (Cook, 1957, fig. 46); (2) from the work of Threet to the north (1952, pl. 3), where the east limb of the fold is similarly capped on the upthrown side of the fault; and (3) by analogy with the Iron Springs Gap structure, which is preserved in its entirety, with its unconformable cover of Claron and volcanics, in the Iron Springs district (Mackin, 1954).

Similar cases of alignment of basin-range faults, which control the present topography, with older compressional structures have been described along the eastern border of the Great Basin in central Utah by Eardley (1933, 1951, p. 325-336) and Spieker (1949).

Distortion of an orogenic structure by a Tertiary intrusion.—Figure 8 shows clearly the theory that the Iron Springs Gap structure, a low-angle thrust of Laramide age, was turned on end by emplacement of the Iron Mountain intrusion. The evidence on which this view is based will be presented elsewhere—the structural relationships would be equally effective for present purposes if they were entirely hypothetical. It is evident (1) that analysis of the Laramide structure must start with subtraction from it of the deformational effects of the intrusion, and (2) that this operation is dependent on the presence of the Claron in the role of a reference plane known to have been flat after the orogeny and prior to the intrusion.

It might seem that the best way to learn the form of the Laramide structure would be to map it in places where there is no intrusive distortion. The difficulty is that there are no such places. At least six intrusions of the Iron Mountain type are aligned along the structure in southwestern Utah, and it is exposed only where the intrusive uparching has caused removal of the Tertiary cover.

The Claron and the volcanics make it possible not only to separate the deformational effects of the orogeny from those of the intrusion, but also to establish their relative ages. The six intrusions mentioned above are evidently localized along the orogenic structure, but this does not mean that they were formed during the orogeny, as might appear likely on deductive grounds. Emplacement of the intrusions is definitely post-orogenic; the interval was long enough for beveling of the Iron Springs Gap thrust, deposition of the nonvolcanic "red Claron" and the tuffaceous "gray Claron," and spreading of two sequences of ignimbrites.

The complexity resulting from superposition of intrusive structures on older orogenic structures is such that the two generations of structures are apt to be confused, particularly if conclusions are based on study of an area too small in size to provide an adequate variety of structural and stratigraphic relationships. For example, the Iron Springs Gap thrust, which can be readily proven to be a regional tectonic structure, might easily be connected underground or through the air in figure 8C with the slide plane which passes beneath the chaotic structure in Tertiary rock in the outer part of the intrusive border zone. This type of error results in a misreading of both the orogenic and post-orogenic history. In this instance both the Laramide thrust and the Tertiary slide are lost to the record, and their unhappy combination is a Tertiary thrust which is not there.

GENERAL SUMMARY

Gilbert and his colleagues concluded, primarily on physiographic grounds, that the ranges of the Great Basin were formed by a type of deformation—"dominantly vertical displacements of comparatively rigid blocks"—markedly different from the deformation recorded by the tight folds, low angle thrusts, and other orogenic structures exhibited by the pre-Tertiary rocks composing the ranges. Many later students of the Great Basin have been led by physiographic and other lines of evidence to the same fundamental generalization: that the block fault type of tectonism represents not merely the waning of the orogeny, but a distinctly different phase of the diastrophic cycle, with habits of deformation different in kind from those of the orogenic phase.

Within this generalization there are many questions: Was the block faulting episodic in a regional sense, with brief periods of province-wide faulting separated by protracted periods of crustal quiet? Or was it in some other manner systematic, as spreading in one or more waves entirely across the Great Basin from one side to the other, or outward from the center toward both sides? Or was it seemingly haphazardly distributed in space and time? Was there a period of quiesence between the close of the orogeny and the beginning of the block faulting? Or was the deformation continuous, merely changing in type, abruptly or gradually, and everywhere at the same time or at different times in different places? Equally critical to any analysis of the post-orogenic deformation is a knowledge of the geometry of the fault blocks, including their sizes, the dip of the faults relative to the direction of tilting, and especially whether the tilt directions are haphazard or are systematically oriented in different parts of the province.

The principal point made in this paper is that ignimbrites, formed by nuées ardentes of incredible magnitude which swept with hurricane velocity across much of the Great Basin again and again during the post-orogenic period, provide a basis for cross-dating the block faulting and other geologic events with the precision required if the questions as to relative timing outlined above are to be answered. Because they were originally flat-surfaced, the ignimbrites permit exact and detailed measurement of the post-orogenic crustal movements. And they are unique stratigraphic units in still another sense—most of them contain enough radioactive material to permit determination of "absolute" age within certain limits of error, which will surely be reduced as the methods are perfected.

It might be argued that, because there has been strongly compressive deformation during the Tertiary in California, there *should* have been folding and thrusting at the same time in the Great Basin. This sort of deductive reasoning, whether based on observed relationships in an adjoining province or on general concepts as to stress conditions in or under the crust, is all right in its way. But it has been demonstrated in district after district, by physiographic evidence and by mapping of the Tertiary volcanics, that the Gilbert theory of the block fault origin of the Basin ranges is valid, and that the range front faults are as a rule normal. This does not by any means eliminate the possibility that there were episodes of strongly compressive regional tectonism in the Great Basin in the Tertiary. It may be even true that all of the post-orogenic deformation has been compressive in some places. Perhaps some of the ranges *are* doubly-plunging Pliocene anticlines. The point made here is that, in a province where the characteristic type of Tertiary deformation has been a jostling of blocks bounded by normal faults, evidences of strongly compressive regional tectonism are of special interest and importance to our eventual understanding of causes and mechanisms of the post-orogenic movements, and should be fully reported. An obvious requirement of such reports is a statement of the evidence indicating that the compressional structures *are* post-orogenic, and that they were not formed by emplacement of hypabyssal intrusions, nor by gravity sliding from relief features raised by intrusion or high angle faulting.

The Tertiary ignimbrites have been considered here primarily as rock layers of great areal extent which permit the working out of the post-orogenic deformational history in a degree of accuracy and detail that would not otherwise be possible; the "structural significance of the volcanic rocks" in this article is entirely descriptive. An article to follow shortly will develop the hypothesis that the eruptive activity and the deformation are related also in a genetic sense, that is, that episodes of block faulting which have occurred from time to time and from place to place during the Tertiary represent failures of the crust due to withdrawal of lateral support caused by frothing eruption of many thousands of cubic miles of magma formed by fusion of crustal rock.

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Origin of Quaternary Basalts from the Black Rock Desert Region, Utah

ABSTRACT

Known relative age relations and element distributions in Quaternary high-alumina and tholeiitic basalts from the Black Rock Desert region in Utah are adequate to identify both long-term ($\sim 10^6$ yrs) and short-term ($\lesssim 10^3$ yrs) geochemical trends. One major long-term trend is a decrease in Sr from the oldest to the youngest basalts. Sr distribution coefficients determined from plagioclase phenocryst-groundmass pairs suggest an origin for this decrease involving removal of about 40 percent plagioclase by fractional crystallization. Progressive increases in K, Rb, and REE, and approximate constancy of most major and some trace elements over this range indicate in addition to removal of plagioclase, removal of small amounts ($\sim$ 7 percent) of olivine, orthopyroxene, and Fe-Ti oxides, and also contamination of the magmas with about 10 percent of Sr-poor granitic rock. More than enough heat is available from the latent heats of crystallization to melt this amount of contaminant. A model is proposed in which primary olivine tholeiite magmas are initially collected in deep (15 to 35 km) crustal chambers and receive small additions of mantle-derived magmas as they move upward in the crust and undergo extensive fractional crystallization and minor contamination over the last million years.

Short-term, time-dependent geochemical trends occur in the flows of the youngest volcanic field (the Ice Spring field). These trends show increasing Fe, Ca, Zn, Cu, Ti, Mn, and Sr and decreasing Si, Ni, Co, Mg, Na, K, Rb, and Nb with age of eruption. To explain these trends, a model is proposed involving both progressive tapping of a zoned magma chamber and removal of 10 to 15 percent of Mg-rich orthopyroxene during fractional crystallization.

INTRODUCTION

The basalts of the Black Rock Desert region in western Utah (Fig. 1) were first described by Gilbert (1890). Field studies by the author have shown that Gilbert's early field work was accurate and thorough. The basalts occur near the eastern edge of the Great Basin province and occupy the central part of the Black Rock Desert Valley which is a graben bounded on the west by the Cricket Mountains horst and on the east by the Pavant Range horst.

Existing data indicate that basaltic volcanism began in the Black Rock Desert region $\sim 10^6$ yrs ago and continued sporadically until perhaps a few thousand years ago. Many of the basalt flows in the region are closely associated with Pleistocene Lake Bonneville deposits and terraces. Some were extruded prior, some during, and some after Lake Bonneville time. All three types of basaltic lava, aa, pahoehoe, and block, occur in the region, with block lava being most abundant. Field work by Condie indicates that a minimum of seven basaltic volcanic fields can be defined in the area. From north to south, these are the Deseret, Pavant, Ice Spring, Tabernacle, Kanosh, Black Rock, and Cove Fort fields (Fig. 1). A zone of small north-trending, high-angle faults is coincident with the major centers of volcanism (Fig. 1) and may be a surficial expression of deeper fracture zones controlling the locations of these centers.

The chronology of Lake Bonneville still remains uncertain, especially in terms of an absolute time scale (Crittenden, 1963; Morrison, 1966). The lake fluctuations as described by Morrison (1966) are summarized in modified form in Figure 2. In terms of the interrelations of the basaltic eruptions to the stages of Lake Bonneville, the following factors are important (Eardley and others, 1957; Bissell, 1963; Morrison, 1966): (1) The white marl is assumed to have been deposited during the Bonneville 1 level; (2) the Provo lake tufa so abundant at some locations on the Provo shoreline is assumed to have been deposited at the maximum lake level during the Provo stage; (3) the Bonneville shoreline is assumed to

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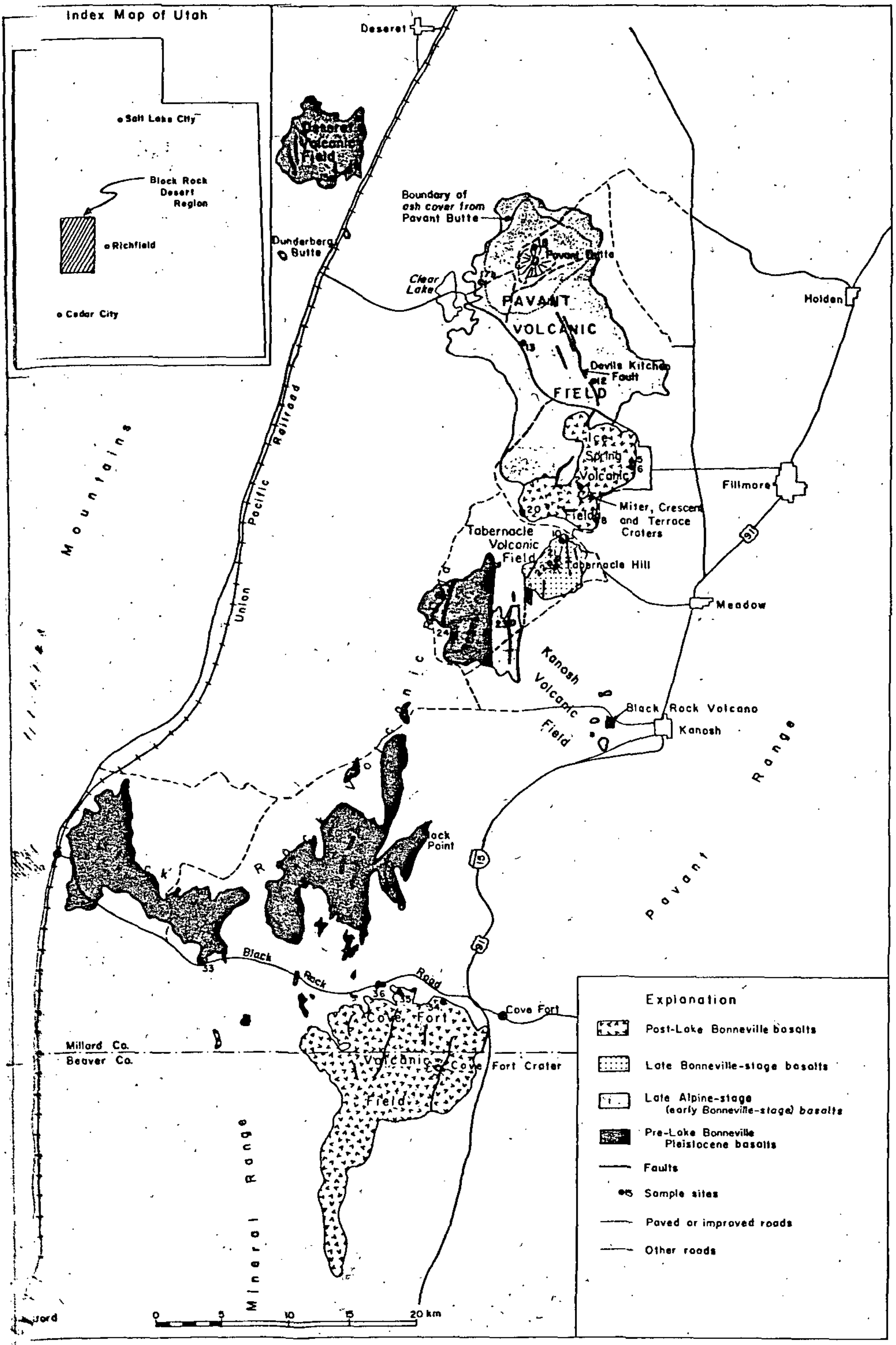

ure 1. Geologic map of Quaternary basalts in Black Rock Desert region; modified from the Geologic Map of Utah (Stokes, 1962).

have formed at the Bonneville 2 level; and (4) the intermediate shorelines are assumed to have formed during the Alpine stage. Employing these factors, the age relations between the lake levels and the basalts in the Black Rock Desert region are shown in Figure 2.

The Quaternary basalts of the Black Rock Desert region are of particular interest in that they record sporadic basaltic volcanism that occurred in a rather small geographic area during the last $\sim 10^6$ yrs. It is the purpose of this investigation to report geochemical variations of these basalts as a function of their ages of eruption in an attempt to more accurately evaluate the relative roles of fractional crystallization and of crustal contamination in the genesis of basaltic magmas.

ANALYTICAL METHODS

After mapping and studying field relations of each volcanic field, 21 samples of basalt were selected for detailed geochemical work. Sample locations are shown in Figure 1. Thin sections were prepared from each sample and at least one polished section from each volcanic field. Modal analyses were made of some samples and modal estimates of all samples. The results are summarized in Table 1 in terms of modal ranges for each volcanic field.

Plagioclase phenocryst compositions were determined optically by the Michel-Levy method and checked in some cases by x-ray diffraction. Plagioclase phenocrysts were separated from three samples (21, 22, and 24) by combined use of heavy liquids and a Franz magnetic separator. The first sink portion of the heavy liquid separation was found to closely represent the groundmass and was analyzed as such.

Major elements (except Na) and Rb, Sr, Ba, K, Ni, Zr, Cu, and Zn were determined by nondestructive x-ray fluorescence using methods previously described (Reynolds, 1963; Condie, 1967a, 1967b; Condie and others, 1969). Calibration curves were constructed from pellets of standard rocks (W-1, BCR-1, AGV-1, GSP-1, Syenite-1, Gr, and T-1); W-1 was used as the standard for the trace elements. Na, Mn, Sc, Hf, Co, and six rare earth elements (REE) (La, Ce, Sm, Eu, Tb, Lu) were determined by nondestructive neutron activation analysis, using a NaI detector with a 400 channel analyzer (Na, Mn) and a Ge (Li) detector with a 1024 channel analyzer (Sc, Hf, Co, and REE). Details of the methods are described in Condie (1967b), Condie and others (1969), Gordon and others (1968), and Condie and Lo (1972). Nb was determined by a modified Nb thiocyanate spectrophotometric method (Grimaldi, 1960) and K in the plagioclase separates by atomic absorption spectrophotometry. Major element analyses and trace element analyses are given in tables on deposit with NAPS.[1] Trace element analyses are also given in Table 2.

Estimated analytical errors are as follows: Covell's method (Covell, 1959) was used to calculate the errors for Sc, Hf, Co, and REE: (a) ≤ 5 percent, Si, Al, Ti, Fe, Mg, Ca, K, Na, Rb, Sr, Zr, Cu, Zn, Mn, Co, Sc, La, Ce, and Sm; (b) ≤ 10 percent, Ni, Ba, and Lu; (a) ≤ 25 percent, Eu, Tb, and Hf. Although Eu and Tb have rather large calculated errors, the observed precision allows a Eu anomaly to be reproduced within about 5 percent where Eu/Eu* is equal to the observed chondrite-normalized Eu value divided by the value obtained by drawing a straight line between Sm and Tb.

GEOLOGIC SETTING AND PETROGRAPHY

Black Rock Volcanic Field

The Black Rock volcanic field is herein defined as the series of basalt flows extending east from Black Rock Station and then north to Beaver Ridge (about 15 km west of Meadow, Utah; Fig. 1). The discontinuous nature of the field on the geologic map is due to a partial covering with Lake Bonneville and Holocene stream deposits. The basalts of this field form the resistant cap rock on plateaus with abrupt escarpments east of Black Rock Station and along the western edge of Beaver Ridge. Several small outliers of the field are overlain by gypsum lake deposits and then by basaltic andesites of the Cove Fort field just south of Black Rock road. On the extreme northeastern corner of the field, flows of the Tabernacle field overlie the flows of the Black Rock field. The lower contact of the oldest flows in the field is exposed at several localities west of Black Point (Fig. 1) and along the cliff faces east of Black Rock Station and on Beaver Ridge. At these localities, the basalts rest on white tuffaceous clays, marls, and siltstones of the Sevier

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[1] These tables (NAPS no. 01621) may be obtained by writing to CCM Information Corp.–NAPS, 909 Third Ave., New York, New York 10022, enclosing $5 for photocopies, or $2 for microfiche. Make checks payable to NAPS.

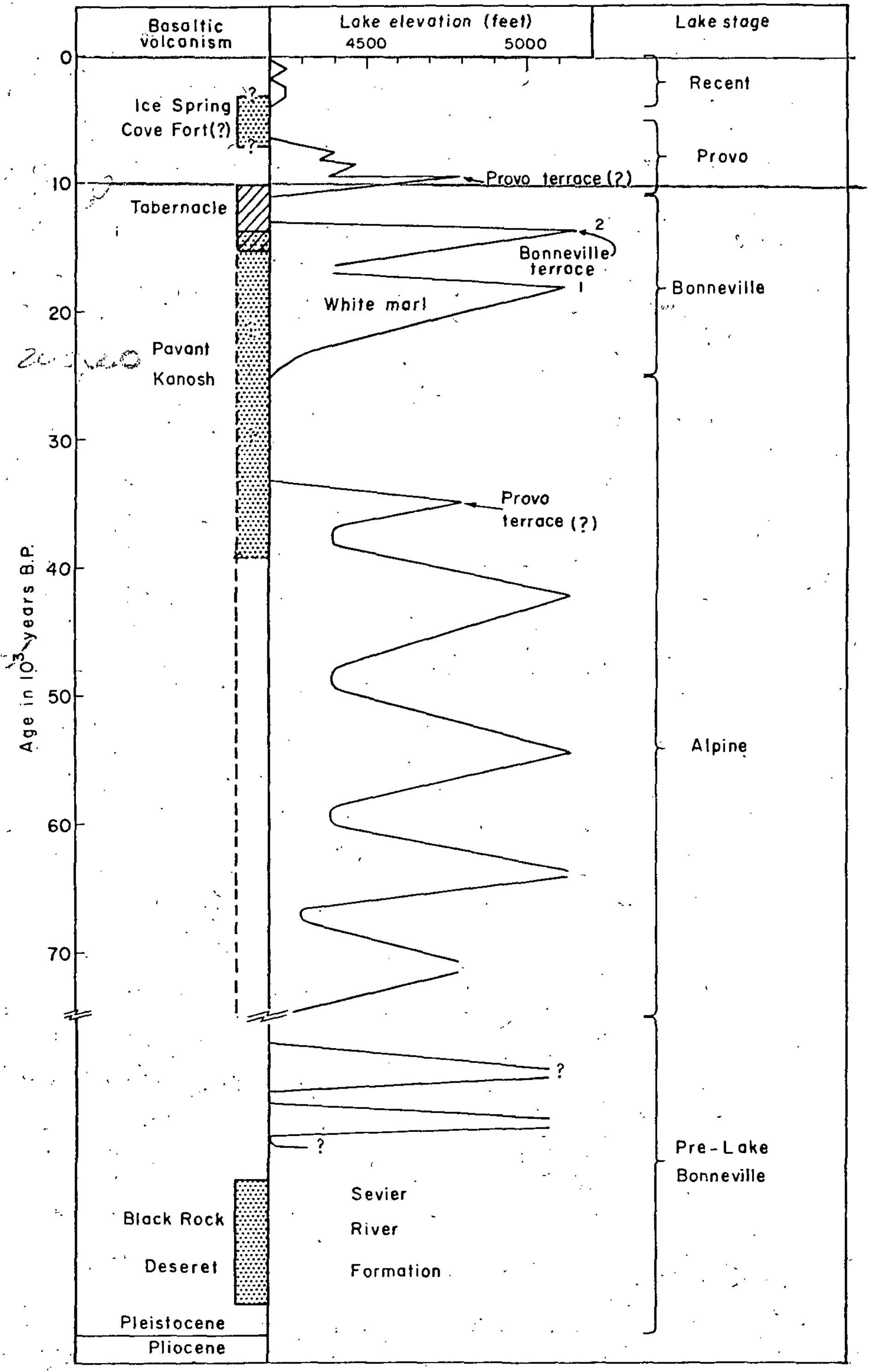

Figure 2. Age relations of Lake Bonneville stages and Quaternary basaltic eruptions in the Black Rock Desert region. Lake Bonneville chronology modified after Morrison (1966).

graphic similarity of basalts of the Deseret field to those of the Black Rock field suggests a similar age of extrusion.

Petrography. The Deseret basalts are composed of about equal amounts of plagioclase (An_{50}) and augite and exhibit a well-developed ophitic texture. Augite crystals up to 2 mm long may completely engulf smaller (~ 0.5 mm) plagioclase crystals. Plagioclase is often zoned. Vesicles, some lined with calcite, compose as much as 30 percent of the rocks and iddingsite alteration is common in the olivine which occurs as small (< 0.1 mm) interstitial crystals. Fe-Ti oxides occur chiefly as euhedral microphenocrysts, although some irregular grains occur in residual glass. Unlike other basalts in the Black Rock Desert region, the opaque fraction of these samples is composed chiefly of ilmenite which occurs as tabular crystals as much as 0.3 mm long.

Pavant Volcanic Field

The Pavant field is named for the prominent volcanic cone, Pavant Butte (Sugarloaf Mountain) located about 25 km west of Holden, Utah. In addition to Pavant Butte, the field consists of numerous basalt flows around and to the south of the butte (Fig. 1). Pavant Butte, first described by Gilbert (1890), is a large tuff-cone about 270 m high. It is composed of partially to completely cemented and well-bedded, yellow and gray cinder and ash with sparsely distributed larger pyroclastic fragments. A well-formed crater about 0.5 km in diameter is breached on the south and both the Bonneville and Provo terraces are well developed on the butte; the absence of the Alpine terraces of Lake Bonneville, however, indicates a post-Alpine age for the butte. Gilbert (1890) suggested subaqueous eruption for the butte and cited evidence that although most of the activity occurred prior to the development of the Bonneville shoreline, some activity occurred after the lake receded from the Bonneville level (Gilbert, 1890, p. 326–327).

Most of the basalts in the Pavant field are the pahoehoe type and contain abundant pressure ridges, lava tubes, and polygonal joints. They are covered in varying amounts by ash from Pavant Butte, Lake Bonneville sediments, and Holocene sand dunes. A major fault zone, the Devil's Kitchen fault (Fig. 1) trends northwest through the south-central part of the field. Excellent columnar joints as well as the best flow cross sections are exposed on the west-facing fault scarp. One to two flows can be seen along the scarp; the upper flow is 1 to 2 m thick and the lower one is > 18 m thick (the base is not exposed).

Sample 13 from the central part of the Pavant field gives a K-Ar whole-rock age of 220,000 ± 260,000 yrs (C. E. Hedge, 1970, personal commun.). How meaningful the age is, however, is questionable because of its large uncertainty. If the date is approximately accurate and the sample contains negligible excess Ar^{40}, it would appear that some volcanic activity began in the Pavant field as much as 200,000 yrs ago. Most data, however, suggest that the major period of volcanism began at Pavant Butte in late Alpine time and persisted until the latter part of the Bonneville stage (Fig. 2).

Petrography. The Pavant basalts exhibit greater petrographic variability than any of the other basalts in the Black Rock Desert region. As shown in Table 1, they are composed chiefly of plagioclase, clinopyroxene (augite), Fe-Ti oxides, and olivine. Traces of apatite and cristobalite occur in some samples. Vesicles, sometimes partially filled with calcite, limonite, and chlorite, compose as much as 20 percent of the samples. The average groundmass crystal size ranges from 0.05 to 0.3 mm, and the textures range from intergranular to intersertal. Plagioclase occurs in three distinct manners: groundmass crystals (43 to 60 percent); microphenocrysts (5 to 20 percent); and phenocrysts (2 to 5 percent). The microphenocrysts range from 0.5 to 1 mm in length and the phenocrysts from several millimeters to ~ 1 cm. Both are approximately the same in composition, ranging only from An_{50} to An_{51}, and both show pronounced oscillatory zoning. The phenocrysts of plagioclase commonly have altered centers and show varying degrees of resorption, while the microphenocrysts are extremely fresh and show only slight effects of resorption. Augite is limited chiefly to the groundmass where it occurs intergrown with plagioclase. Olivine, without reaction rims, occurs as microphenocrysts ($\lesssim$ 0.5 mm in size) closely associated with plagioclase microphenocrysts. Fe-Ti oxides vary greatly in abundance, composing as much as 10 percent in some samples. Magnetite predominates over ilmenite as the primary oxide phase. The magnetite occurs as irregularly shaped, interstitial groundmass crystals ($\lesssim$ 0.2 mm in size), while ilmenite occurs chiefly as platelike crystals in residual glass.

Kanosh Volcanic Field

The basalt flows located west and northwest of Kanosh (Fig. 1) are herein designated the Kanosh volcanic field; Black Rock Volcano located about 3 km west of Kanosh appears to have been the major eruptive center for the field. The volcano is composed chiefly of a dissected cinder cone with basalt flows near the base. Although lacking the Alpine terraces of Lake Bonneville (5100 to 5280 ft), Black Rock Volcano is cut by the Bonneville terrace, and cinder and ash near the base of the cone have been reworked by lake currents. The absence of intermediate terraces indicates a late- or post-Alpine age for the volcano. Because of their similar mineralogy, the basalt flows occupying the fault block east of Beaver Ridge (Fig. 1) are considered to be part of the Kanosh field. The sparsity of Bonneville sediments on these flows suggests a mid- to late-Bonneville age. Evidence was not found to support a subaqueous origin for the flows. Existing data suggest that the Kanosh volcanism was at least in part contemporary with the volcanism in the Pavant field to the north.

Petrography. Basalts from the Kanosh field are similar in most respects to basalts from the southern part of the Pavant field. They differ from the latter basalts, however, in that they contain more plagioclase, less clinopyroxene, and abundant microphenocrysts of magnetite. The composition of the plagioclase is also somewhat more sodic (An_{48}) (Table 1).

Tabernacle Volcanic Field

The Tabernacle field, located about 8 km northwest of Meadow (Fig. 1), is the smallest field in the Black Rock Desert region, covering an area of only about 12 km^2. The field is composed of basaltic flows which were erupted from the base of Tabernacle Hill, a small tuff-cone near the center of the field. This cone, which contains an outer crater approximately 0.5 km in diameter breached on the northwest, is composed of partially to completely cemented cinder and ash (tuff-breccia) with abundant inclusions of country rock. The cemented nature of the cone, as pointed out by Gilbert (1890), may indicate subaqueous eruption. Two small spatter cones near the center of the crater were produced during late stages of the volcanic activity and were probably subaerial eruptions (Gilbert, 1890). The Provo and Alpine terraces of Lake Bonneville do not occur on Tabernacle Hill.

The basalt flows in the field are the pahoehoe type containing abundant pressure ridges and lava tubes of varying sizes and degrees of collapse. Unlike the Pavant and Kanosh fields, only a small amount of Lake Bonneville sediment covers the Tabernacle flows. This fact, together with the field's prominent topographic expression, attests to the youthfulness of the volcanism. An unusual pillowlike and brecciated character of the outer edges of the flows may have been produced as the flows advanced into Lake Bonneville waters with the lava fronts at approximately water level. Existing data suggest that volcanic activity began at Tabernacle Hill sometime during the Bonneville 2 lake level forming the outer subaqueous tuff-cone (Tabernacle Hill) and continued into the late Bonneville and perhaps early Provo stages when most of the lavas were erupted.

Petrography. The basalt flows of the Tabernacle field are uniform in mineralogical composition. They are porphyritic, containing from 10 to 15 percent of large plagioclase phenocrysts (2 to 8 mm long) in a fine-grained intersertal groundmass of plagioclase, augite, and Fe-Ti oxides. Most of the samples contain from 10 to 50 percent vesicles, often lined with calcite. The plagioclase phenocrysts are strongly resorbed and zoned, having an average composition of about An_{65}. Augite and olivine occur principally as groundmass phases. Fe-Ti oxides (chiefly magnetite) compose as much as 11 percent of the rocks and occur as small ($\lesssim 25\mu$) groundmass crystals.

Ice Spring Volcanic Field

The Ice Spring field is located about 15 km west of Fillmore and occupies an area of about 20 km^2. This field, which was described by Gilbert (1890), is composed of basalt flows that were erupted from a complex volcanic center in the south-central part of the field. This center consists of three large craters and several smaller ones in varying degrees of preservation. The large craters are Cresent (0.5 km diam.), the oldest of the three; Miter (300 m diam.); and Terrace, a collapsed crater (300 m diam.). Cresent and Miter craters are breached on the west where most of the lavas appear to have erupted. The complete absence of Lake Bonneville sediments on the flows as well as the absence of Lake Bonneville terraces developed on the craters indicates a post–Lake Bonneville age for the volcanism (Fig. 2). The sparsity of plant and soil cover also attest to the youthfulness of the field.

The basalts of the Ice Spring field are of the aa type except near the eruptive center where pahoehoe dominates. It appears that the basalts were very fluid at the time of eruption (forming pahoehoe), loosing their volatiles and increasing in viscosity as they moved outward, thus developing aa structure. The flows were erupted onto the Pavant flows along the northern edge of the field. It appears that the oldest flows in the field moved northward, forming the northern lobe of the field, while later ones moved westward, and the youngest ones flowed southward. Insufficient exposure does not permit a more detailed account of flow stratigraphy or of relations of crater development to flow eruption.

Petrography. The Ice Spring basalts are the finest grained and most enriched in Fe-Ti oxides in the Black Rock Desert region; the groundmass exhibits an intersertal texture, and the average grain size is $\lesssim$ 0.05 mm. Vesicles occasionally lined with calcite compose from 5 to 30 percent of the flows. Zoned plagioclase microphenocrysts (0.1 to 0.3 mm long) occur in some samples. Rare large ($\leq$ 1 cm long) plagioclase phenocrysts, which are strongly zoned and resorbed, occur in most samples. Unlike all other basalts in the Black Rock Desert region, the Ice Spring flows contain orthopyroxene as microphenocrysts ($\sim$ 1.5 mm long) and as a groundmass phase. Traces of augite also occur as microphenocrysts and in the groundmass, but olivine was not observed in any of the rocks. Extremely fine-grained Fe-Ti oxides (chiefly magnetite) compose as much as 15 percent of the samples. Rare granitic rock fragments $\lesssim$ 4 cm in size were found in the flows near Ice Spring on the northeastern edge of the field. The presence of such rock fragments suggests that the Ice Spring flows may have been contaminated to a small degree with sialic crustal material.

Cove Fort Volcanic Field

The Cove Fort field, located southwest of Cove Fort, Utah, is composed of a sequence of basaltic andesites (with silica contents > 56 percent) which were erupted from the base of Cove Fort crater near the eastern extremity of the field (Fig. 1). Cove Fort crater is composed of loose red cinder and ash and is about 1 km in diameter; flows appear to have moved chiefly to the west and south from the crater. One long tongue of lava extends southwest from the crater for about 20 km.

The basaltic andesite flows in the Cove Fort field are for the most part poorly exposed due to extensive soil and plant cover. Along the northern edge of the field, the flows rest on gypsum deposits which have been interpreted as deposits from an evaporite lake associated in time with the last stages of Lake Bonneville (Zimmerman, 1961). If this interpretation is correct, the Cove Fort field is post–Lake Bonneville in age (Fig. 2). Perhaps the most unique feature of the Cove Fort flows is the ubiquitous presence of quartz xenocrysts and the occasional presence of small granitic rock fragments.

Petrography. The basaltic andesites from the Cove Fort field are composed chiefly of plagioclase with small amounts of augite and Fe-Ti oxides. Plagioclase occurs both as phenocrysts and in the groundmass; the phenocrysts, which range from 1 to 5 mm long, are strongly resorbed and zoned. Textures range from intergranular to intersertal. These basaltic andesites are unique among the basaltic rocks of Black Rock Desert region in that they contain 1 to 2 percent of quartz xenocrysts. The quartz occurs as rounded grains ranging from 1 to 3 mm in diameter and as composite (quartzite) grains several millimeters in size. Individual grains are always surrounded by reaction rims of augite. The quartz appears to have been derived from granites and quartzites (or sandstones) from the basement. Of the Fe-Ti oxides, magnetite greatly exceeds ilmenite and both phases are limited to the groundmass.

GEOCHEMICAL VARIATION

Major Elements

When plotted on an Al_2O_3 versus Na_2O + K_2O diagram (Fig. 3) (Kuno, 1960), the basalts from all volcanic fields in the Black Rock Desert region except the Ice Spring, Deseret, and Cove Fort fields are high-alumina basalts. Those from the Black Rock and Tabernacle fields are particularly rich in Al_2O_3 (> 17 percent). Basalts from the Deseret and Ice Spring fields are tholeiites or transitional tholeiite–high-alumina basalts. Basaltic andesites from the Cove Fort field also fall in the high-alumina field when their quartz xenocryst–corrected SiO_2 values (55 to 57 percent) are considered (Fig. 3). It can be seen in Figure 3

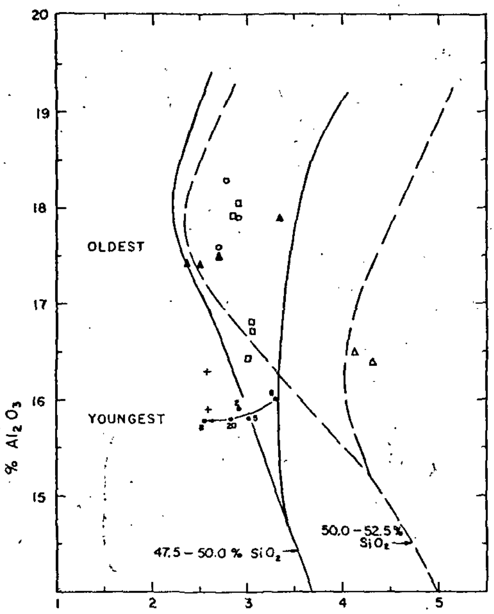

Figure 3. Alumina versus alkalies diagram for basalts from the Black Rock Desert region: (▲) = Black Rock field; (+) = Deseret field; (□) = Pavant-Kanosh fields; (○) = Tabernacle field; (●) = Ice Spring field; (△) = Cove Fort field. Arrow points in direction of decreasing eruptive age for flows of the Ice Spring field.

that, exclusive of the Deseret and Cove Fort fields, a rough trend of decreasing Al_2O_3 with decreasing age exists. K_2O also increases from the oldest to the youngest of these basalts (Figs. 4, 5). Other major elements, however, do not exhibit apparent age-dependent trends over this interval. All of the Black Rock Desert basalts, except those from the Cove Fort field, appear to have evolved along an iron-enrichment trend similar to the Skaergaard intrusion (Wager and Brown, 1967). Over-all secular trends on AFM or Fe versus SiO_2 diagrams are not apparent. It is also clear from Figure 3 and from trace element data discussed below that within-field element trends exist in the Ice Spring field. These trends also appear to be related to eruptive age as discussed later.

The decrease in Al_2O_3 and increase in K_2O from the oldest to the youngest of the Black Rock Desert basalts (excluding the Deseret and Cove Fort fields) suggests a genetic relation for these basalts which were erupted over the last million years. In order to quantitatively evaluate this relation, trace element concentrations have been determined in samples from the Black Rock, Pavant, Kanosh, Tabernacle, and Ice Spring fields.

Alkali and Alkaline-Earth Elements

It is evident from Figures 4 and 5 that K and Rb increase; Sr decreases; and Ba scatters, although perhaps increasing from the oldest to the youngest of the Black Rock Desert basalts. The trends of K and Rb are similar to those observed in most igneous-rock series and to the Skaergaard and Palisades trends (Nockolds and Allen, 1953; Wager and Brown, 1967; Walker, 1969). The approximate constancy or slightly increasing behavior of Ba is similar to that observed in the Skaergaard where Ba remains unchanged until the extreme late fractions when it increases rapidly (Wager and Brown, 1967). It is, however, unlike the Palisades and most igneous-rock series which show a major increase in Ba with fractionation. The striking decrease in Sr with inferred degree of fractionation in the Black Rock Desert basalts (Fig. 5) is unique when compared to most igneous-rock trends which exhibit approximately constant or increasing Sr with fractionation.

In a previous paper, we defined a "normal" and a "Sr-depletion" trend for basaltic magmas (tholeiites and high-alumina basalts) undergoing fractional crystallization (Condie and others, 1969). It is now clear from published geochemical data on basalts that a two-trend model is oversimplified and that a spectrum of trends exists between the two extremes. The basalts from the Black Rock Desert region are unusual in that Sr decreases as a function of K rather than increasing or remaining approximately constant as it is observed to do in all other basaltic provinces for which data were available to the authors. The Black Rock Desert basalts do exhibit, however, typical increases in K/Sr, Rb/Sr, Ca/Sr; this is less pronounced in Ba/Sr with increasing K (Figs. 4, 5). Rb is enriched rapidly relative to K and Ba over this same interval, as evidenced by the rapid decreases in the K/Rb and Ba/Rb ratios (Fig. 4).

It was previously suggested that plagioclase fractional crystallization may be responsible for Sr-depleted basalts (Condie and others, 1969). Since plagioclase is the only mineral being removed from a fractionating basaltic magma which incorporates significant amounts of Sr, it is of interest to further examine plagioclase crystallization as a mechanism for the Sr-

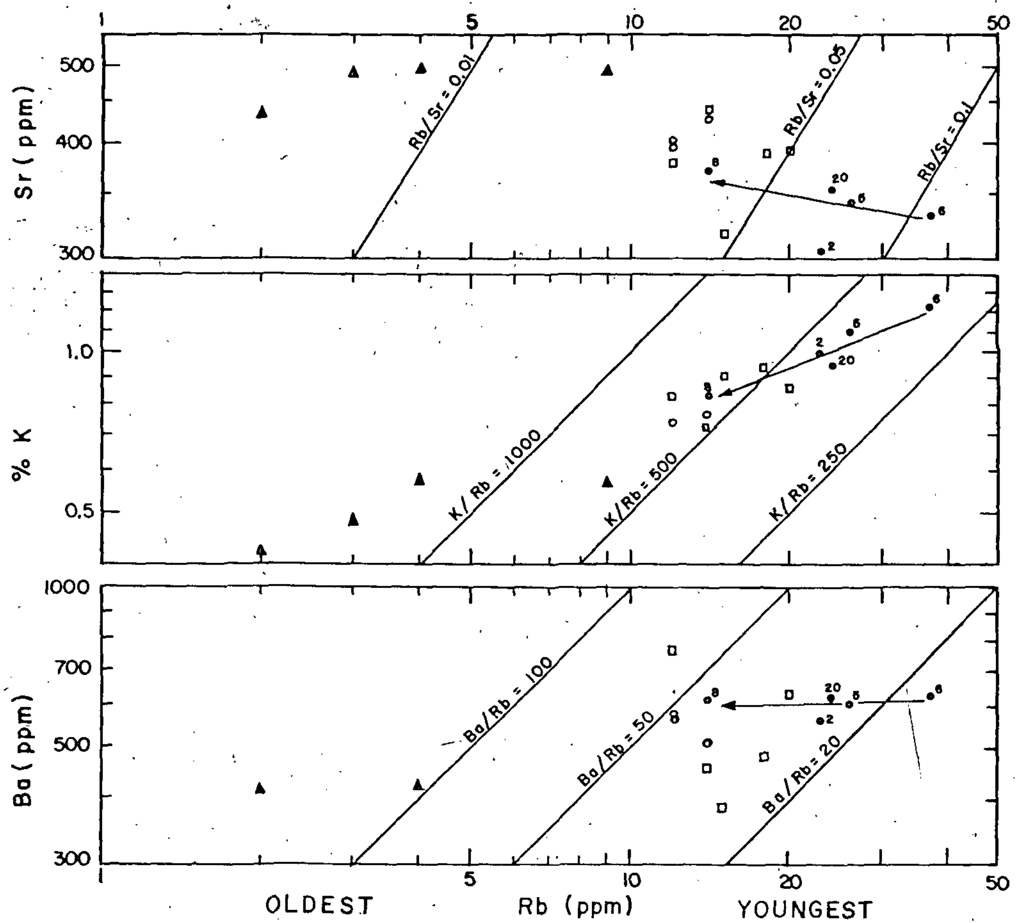

Figure 4. K, Sr, and Ba distributions relative to Rb in basalts from the Black Rock Desert region. Arrow points in direction of decreasing eruptive age for flows of the Ice Spring field. Symbols as in Figure 3.

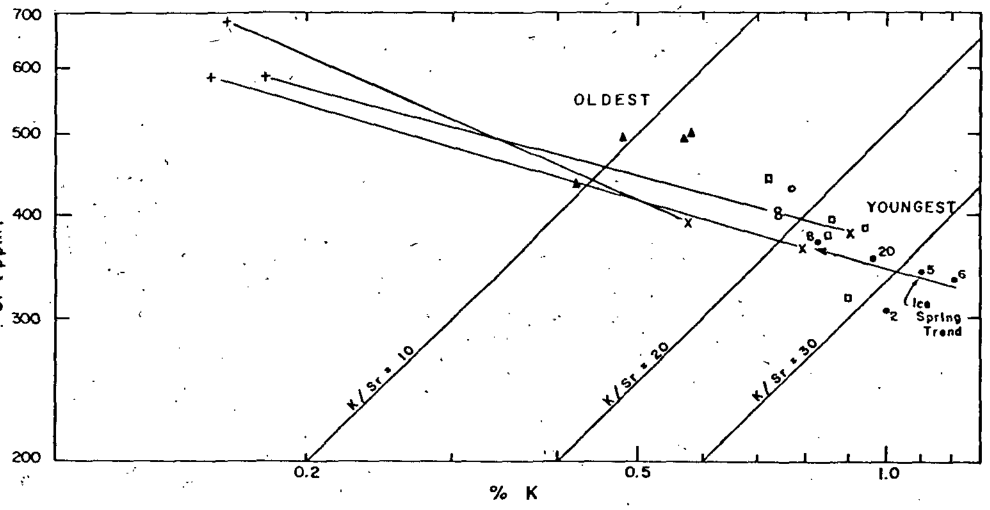

Figure 5. K versus Sr in basalts from the Black Rock Desert region. (+) = plagioclase phenocrysts; (x) = coexisting groundmass; other symbols and arrow as in Figure 3.

depletion observed in the Black Rock Desert basalts. To estimate the distribution coefficient of Sr between plagioclase and coexisting melt ($D_{Sr}^{plag/liq}$), plagioclase phenocrysts were separated from three of the porphyritic samples (21, 22, and 24) and coexisting plagioclase phenocryst-groundmass pairs were analyzed for Sr. K was also determined in these pairs. Rb in the plagioclase was below the level of detectability (~ 1 ppm) by x-ray fluorescence. The results of these analyses are given in Table 2 and plotted together with whole-rock data in Figure 5. It can qualitatively be seen from this figure that removal of plagioclase drives the remaining liquid in the correct direction to produce the observed trend.

To determine the amount of plagioclase necessary to be removed to produce the observed decrease in Sr in the Black Rock Desert basalts, calculations were made using the Rayleigh distribution law, assuming the initial concentration of Sr equal to 500 ppm, a final concentration equal to 300 ppm, and $D_{Sr}^{plag/liq} = 1.8$ (Table 2). The results indicate that 43 percent plagioclase must be removed to produce the observed decrease. Such an amount of crystallization, however, does not explain the extremes of the other element trends shown in Figure 4. For instance, using the observed distribution coefficient for K, $D_K^{plag/liq} = 0.2$ to 0.3 (Table 2), a final liquid is produced with only 0.8 percent K, whereas the observed value is about 1.2 percent. Removal of 43 percent plagioclase (An_{50-60}) also leaves significant deficiencies of Si, Al, Na, and Rb and excesses of Mg, Fe, and Ti in the final basaltic magmas which are not observed.

The excesses of Mg, Fe, and Ti, however, can be overcome by allowing collectively about 7 percent crystallization of olivine (Fo_{85}) (3 percent), clinopyroxene (2 percent), and magnetite (2 percent). In order to compensate for most of the deficiencies, however, it appears necessary to contaminate the fractionating magma with Sr-poor, silica- and alumina-rich rock. This is not unreasonable since, as previously mentioned, small fragments of granitic rock were found in parts of the basalts from Ice Spring field. The amount of contamination of the basaltic magmas with granitic rock of granodiorite composition to produce a final basaltic magma with the observed K, Si, Al, Na, and Rb concentrations was calculated from the data. An average granodiorite composition (Turekian and Wedepohl, 1961; Taylor, 1969) was chosen since it most closely approaches the average composition of the upper Precambrian crust. Any granitic rock between granite and quartz diorite in composition and containing < 400 ppm Sr, however, can be assumed without significantly changing the calculation. The results indicate that 10 percent contamination of the oldest magmas, those of the Black Rock field, together with about 50 percent fractional crystallization (43 percent plagioclase, 3 percent olivine, 2 percent clinopyroxene, and 2 percent Fe-Ti oxides) will almost precisely reproduce the element trends shown in Figures 4 and 5, as well as approximately reproducing the observed major element distributions in the final basaltic magmas. If the smaller Sr distribution coefficient, $D_{Sr}^{plag/liq} = 1.5$ (Table 2), is chosen, about 45 percent plagioclase must be removed to produce the observed decrease in Sr. It is, however, somewhat more difficult to reproduce the other element distribution patterns with this amount of plagioclase crystallization. If the contaminate granitic rock were unusually rich in biotite, hornblende, or magnetite, or contained appreciable interlayers of amphibolite, less than 7 percent of olivine + clinopyroxene + magnetite could be removed from the magmas to preserve material balance for Fe, Mg, and Ti. However, experimental work on basaltic systems (Yoder and Tilley, 1962; Green and Ringwood, 1967) and the presence of olivine and clinopyroxene phenocrysts in many of the older and intermediate-age basalts indicate that it is unlikely that less than 7 percent of these phases were removed.

The rapid decrease in the K/Rb and Ba/Rb ratios with decreasing age (Fig. 4) is probably related to the preferential acceptance of K and Ba (with smaller ionic radii) into the plagioclase structure as compared to Rb. The net result is a relative enrichment in Rb in the fractionating magma. Contamination by granodiorite with a K/Rb $\simeq 230$ and a Ba/Rb $\simeq 5$ would also tend to decrease the K/Rb and Ba/Rb ratios. The rapidly decreasing Sr in the Black Rock Desert basalts is also responsible for the increase in Ca/Sr ratio with decreasing age. This ratio, which is observed to decrease in all basaltic provinces for which data were available to the authors, is a sensitive indicator of the ratio of plagioclase to clinopyroxene crystallized from a magma, as pointed out by Brooks (1968). Since clinopyroxene strongly discriminates against Sr, in most basaltic provinces, enough clinopyroxene relative to plagioclase has been removed from the fractionating magmas to prevent the Ca/Sr from increasing. In the Black Rock Desert basalts, however, the reverse has been true where the plagioclase/clinopyroxene ratio of the phenocrysts being removed is calculated to be in the range of 15 to 30.

It should be pointed out that the model proposed by Griffin and Murthy (1969) involving the partial melting of hornblende and phlogopite-bearing periodotites in the upper mantle may also be employed successfully to produce *relative* Sr-depletion. It will not, however, account for both decreases in Sr and increases in K and Rb as are observed in the basalts from the Black Rock Desert region.

If the proposed model involving dominant plagioclase crystallization and contamination with granitic basement rock is correct, heat must be provided to digest the contaminant rock. Since evidence of superheat was not found in the basalts, a calculation was made to ascertain if enough heat could be obtained from the latent heat of crystallization of plagioclase to melt the granitic contaminant. Assuming a specific heat for granite = 0.25 cal/gm, a heat of fusion for granite = 63 cal/gm, a latent heat of crystallization for plagioclase = 100 cal/gm (Clark, 1966), and a temperature difference of the contaminant and magma of about 700° C, 2400 calories are needed to melt 10 gms (10 percent) of contaminant per 100 gms of melt. Only 24 gms of plagioclase per 100 gms of melt (24 percent) needs to be removed to supply this many calories. Crystallization of olivine, clinopyroxene, and magnetite would supply additional heat, and hence less than one-half of the heat derived from the crystallization of 43 percent plagioclase is needed to melt the contaminant. The remainder of the heat would be lost by conduction and escape of volatiles.

Zirconium and Hafnium

The close geochemical coherence of Zr and Hf in the Black Rock Desert basalts is illustrated in Figure 6. Both elements and the Zr/Hf ratio remain approximately constant from the oldest to the intermediate-age basalts. A striking enrichment in both Zr and Hf, however, occurs in the youngest basalts from the Ice Spring field. The Black Rock Desert basalts differ from most differentiated tholeiite series which show increasing Zr and Hf with fractionation (Gottfried and others, 1968; Brooks, 1969; Walker, 1969). The approximate constancy of the Zr/Hf ratio in the Black Rock Desert basalts is similar to that observed in the Skaergaard complex (Brooks, 1969), but unlike the Great Lake intrusion in Tasmania which exhibits a decreasing Zr/Hf with fractionation (Gottfried and others, 1968). The magnitude of this ratio (~ 70), however, in the Black Rock Desert basalts is larger than that observed in the Skaergaard and many other basaltic rocks (35 to 40) (Brooks, 1969, 1970).

Crystallization of large amounts of plagioclase and small amounts of olivine, clinopyroxene, and Fe-Ti oxides should enrich residual magmas in Zr and Hf since these elements do not substitute to any degree in the above minerals. Fe-Ti oxides, however, may be an exception. Walker (1969) has recently reported approximately 300 ppm of Zr in magnetite from the Palisades sill. A Zr distribution coefficient of approximately 2 is suggested, if the chilled margin of the Palisades is used to estimate the liquid composition. A distribution coefficient > 10, however, would be necessary to prevent the residual magmas in the Black Rock Desert region from becoming enriched in

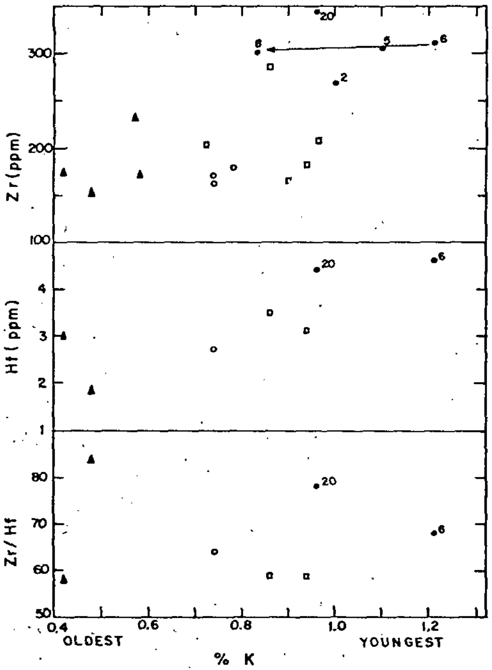

Figure 6. Zr, Hf, and the Zr/Hf ratio in basalts from the Black Rock Desert region as a function of K. Symbols and arrow as in Figure 3.

Zr if only 2 percent magnetite is removed. For this reason, it is suggested that the approximately constant Zr and Hf distributions reflect both Fe-Ti oxide and minor zircon removal during fractional crystallization. The enrichment in Zr and Hf in the Ice Springs basalts appears to reflect the injection of a new batch of mantle-derived magma into the system that is enriched in Zr and Hf.

Niobium, Titanium, Manganese, and Scandium

Nb increases rather smoothly from the oldest to the youngest of the basalts (Fig. 7). The commonly observed close coherence of Nb and Ti (Fleischer and others, 1952; Gottfried and others, 1968), however, is not found in the Black Rock Desert basalts. Ti remains approximately constant and hence the Nb/Ti gradually increases with fractionation (Fig. 7). The approximate constancy of Ti can be accounted for by the removal of about 2 percent of Ti-bearing magnetite and contamination of the magma by 10 percent granodiorite as suggested by the model calculations. If most of the Nb in the Black Rock Desert basalts resides in Fe-Ti oxides as suggested by Gottfried and others (1968) for Nb in mafic rocks, it must have been rejected relative to Ti as fractionation progressed, to account for the increasing Nb/Ti ratio. The Ti contents of the Ice Spring basalts are somewhat higher than the older basalts in the Black Rock Desert region which average about 0.85 percent Ti (Fig. 4). This increase may reflect, as with Zr and Hf, the injection of a new batch of Ti-rich magmas into the system just prior to the extrusion of basalts at the Ice Spring stage.

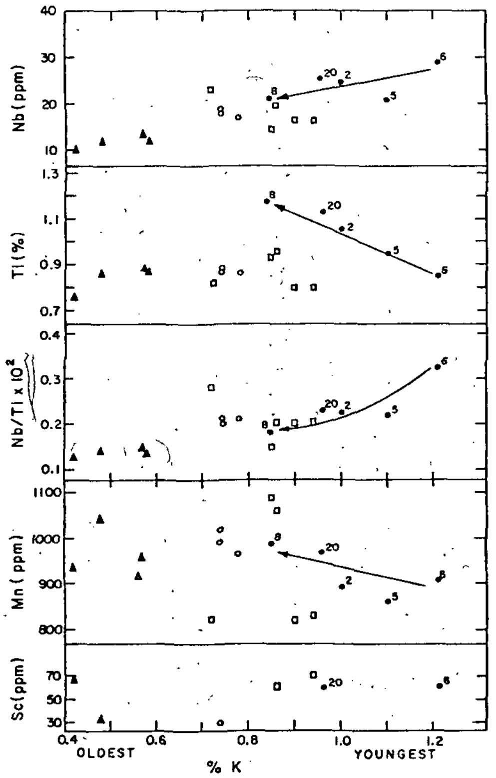

Figure 7. Nb, Ti, Mn, Sc, and the Nb/Ti ratio in basalts from the Black Rock Desert region as a function of K. Symbols and arrow as in Figure 3.

Mn and Sc remain approximately constant over the observed fractionation interval (Fig. 7). This distribution of Mn is different from that observed in most stratiform sheets which show increasing Mn with fractionation (Wager and Brown, 1967; Walker, 1969). Sc behaves differently in various intrusions. It shows a distinct maximum in the Skaergaard layered series (Wager and Brown, 1967), decreases with fractionation in the Great Lake intrusion (Greenland and Lovering, 1966), and like the Black Rock Desert basalts, remains approximately constant in the Palisades sill (Walker, 1969). Sc also does not show strong coherence with any major element in the Black Rock Desert basalts, a characteristic which has previously been noted for Sc in many igneous rocks (Norman and Haskin, 1968). In order to remain approximately constant in the Black Rock Desert basalts, Mn and Sc must have been removed from the magmas in sufficient amounts to offset their corresponding enrichment caused by the extensive plagioclase removal. Because of the very small amounts of minerals removed which accept Mn or Sc, or both (olivine, clinopyroxene, and Fe-Ti oxides), during fractional crystallization, large distribution coefficients (≥ 10) for these elements are implied.

Copper and Zinc

Cu remains approximately constant and Zn shows an irregular distribution roughly increasing from the oldest to the youngest of the Black Rock Desert basalts; such distributions result in a slightly increasing Zn/Cu ratio (Fig. 8). The rather constant Cu distribution contrasts strikingly to stratiform sheets which show increasing Cu with fractionation until the

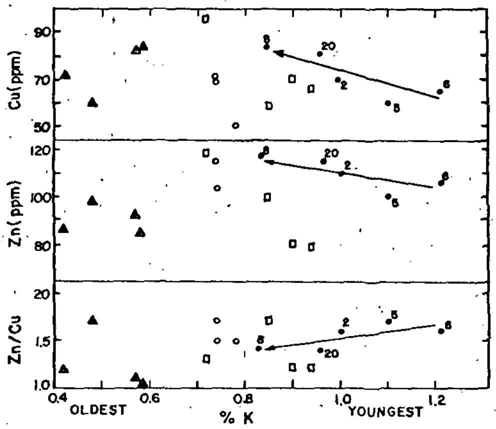

Figure 8. Cu, Zn, and the Zn/Cu ratio in basalts from the Black Rock Desert region as a function of K. Symbols and arrow as in Figure 3.

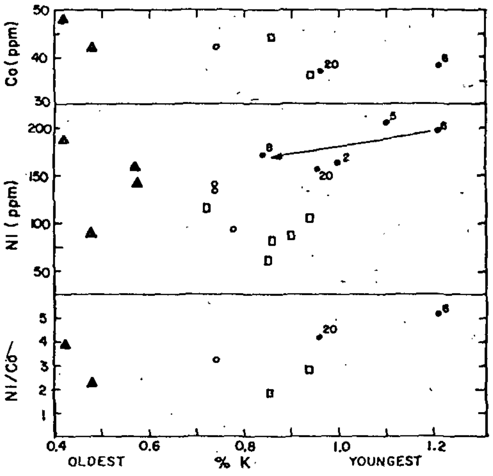

Figure 9. Co, Ni, and the Ni/Co ratio in basalts from the Black Rock Desert region as a function of K. Symbols and arrow as in Figure 3.

very late stages (Wager and Brown, 1967; Greenland and Lovering, 1966; Walker, 1969). Crystal field theory distortion effects (Curtis, 1964) predict that Cu^{+2} should be preferentially rejected from octahedral sites relative to most other divalent transition elements and Mg^{+2} during fractional crystallization. The increase in Cu as a function of increasing fractionation in stratiform sheets can be explained by such distortion effects. Cu also may occur as Cu^{+1} which can be extracted from a magma to a limited degree by substitution in crystallizing plagioclase (Taylor, 1965; Damon, 1968). Such Cu removal may have been significant in the Black Rock Desert basalts where plagioclase was the dominant crystallizing phase. It is suggested Cu^{+1} removal in plagioclase and Cu^{+2} enrichment caused by crystal field distortion effects approximately balanced each other in the Black Rock Desert magmas resulting in an approximately constant Cu distribution.

The geochemical behavior of Zn is not well known in stratiform sheets; however, total bond energy calculations (Damon, 1968) predict that Zn^{+2}, like Cu^{+2}, should be enriched relative to other transition elements and Mg^{+2} as fractionation proceeds. The rough increase in Zn from the oldest to the youngest of the Black Rock Desert basalts is consistent with this prediction.

Nickel and Cobalt

Ni, Co, and the Ni/Co ratio decrease from the oldest basalts to those of intermediate age; Ni, however, is anomalously enriched in the young Ice Spring basalts (Fig. 9). Also a fair coherence of Ni and Co with Mg (but not with total Fe) exists in the Black Rock Desert basalts. Decreasing Ni and Co with fractionation and a coherence with Mg also characterize stratiform sheets and igneous-rock series (Nockolds and Allen, 1953; Greenland and Lovering, 1966; Wager and Brown, 1967; Walker, 1969). Such trends are also predicted from total bond energies and crystal field theory (Curtis, 1964; Damon, 1968). Analyzed olivine and pyroxene phenocrysts from Hawaiian tholeiites have Ni distribution coefficients of 10–25 and 2–5, respectively (Anderson, 1970, and 1970, personal commun.). Using distribution coefficients in these ranges and the Rayleigh distribution law, the observed decrease in Ni (from 150 to 75 ppm) from the oldest to the intermediate-age basalts can be produced by approximately the same amounts of fractional crystallization and contamination calculated in the Sr-depletion model. The striking increase of Ni in the Ice Spring basalts is interpreted (as with Ti, Zr, and Hf) as having been produced by the injection of a new batch of mantle-derived magma into the system which was Ni-rich.

Rare Earth Elements

The concentrations of the rare earth elements (REE) in the Black Rock Desert basalts are similar to those reported in other tholeiitic basalts (Frey and others, 1968). Both individually and collectively, the REE increase in abundance from the oldest to the youngest of the basalts (Fig. 10). The average concentration of 4 REE (ΣLa + Ce + Sm + Eu) is 77, 87, and 117 ppm in the oldest, intermediate-age and youngest basalts, respectively. As shown in Figure 11, however, the relative REE distribution patterns do not change appreciably from the oldest to the youngest basalts.

In order to quantitatively evaluate these trends in terms of the proposed fractional crystallization model, plagioclase-groundmass pairs from two porphyritic samples were analyzed for several REE and distribution coefficients (plag/grdm) were calculated (Table 2). The distribution coefficients are similar to those reported by Schnetzler and Philpotts (1970) for a variety of volcanic rocks and predict that if plagioclase is the major crystallizing phase, the residual liquids should increase in REE as observed in the Black Rock Desert basalts. Employing the Rayleigh distribution law and allowing for 10 percent contamination with average granodiorite (Towell and others, 1965; Taylor, 1969), the increase in REE as a function of decreasing age of the basalts can be reproduced by crystallizing approximately 40 percent plagioclase and small amounts of olivine, clinopyroxene, and magnetite as previously proposed.

The fact that Sr decreases yet Eu increases from the oldest to the youngest basalts indicates that Eu did not significantly follow Sr during fractional crystallization; the distribution coefficients in Table 2 support this conclusion. However, as has been shown by Philpotts and Schnetzler (1968) and Schnetzler and Philpotts (1970) in other volcanic rocks, Eu is concentrated more in plagioclase than the other REE (Table 2), reflecting the fact that Eu can occur in the +2 as well as the +3 valence state. Assuming the distribution coefficients in Table 2 and employing the Rayleigh distribution law in the manner suggested by Philpotts and Schnetzler (1968), a 17 percent negative Eu anomaly should exist in the young Ice Spring basalts after the proposed 50 percent (43 percent plagioclase) fractional crystallization. Since the estimated precision of the Eu/Eu* is about 5 percent, an anomaly of at least 12 percent should be observed. The digestion of 10 percent of granodiorite would either not affect the Eu anomaly of the magmas or cause it to be even more negative, as Eu/Eu* in granodiorite ranges from about 0.7 to 1. The absence of a Eu anomaly in the young basalts may reflect progressively increasing oxidizing conditions accompanying fractional crystallization and contamination. Towell and others (1969) have discussed the possible role of oxidation and reduction in controlling Eu anomalies in crystallizing magmas. Progressive oxidation accompanying fractionation of the Black Rock Desert basalts would

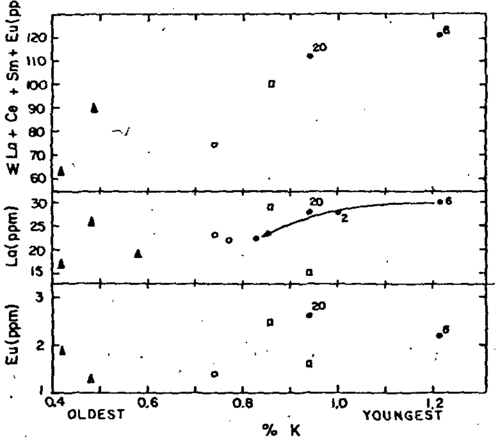

Figure 10. Rare earth elements in basalts from the Black Rock Desert region as a function of K. Symbols and arrow as in Figure 3.

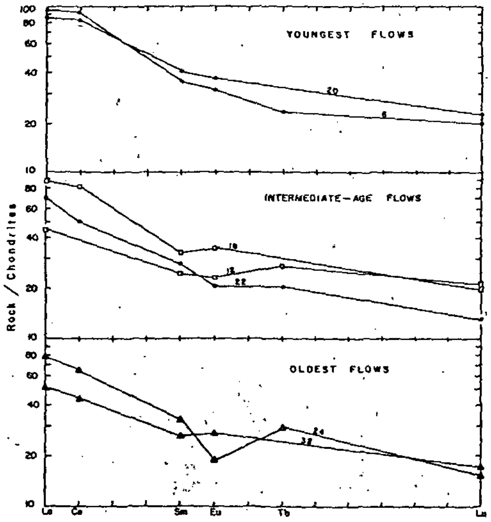

Figure 11. Chondrite-normalized rare earth element distributions in basalts from the Black Rock Desert region. Symbols as in Figure 3.

convert more Eu^{+2} to Eu^{+3}, and thus progressively concentrate Eu in the later liquids relative to the earlier ones. Such an increase may have approximately offset the Eu decrease due to preferential removal of Eu^{+2} in plagioclase.

TRENDS IN THE ICE SPRING FIELD

The only volcanic field in the Black Rock Desert region to exhibit clearly defined within-field geochemical variation is the Ice Spring field. More extensive sampling of the other fields, however, may also reveal such variations. Figures 3 through 10 show systematic variation of most elements. Although, as previously mentioned, the critical field relations in the Ice Spring are not conclusive as to the details of flow stratigraphy, they do suggest that the northern lobe of the field (where samples 5 and 6 were collected) is the oldest and the southeast lobe (where sample 8 was collected) is the youngest (Fig. 1). Assuming these observations to be correct, the geochemical trends in the Ice Spring field appear to be related to relative ages of flow eruption, perhaps representing a time span on the order of 1000 yrs. The trends are indicated in Figures 3 through 10 by arrows pointing in the directions of inferred decreasing age of eruption. The results indicate that Fe, Ce, Zn, Cu, Ti, Mn, and Sr increase and Si, Ni, Co, Mg, Na, K, Rb, and Nb decrease from the oldest to the youngest flows. To explain these distributions, a model is herein proposed, involving both progressive tapping of a zoned magma chamber and fractional crystallization accompanying eruption. A zoned magma produced by earlier fractional crystallization is envisioned just prior to eruption. The earlier fractional crystallization involving chiefly the removal of plagioclase resulted in an enrichment of K, Rb, Na, Ba, Zr, Hf, Nb, and volatiles (principally H_2O), and a depletion in Ca and Sr in the upper part of the magma chamber. Tapping of progressively deeper levels in the chamber during eruption can hence account for the observed decreases in K, Rb, Na, Nb, and in the K/Sr and Rb/Sr ratios (Figs. 4, 5), and increases in Sr and Ca in the flows with decreasing eruptive age. The increase in K/Rb and Ba/Rb over this same interval indicates that Rb was more concentrated in the upper part of the magma chamber than were K and Ba.

It is not likely that the decreases in Si, Mg, Ni, and Co were produced by the proposed zoning, since progressive tapping of the zoned magma chamber should produce increases rather than decreases in these elements. It is proposed, therefore, that these decreases reflect further fractional crystallization during and between eruptions involving chiefly removal of Mg-rich orthopyroxene rather than plagioclase. The fact that orthopyroxene occurs as microphenocrysts in the Ice Spring basalts supports this model. The change in the major crystallizing phase from plagioclase to orthopyroxene may be related to an increase in water pressure, particularly in the upper parts of the magma chamber. Experimental studies of Yoder and Tilley (1962) indicate that increased water pressures can significantly lower the melting points of plagioclase without appreciably affecting pyroxenes and olivine. It is unlikely that the water pressure in the Ice Spring magma chamber exceeded 2500 kb, however, because amphibole becomes a major liquidus phase above this pressure (Yoder and Tilley, 1962).

Calculations indicate that removal of 10 to 15 percent of Mg-rich orthopyroxene (including perhaps some olivine) from the original Ice Spring magma can produce the observed decreases in Mg, Si, and Ni. A Ni distribution coefficient, $D_{Ni}{}^{opx/liq} = 2$, which is close to the average of distribution coefficients determined from the orthopyroxene-groundmass pairs in Hawaiian basalts (Anderson, 1970, and also 1970, personal commun.) was used in the calculations employing the Rayleigh distribution law. The close coherence of Ni and Co in minerals from mafic igneous rocks (Smirnova and others, 1969) suggests that the Co decrease is also controlled by orthopyroxene removal. The observed increases in Fe, Zn, Cu, Ti, and Mn are consistent with 10 to 15 percent removal of orthopyroxene, provided negligible amounts of these elements are contained in the orthopyroxene.

The suggested slight decrease in Al from the oldest to the youngest flows (Fig. 3) suggests that a small amount of plagioclase accompanied the orthopyroxene crystallization—not enough, however, to disturb the K, Rb, Sr, and Ca zonation in the magmas. The presence of a few plagioclase microphenocrysts in the basalts is consistent with this interpretation. The absence of increases in Ba, Zr, and Hf with eruptive age is puzzling, since these elements should be almost completely rejected from orthopyroxene. A small amount of zircon crystallization may have offset any enrichment in Zr and Hf, and Ba zonation in the magma chamber may have offset any Ba enrichment. Since Sc is not observed to increase during the earlier fractionation periods and hence should not be zoned in the magma chamber, an orthopyroxene distribution coefficient $\simeq 1$ is the most probable cause of the approximate constancy of this element (Fig. 7).

Although only two samples from the Ice Spring field were analyzed for more than three REE, the data suggest approximately constant or slightly decreasing REE contents from the oldest to the youngest flows; La, for which four analyses are available, supports this conclusion (Fig. 10). Differences in the relative REE distribution patterns are not apparent during the eruptive history (Fig. 11). The approximate constancy or slight fall in the REE with eruptive age is interpreted in terms of progressive tapping of the proposed zoned magma chamber with REE concentrated toward the top, together with the orthopyroxene crystallization which would tend to concentrate REE in the later liquids. These two opposing effects may have produced the approximately constant or only slightly falling REE trends. The absence of a change in the Eu/Eu* over this interval supports the proposed model, suggesting that plagioclase was not an important crystallizing phase and also implies that oxidizing conditions were approximately constant.

CONCLUSIONS AND DISCUSSION

Recent geochemical studies of young basalts from the Basin and Range province indicate that alkali basaltic volcanism was important in this region during the late Cenozoic (Best and others, 1966; Wise, 1969; Lipman, 1969; Leeman and Rogers, 1970). Leeman and Rogers (1970) have further suggested petrologic provincialism in the western United States with high heat flow, thin crust, and alkali basaltic volcanism characterizing the Basin and Range province. The data reported herein for the basalts from the Black Rock Desert region together with sparse data from other localities (LeMasurier, 1968; Leeman and Rogers, 1970; K. C. Condie, unpub. data) suggest, however, that tholeiitic or high-alumina basalts were the dominant basalts erupted in the northern and eastern Great Basin during late Cenozoic time. In general, crustal thickness and the degree to which the lower crust can be defined increase northward in the Great Basin (Prodehl, 1970); such changes are paralleled by an increase in the abundance of late Cenozoic tholeiitic and high-alumina basalt. Thin crust ($\lesssim 35$ km), however, characterizes the eastern Great Basin. In the Black Rock Desert region, for instance, the crust ranges from about 30 to 34 km (Prodehl, 1970). The eastern Great Basin appears to be a major exception to the general association of thin crust with late Cenozoic alkali basalts described by Leeman and Rogers (1970).

The existence of a rough trend from high-alumina to more tholeiitic basalt (as well as systematic trends in K_2O and many trace elements) as a function of decreasing ages of eruption suggests a genetic relation between most of the basalts in the Black Rock Desert region. Basalts from the Deseret and Cove Fort fields are notable exceptions and do not appear to be directly related to the main sequence of basaltic evolution. A decrease in Sr from the oldest to the youngest of the Black Rock Desert basalts is most readily interpreted in terms of fractional crystallization involving removal of about 40 percent plagioclase. The results of this study indicate that Sr may provide a valuable index to the amount of plagioclase removal in magmas that have undergone fractional crystallization in chambers ≤ 35 km deep. In order to reproduce most major and trace element distributions in the Black Rock Desert basalts, it is also necessary to crystallize small amounts of olivine (3 percent), clinopyroxene (2 percent), and Fe-Ti oxides (2 percent) and to contaminate the magmas with about 10 percent of Sr-poor granitic rocks. Calculations indicate that more than enough heat is available from the heat of crystallization of the minerals being removed to melt this amount of granitic component.

In terms of recent experimental studies (Green and Ringwood, 1967), it appears that the rough trend from high-alumina to more tholeiitic basalt in the Black Rock Desert region is most readily interpreted in terms of progressively shallower levels of fractional crystallization as a function of time. The data are most consistent with a model involving the collection of mantle-derived olivine tholeiite magma in a deep (15 to 35 km) crustal reservoir or reservoirs $\sim 10^6$ yrs ago. Part of this magma was extruded to form the oldest volcanic field, the Black Rock field. Further fractional crystallization and contamination of the magma as it moved upward in the crust, together with small additions of mantle-derived magma, produced later magmas which were extruded to form the younger volcanic fields. Although varying degrees of partial melting in the mantle may also have influenced the history of the basalts, geochemical variations indicate that crustal fractional crystallization and minor contamination played the dominant roles. With exception perhaps of Zr, Hf, Ti, and Ni in the younger basalts, any geochemical patterns resulting from varying degrees of partial melting in the mantle appear to have been masked by the extensive crustal fractional crystallization. New batches of magma entering the crustal reservoirs as fractionation proceeded either represented only minor contributions that did not disturb the fractionation trends or/and fractionation proceeded just far enough after each addition to return the magma to the previous or to an advanced stage of fractional crystallization before the next eruptive period. The large amount of Zr, Hf, Ni, and Ti in the youngest basalts (Ice Spring field) may reflect the addition of a new batch of mantle-derived magma rich in these elements. In terms of the experimental data of Green and Ringwood (1968), the basaltic andesites from the Cove Fort field may have been produced by fractional crystallization of hydrous alkali basalt at depths of 30 to 40 km. Significant contamination of these basaltic andesites with sialic crustal material may be also in part responsible for their anomalous character as compared to most other basalts in the Black Rock Desert region.

Why the basalts from the Black Rock Desert region (and the eastern Great Basin in general) were collected in shallow fractionation chambers while the alkali basalts which characterize much of the Basin and Range province were collected and underwent fractional crystallization in deep (>35 km) chambers is unknown. The reason, however, may be related to the Wasatch Fault zone (including subsidiary faults) which forms the eastern edge of the Great Basin. This fault zone, which developed along an earlier structural discontinuity (pre-Cenozoic and perhaps Precambrian in age; Condie, 1966) may have roots extending into the upper mantle which provided easy access for basaltic magmas in the eastern Great Basin to move into crustal fractionation chambers. A corollary to this hypothesis would suggest that the alkali basalts which characterize much of the Basin and Range province did not accumulate in shallow fractionation chambers because most basin and range fracture systems extend only to shallow ($\lesssim$35 km) depths; only at times of eruption when gas pressures were high did these magmas move rapidly to the surface through the shallow fracture systems.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of C. B. Belt, Jr., who analyzed the plagioclase separates for K by atomic absorption, and David Gottfried who analyzed the basalt samples for Nb. M. J. Potts, Scott Sibley, Stanley Sun, and M. M. Murray are thanked for their help with analytical work and computer programs. The cooperation of A. E. Elliott at the reactor facility at the University of Missouri at Rolla is also gratefully appreciated. A critical review of part of the paper by W. S. Wise, M. G. Best, and R. V. Fisher has resulted in significant improvements. The research was sponsored in part by NASA Grant NGR26-008-006.

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RELATIONS OF THE BROWNS PARK FORMATION AND THE BISHOP CONGLOMERATE, AND THEIR RÔLE IN THE ORIGIN OF GREEN AND YAMPA RIVERS[1]

BY JULIAN D. SEARS

(Presented before the Society December 28, 1923)

CONTENTS

INTRODUCTION

Is the course of Green River across the Uinta Mountains that of an antecedent or a superposed stream? If superposed, on what formation was its course established? These questions have been the subject of lively discussion for half a century, without being conclusively answered. Much interest has been manifested also in two formations of this region, the Bishop conglomerate and the Browns Park formation, the age, origin, and interrelations of which have not been completely understood.

During field-work for the United States Geological Survey in 1921 and 1922 the writer had an opportunity to study the Browns Park formation throughout its entire known area of outcrop, and has become con-

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[1] Manuscript received by the Secretary of the Society January 28, 1924.
Published by permission of the Director of the U. S. Geological Survey.

vinced that this formation supplies the key to the relations of Green River and the Uinta Mountains.

Before presenting the problems and the proposed solutions, the writer wishes to express his deep obligation to his associates, W. H. Bradley, James Gilluly, and K. K. Landes, for their splendid cooperation in this study and for many valuable suggestions that they have contributed. At all times during the progress of the work ideas have been so freely exchanged that it is impossible to give more specific credit to each man.

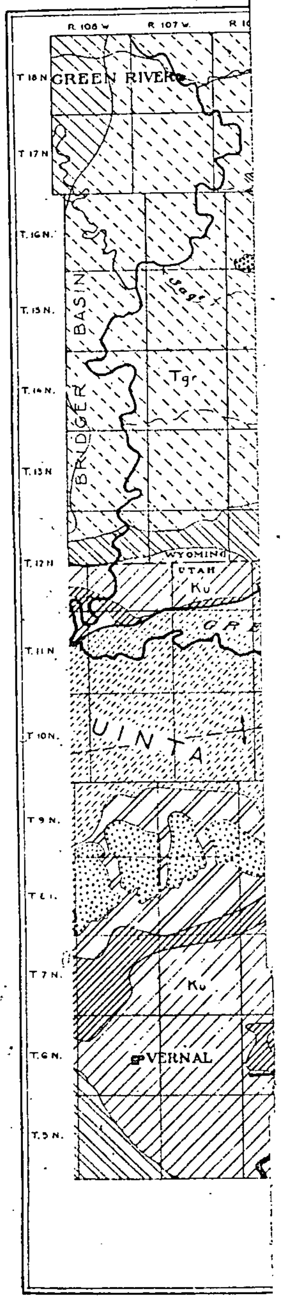
REGIONAL GEOLOGIC RELATIONS

The Uinta Mountain anticline is a broad, flat-topped, east-west fold, approximately 150 miles long and 30 to 40 miles wide, but only the eastern portion of the major arch lies within the area here described (figure 1). The axis of upfolding is continued to the southeastward, however, as the less prominent Axial Basin anticline, on which are the two sharp domes of Cross and Juniper Mountains. The Uinta Mountain-Axial Basin arch is flanked on each side by a great structural basin, the one on the north being known as the Green River basin and the one on the south as the Uinta basin.

The oldest rocks of the region are exposed in the middle part of the Uinta Mountain anticline and in the Cross and Juniper Mountain domes. These rocks consist principally of the "Uinta" red quartzites and sandstones, about 12,000 feet thick, which are possibly of early Cambrian age. Younger Paleozoic and Mesozoic formations make up the flanks of the arch. Eocene formations cover the outer edges and fill the Green River and Uinta basins. In a broad zone along the crest of the eastern half of the Uinta Mountain-Axial Basin arch the Browns Park formation lies on older rocks with angular unconformity ranging from 10 to 100 degrees. The Bishop conglomerate, capping isolated peaks and uplands north of the arch, also occurs in isolated areas high on the southern slope of the Uinta Mountains.

MAJOR PROBLEMS

Of the many problems to be found in this region, two stand out with especial sharpness: The first is the origin of the present courses of Green and Yampa rivers, which have carved remarkable canyons in the upfolds without apparent regard for structure or the relative hardness of strata. The second problem deals with the curious attitude of the Browns Park formation, which, though lying approximately on the crest of the Uinta Mountain-Axial Basin arch, has the structure of a well-defined syncline. In seeking an explanation of the second problem—this



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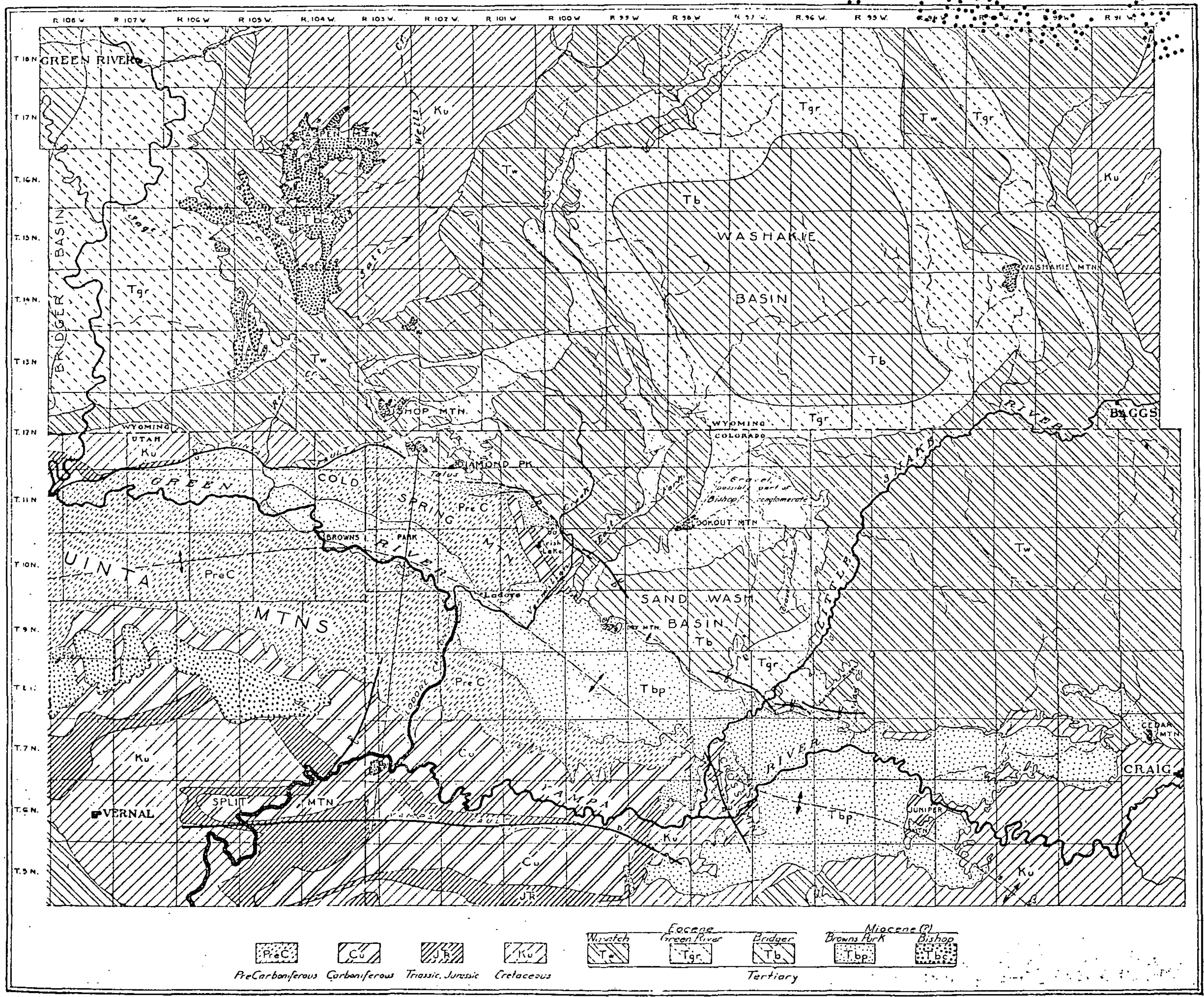

Figure 1.—*Geologic Map of the eastern End of the Uinta Mountains and Vicinity*

Showing relations of the Browns Park formation and the Bishop conglomerate.

unusual structural relationship—data have been found which the writer believes supply a satisfactory solution of the first problem.

Origin of the Courses of Green and Yampa Rivers

Green River flows southward in Wyoming for many miles on soft, nearly horizontal Eocene beds; then, without deflection, plunges into the north flank of the Uinta Mountains. Southward and eastward its course is through a number of canyons eroded in the hard Mesozoic and Paleozoic rocks which here constitute the mountain mass. From these canyons the river emerges into the open valley of Browns Park. Even here, however, it does not keep within the soft sandstones of the Browns Park formation, but makes several detours through spurs of the mountain by short canyons cut in the "Uinta" quartzite. Beyond the park the obvious course of Green River would be a continuation southeastward, through low country and soft rocks, to a junction with the Little Snake, but instead the river swings sharply southward and has cut its way across the main range by way of Lodore Canyon, about half a mile deep in the "Uinta" quartzite (figure 2). The river, after cutting through the main range and being joined by the Yampa, emerges into a synclinal valley, through which it could apparently find an easy outlet westward in soft beds to the lowlands south of the mountains, but instead it again pursues the harder way and crosses Split Mountain by a deep canyon.

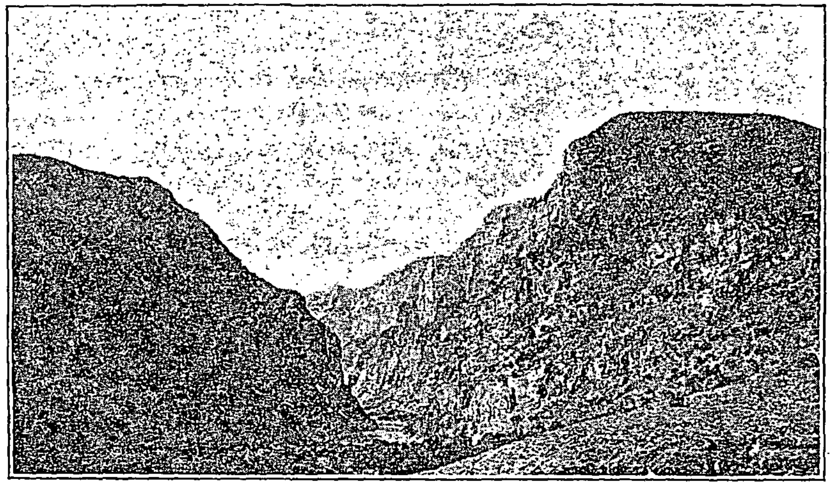

FIGURE 2.—*Lodore Canyon*

Looking downstream.

The course of Yampa River is no less remarkable. Its intrenched meanders cut in Mesaverde rocks on the north flank of the Axial Basin anticline, its deep canyons through the hard rocks of Juniper and Cross Mountains, and its bold entrance into the eastern end of the Uinta Mountains are more notable because the river apparently could have easily avoided obstructions by a course through low country in soft beds of the Browns Park formation.

The interest of early explorers and later students of this region was keenly aroused by these striking canyons, and numerous attempts have been made to explain their origin. Powell[2] felt sure that Green River is an antecedent stream, and that it maintained its course across the slowly rising arch, "as the saw revolves on a fixed pivot, while the log through which it cuts is moved along." On the other hand, Emmons[3] was convinced that both Green and Yampa rivers were superposed, their courses being established on soft overlying Tertiary formations. Powell's conception was accepted by C. A. White, Le Conte, Geikie, and others; Emmons' theory was adopted by King, Irving, W. M. Davis, and Suess. Modifications have been suggested by other students, but in the main these two theories have formed the basis of all explanations offered. The opposing views have been summarized by Hancock,[4] who also contributes several valuable points in favor of a superposed origin for Yampa River.

The writer is convinced by the reasoning of others and by his own observations that the theory of antecedence is absolutely untenable. It is difficult to picture such an even balance between elevation and erosion that Green River could maintain its course across an uplift of 25,000 feet, including a fault on which, according to Powell's figure, the rocks were upthrown 23,000 feet against the river. Granting that such a balance might persist, nevertheless it seems impossible that the present courses of Green and Yampa rivers were established prior to the deposition of the Eocene beds in Green River basin and of the Browns Park formation on the eastern part of the arch. This deposition would have buried such earlier channels under several thousand feet of sediment, and it seems inconceivable that the rivers could reestablish themselves and cut down to rediscover their original channels at all points. Other reasons which seem to render untenable the theory of antecedence will be brought out farther on in this paper.

There remains the explanation by superposition. If this be accepted, a further question arises: On what formation were the river courses established? It could not have been the Cretaceous beds, as these shared fully in the arching. Only Eocene and later deposits, therefore, need be considered.

The Eocene rocks (Wasatch, Green River, and Bridger formations) must also be excluded as a possible basement. In the first place, at some time after the close of the Eocene the valley of Browns Park was eroded, and later this depression, as well as territory far to the eastward, on the axis of the arch, were buried beneath many hundred feet of the Browns Park formation. No previously established rivers could have maintained their courses across such an area of erosion and deposition. In the second place, the writer believes that the eastern end of the Uinta Mountain arch was never covered by Eocene formations. The fact that no remnant of such Eocene cover has ever been authentically reported is negative evidence for this statement. More positive evidence is that the Eocene sediments of Green River and Uinta basins were derived largely from the Uinta Mountains, and, though connecting eastward around the arch over the site of the present Axial Basin anticline, they overlapped only the outer edges of the main arch. Details of this evidence, which is presented more fully in another paper,[5] may be summarized here. On the north side of the arch the mountainward limit of Eocene deposition is shown in four ways: (*a*) several bodies of conglomerate, with boulders up to six feet in diameter, occur near the mountains in the Wasatch and Green River formations; by their position, lithology, and rapid gradation basinward into fine sediments, they can best be interpreted as alluvial fans; (*b*) distinct overlap and attendant thinning of the Wasatch southward is seen on Vermilion Creek; (*c*) in sections 23 and 24, township 9 north, range 100 west, the Bridger rests directly on Cretaceous and Jurassic rocks, having overlapped the edge of the Wasatch and Green River deposits; (*d*) the Bridger at this locality contains many layers of coarse conglomerate, although notably free from them farther out in the basin.

Possibilities are thus narrowed down to the post-Eocene rocks—the Browns Park formation and the Bishop conglomerate. Emmons[6] believed that the course of Green River was established on the Bishop conglomerate, which at one time covered most of the eastern part of the mountains; Hancock[7] suggested that Yampa River was superposed from

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[2] J. W. Powell: Exploration of the Colorado River of the West and its tributaries, 1875, p. 152.

[3] S. F. Emmons: U. S. Geol. Expl. 40th Par., vol. 2, 1877, pp. 194, 197.

[4] E. T. Hancock: The history of a portion of Yampa River, Colorado, and its possible bearing on that of Green River. U. S. Geol. Survey Prof. Paper 90, 1915, pp. 183-189.

[5] J. D. Sears and W. H. Bradley: Relations of the Wasatch and Green River formations in northwestern Colorado and southern Wyoming. U. S. Geol. Survey Prof. Paper 132-F (in preparation).

[6] S. F. Emmons: U. S. Geol. Expl. 40th Par., vol. 2, 1877, p. 205.

[7] E. T. Hancock: The history of a portion of Yampa River, Colorado, and its possible bearing on that of Green River. U. S. Geol. Survey Prof. Paper 90, 1915, p. 188.

the Browns Park formation. As the Bishop conglomerate has always been considered distinctly younger than the Browns Park, these concepts and the evidence submitted in their support have seemed to be in conflict. The writer proposes to reconcile these conflicting views by showing that the Bishop conglomerate is actually the basal part of the Browns Park formation; that the synclinal attitude of the Browns Park was caused chiefly by deformation; and that the courses of both rivers were established on the Browns Park.

BROWNS PARK FORMATION

CHARACTER AND SOURCE

The Browns Park formation, named by Powell[8] from its typical exposures in Browns Park, consists predominantly of soft, chalk-white sandstone. Its color, the peculiar lumpy appearance of its weathered fragments, and the ease with which it breaks down into loose, deep sand differentiate it sharply from all other formations of the region, except possibly the Nugget sandstone, of Jurassic age, which is distinguished by its remarkable cross-bedding. In general, the Browns Park is well bedded, although cross-bedding is not uncommon, especially east of Cross Mountain. Unequal resistance to weathering of the various sandstone layers gives the impression of many shale beds alternating with the sandstones; in reality, there is very little clay in the formation. The sandstone is made up almost wholly of well rounded quartz grains cemented with lime. At places west of Little Snake River hard layers of chert and chalcedony occur in the lower part of the formation.

FIGURE 3.—*Basal Conglomerate of the Browns Park Formation*

This photograph was taken in section 1, township 9 north, range 101 west, Colorado.

A conglomerate of varicolored pebbles is found at the base of the Browns Park formation east of Little Snake River; it crops out conspicuously north of Yampa River upstream from the Juniper Mountain canyon. Farther west the base of the formation is marked by a conglomerate of red quartzite pebbles and boulders reaching a diameter of two feet (figure 3). This red conglomerate, ranging in thickness from a few inches to several hundred feet, is in striking contrast to the white sandstone above. It is seen almost everywhere along the northern edge of the Browns Park outcrops between Little Snake River and Vermilion Creek, in the outlier of the formation north of Cold Spring Mountain, and also at the northwestern end of Browns Park. Just west of Little Snake River, where the Browns Park formation rests on southward-dipping Bridger beds with a marked angular unconformity, the boulders of the conglomerate are inconspicuous, though the red color is noticeable. At this locality the relations were misunderstood and ingeniously misinterpreted by geologists of the King Survey.[9] Bridger beds, faulted down against Green River shales lying to the north, were thought to underlie the Green River, and hence were called Wasatch. The red conglomerate was described as a band of red shale, and with some of the overlying cherty layers of the Browns Park was also included in the Wasatch. The discordance in dip was explained as an intraformational unconformity in the Wasatch. The true relations are shown in figure 4.

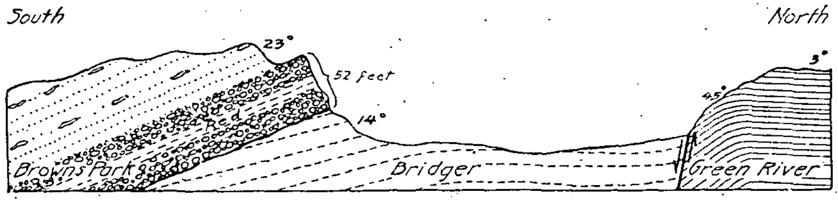

FIGURE 4.—*Sketch Section showing Relations of the Browns Park, Bridger, and Green River Formations west of Little Snake River, Colorado*

There can be no doubt that the basal conglomerate of the Browns Park formation west of Little Snake River was derived chiefly from the red "Uinta" quartzite. It will be shown that there is also good reason

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[8] J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto, 1876, p. 44.

[9] Clarence King: U. S. Geol. Expl. 40th Par., vol. 1, 1878, pp. 366, 385-386.
S. F. Emmons: Idem, vol. 2, 1877, p. 220.

to believe that the white sand making up the body of the formation had the same source. It has long been recognized that Mesozoic and Carboniferous rocks of the Uinta Mountains furnished the sediments of the Wasatch, and that Carboniferous rocks supplied the material for the Green River formation. Conglomerates of Mississippian gray cherty limestone are abundant in the Bridger near its margin. By Browns Park time erosion had cut down into the great mass of red "Uinta" quartzite forming the core of the arch, and after the outpouring of the coarse material that later consolidated as the conglomerate, further weathering and erosion involved the breaking down and leaching of the quartzite to white sand. Such a color change is unusual, but the red quartzite does today produce just such white sand. At places in the mountains tiny alluvial fans of pure white sand are found where gullies emerge from steep slopes of red quartzite. Boulders of the quartzite show various stages of leaching, the color change passing from red through a dirty yellow to white. Some cobbles were found to be in part yellow and in part the original brick red. Sections of quartzite viewed under the microscope show that the red color belongs to the cement which fills the spaces between the secondarily enlarged white or colorless quartz grains. Another indication of the origin is given by small grains of yellow and brown agate found in the Browns Park at least as far east as Godiva Ridge; these are similar to agates observed in the "Uinta" quartzite of the mountains.

The thickness of the formation is at least 1,200 feet, as shown by measurements east of Vermilion Creek; before erosion it was probably much thicker.

AGE

The age of the Browns Park has long been in dispute and guesses have ranged from Eocene to Pliocene. By various authors the formation has been correlated with the Green River, the Bridger, and the Uinta (all of Eocene age); parts of it have been mapped as Wasatch, Green River, Cathedral Bluffs red beds member of the Green River, Laney shale member of the Green River, and Bridger. Until a discovery by Professor Douglass in 1923, no identifiable fossils had ever been obtained from it. The writer, like all earlier workers, found only certain thin branching tubes which have the appearance of stems or twigs. It can be stated with certainty, however, even without the evidence of fossils, that the formation is younger than the Bridger. The writer has personally traced the contact of Browns Park and Bridger continuously between Little Snake River and Vermilion Creek, a distance of 20 miles. The lithology of the two formations is quite different; the Browns Park lies on the Bridger with an angular unconformity nowhere less than 10 degrees, and almost all of the way the base of the Browns Park contains its striking red conglomerate. These facts were recognized and clearly understood by Powell,[10] who said: "The unconformity with the . . . Green River and Bridger beds is well exhibited in the Dry Mountains in many fine exposures. . . . Conglomerates are found at the base, in some localities having a great development."

Again, in describing the relations on Little Snake River, interpreted by King and Emmons as an unconformity within the Wasatch, Powell[11] wrote: "The [Browns Park] group is exposed from summit to base, and is seen to rest unconformably upon Bridger beds." It is remarkable that such definite statements should have been generally overlooked, and that so many students have assigned the Browns Park to an earlier date.

In August, 1923, was published a statement[12] that Prof. Earl Douglass had recently made "three very important discoveries of fossils in the Browns Park formation south of Sunbeam, Colorado." These were remains of vertebrates, mostly of carnivorous types. Professor Douglass was quoted as believing the formation to be probably of Miocene age. These fossils were later examined by Mr. O. A. Peterson,[13] who says he believes them to be probably of lower Miocene age, although they may belong to the uppermost Oligocene.

THE SYNCLINAL STRUCTURE AND ITS CAUSE

Through its entire area of outcrop the Browns Park formation (as generally understood) has the structure of a flat-bottomed syncline with sharply upturned edges. Along its southern margin the northward dips range from 3 to 26 degrees; on its northern margin the beds dip southward 6 degrees in the vicinity of Cedar Mountain and reach a maximum of 60 degrees on the southern edge of Sand Wash basin. This attitude is in striking contrast to that of the underlying beds, for the syncline is superposed directly on the crest of the Uinta Mountain-Axial Basin arch. Between the outward-dipping older rocks and the inward-dipping sandstones of the Browns Park, there is angular unconformity ranging from 10 to 100 degrees (figure 5).

During the first season's work in the eastern part of the field no dips greater than 30 degrees and no evidence of post-Browns Park movement were observed. The unusual structure seemed most readily explainable

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[10] J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto, 1876, p. 168.

[11] Idem, p. 44.

[12] Salt Lake Min. Rev., vol. 25, no. 10, 1923, p. 14.

[13] Letter to Mr. T. W. Stanton, November 8, 1923.

as original dip, caused by deposition of the formation on the sloping margins of an old erosion trough. Browns Park itself is clearly such a trough, and its eastward continuation seemed plausible enough, as the formation is bounded by ridges on the north and south. By this conception the upturned edges of the Browns Park would actually mark the original limits of sedimentation.

Later studies showed conclusively that depositional slope could have been no more than a minor factor, possibly sufficient to cause the gentle dips along the south margin and the eastern part of the north margin. For the dips of 30 to 60 degrees, post-Browns Park movement must be invoked, and of such movement there is abundant proof. This late tilting and faulting not only explains the present attitude of the Browns Park, but also furnishes the key for correlating the Browns Park with the Bishop conglomerate; it will therefore be discussed more fully in the section on the equivalence of these formations.

FIGURE 5.—*Pronounced angular Unconformity between the Browns Park and Wasatch Formations*

Photograph taken in section 10, township 7 north, range 96 west, Colorado. Browns Park dips 15 degrees to the right; Wasatch dips 40 degrees to the left. Note also angle between the contact and the bedding of the Browns Park.

BISHOP CONGLOMERATE

CHARACTER AND SOURCE

The Bishop conglomerate, so named by Powell[14] because of the remnant which caps Bishop Mountain, consists of waterworn and subangular pebbles and boulders embedded in a finer gravel and sand matrix. The material is predominantly red quartzite (in part leached to dirty yellow or white) and to a lesser extent gray cherty limestone. Patches of the conglomerate are found high on the south flank of the Uinta Mountains. North of the arch the formation caps several peaks and the ridges and upland sloping gently northward to Aspen Mountain, and also caps Washakie Mountain.

Lithology and distribution show clearly that the conglomerate in this region was derived from the Uinta Mountains. In an excellent paper Rich[15] describes the formation north of the Uinta Mountains as gravel consolidated at the base, loose at the top, and ranging in thickness from 8 to 200 feet; he points out that the conglomerate truncates the structure of the older formations, and concludes that it was laid down on a remarkably even peneplain sloping away from the Uinta Mountains.

AGE

Earlier writers seem to have been unanimous in believing the Bishop conglomerate to be younger than the Browns Park. Doubt may have been implied, but was not expressed, by the statement of Powell that "the Bishop Mountain conglomerate . . . has been found to lie unconformably on all the other geological formations of this region, except the Browns Park, and possibly on the latter also." So far as the writer knows, this view is not supported by any example of undoubted Bishop conglomerate resting on the Browns Park. Such an example may possibly be furnished by boulders of gray limestone scattered over the Browns Park on the Yampa-White River divide, but this is very questionable.

CORRELATION OF THE BROWNS PARK FORMATION AND THE BISHOP CONGLOMERATE

The lack of known Bishop conglomerate resting on the Browns Park merely opens the way for correlating the two formations. Other facts indicate more positively that the Bishop conglomerate is in reality the basal conglomerate of the Browns Park, laid bare by the removal of the soft white sandstone.

In appearance the two conglomerates are practically identical. Both consist almost wholly of red quartzite and contain relatively little of the gray limestone which forms the bulk of the conglomerates in the Eocene formations. Boulders and pebbles in the Browns Park and the Bishop

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[14] Idem, p. 44.

[15] J. L. Rich: The physiography of the Bishop conglomerate, southwestern Wyoming. Jour. Geology, vol. 18, no. 7, 1910, pp. 601-632.

are well rounded or subangular. The mingling of many sizes indicates lack of thorough sorting during deposition. This lithologic resemblance is so complete that at certain localities it led earlier workers to identify as Bishop a conglomerate that can be definitely shown to form the base of the Browns Park formation, even though they believed the Bishop to be younger than the Browns Park. One instance, in which the apparent error was corrected, is cited by Powell:[16] "There are some conglomerates on the peaks of the Dry Mountains which at one time I believed to belong to this [Bishop] period, but now I think they are of the Brown's Park age." At this locality, in township 9 north, range 100 west, several conspicuous dip slopes of the conglomerate can be traced with certainty under white sandstone of the Browns Park formation.

A second reason for correlation is presented by Green and Yampa rivers. It has already been shown that these rivers must have established their courses on either the Browns Park or the Bishop conglomerate. Let us assume for the moment that the Bishop is actually the younger of the two formations. In this case the rivers could not have established their present courses on (*a*) the Browns Park, for their channels would have been afterward buried by the Bishop conglomerate. Furthermore, if Green River had established its course before the time of the Bishop, it seems impossible to explain the area of Bishop conglomerate mapped by Powell just south of Green River below the mouth of the Yampa. This area is at an elevation of 7,600 feet, the highest point south of the rivers. Assuming that its material is the characteristic red quartzite, it must have been derived from the main outcrops of the "Uinta" quartzite north and could not have been carried to its present site across a farther north and could not have been carried to its present site across a preexistent canyon of Green River. On the other hand, the present river courses were probably not established on (*b*) the Bishop conglomerate, for in such a case the conglomerate must have covered part, if not all, of the Browns Park formation. It is hardly conceivable that, if this had occurred, no trace of such a cover would remain. Thus the assumption of difference in age leads to a dilemma which can be easily escaped by considering the Bishop conglomerate as the base of the Browns Park.

The third and most important line of evidence for the correlation of the Browns Park formation and the Bishop conglomerate involves the post-Browns Park movement which, as already stated, caused the synclinal attitude of the formation. At first sight the greatest obstacle to correlation seems to be the present marked difference in elevation of the two formations. The surface of the Browns Park ranges from 5,200 feet along Green River to about 7,800 feet in the valley just south of Diamond Peak. The Bishop conglomerate is between 9,000 and 10,000 feet above sealevel on Diamond Peak and Bishop Mountain, and slopes gently northward to an elevation of 7,600 feet near Aspen Mountain. This discordance of elevation is probably the main reason that led Powell and others to consider the Bishop conglomerate and the Browns Park formation of different ages. The difficulty disappears and the correlation is given greater weight by an analysis of the deformation and paleophysiography before and after Browns Park time. Powell advanced the theory that after Browns Park deposition the eastern end of the Uinta Mountain arch collapsed and a graben was formed on its crest. Additional proofs of this movement have been gathered, and the writer is convinced that by the collapse of the arch the two parts of the Browns Park formation were brought to different levels. Data on which this conception is based may be outlined as follows:

(1) The south flank of the arch is cut by a great fault, nearly 50 miles long, extending from the eastern end of the uplift westward to and beyond Green River. This was called the Yampa fault by Powell,[17] who says that the rocks on the north side are downthrown from 3,000 to 5,000 feet. The Yampa fault marks the southern edge of the graben.

(2) The west side of Cross Mountain is cut by a north-south fault, with downthrow on the west, which brings Mancos shale against the Carboniferous. Browns Park beds in the angle between Yampa and Little Snake rivers have been mapped by Schultz as stopping abruptly against this fault, showing it to be, at least in part, of post-Browns Park age. This fault seems to mark the eastern edge of the main downward movement. Between the eastern end of the Uinta Mountain arch, Cross Mountain, and the Yampa-White River divide the lower surface of the Browns Park slopes gently northward, owing either to deposition on a sloping surface or to warping into the graben. The basal conglomerate in this vicinity consists mostly of gray limestone boulders.

(3) Eastward from Cross Mountain the effect of the graben movement seems to have been a gentle westward tilting of the Browns Park formation. Although the Browns Park in this area is thought to be derived from the Uinta Mountains, its lower surface now slopes gradually westward, from elevations of 6,800 feet at Cedar Mountain and 6,000 feet at Juniper Mountain to an elevation of 5,000 feet in Browns Park.

(4) Along the northern edge of the Browns Park outcrops, between Cedar Mountain and Sand Creek, that formation dips gently southward. Between Sand Creek and Vermilion Creek the southward dips are much

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[16] J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto, 1876, p. 170.

[17] Idem, p. 208.

steeper, reaching a maximum of 60 degrees. The edge of the Browns Park here lies along the southern border of a zone of disturbance that affects the Wasatch, Green River, and Bridger formations. This zone consists of a number of anticlinal axes and faults *en échelon,* which show unmistakable downward movement on the south side into the graben. The Browns Park, with its basal red conglomerate, ends in northward-facing escarpments; it approaches closely, but at no place crosses, the anticlinal axes or faults. As the Browns Park forms the ridge, and the Eocene beds to the north in Sand Wash basin are at a lower elevation, these escarpments can not mark the edge of deposition which stopped short of the zone of disturbance. The only possible explanation seems to be that the region to the south was depressed after Browns Park time, and that the soft Browns Park beds north of the zone, left at a much higher elevation, have been entirely eroded.

(5) Farther northwest, toward Vermilion Creek, the Browns Park lies on successively older formations, from Cretaceous down to Pennsylvanian. The older rocks dip about 30 degrees northeast; the Browns Park dips 13 degrees southwestward into the graben. Along the contact in this vicinity the soft white sandstone of the Browns Park formation has been generally eroded, and the basal conglomerate, which at places reaches a thickness of several hundred feet, forms a conspicuous dip slope. The surface of this slope is approximately parallel to the surface on which the conglomerate was laid down. Half a mile east of Vermilion Creek the dip slope ends abruptly and the contact swings sharply downstream with the dip. Northwestward, however, the old surface, on which the conglomerate was deposited and from which it has only recently been almost completely removed, continues for several miles as a terrace sloping *toward* the mountain and truncating the edges of the resistant Park City formation and Weber quartzite. This striking topographic feature is shown in figure 6. Still farther northwestward the terrace is interrupted for a mile or two by higher edges of the Park City formation, which must have stood above the general terrace level at the time of its erosion. Beyond this, near Irish Lake, the terrace is resumed, but the surface is practically level instead of sloping toward the mountains. A mile farther northwest the terrace is thickly covered with the red conglomerate of the Browns Park, which here forms a notable dip slope northeastward, *away* from the mountains, and passes northward under white sandstone of the Browns Park formation. This curious terrace is interpreted as the mountainward edge of an old peneplain, most of which has been destroyed by erosion. Its original slope was northeastward, but southeast of Irish Lake it has been twisted and given a southwestward slope by the collapsing of the Uinta Mountain arch.

(6) The outlier of the Browns Park north of Irish Lake extends northwestward around the flank of Cold Spring Mountain, to the head of the creek south of Diamond Peak. Its northern edge is at or near a large fault which extends from East Fork of Vermilion Creek to the southern slope of Diamond Peak. The westward extension of this fault is obscured by debris from Diamond Peak, but most probably it connects with the great Uinta fault, which reaches far westward into Utah. If not continuous, at least the faults are alike in having their planes nearly vertical and the rocks on the south side upthrown. Powell estimated that the throw of the Uinta fault is 23,000 feet. Some of this, as indicated by the mapping of Schultz,[18] must have been post-Wasatch. The fault southeast of Diamond Peak must be also in part later than Wasatch. Mesaverde and Mancos, south of the fault, are brought against Wasatch north of it, and both sides are dragged sharply to a vertical or even much overturned position. For the sake of simplicity, the latter fault will in this paper be treated as the southeastward extension of the Uinta fault.

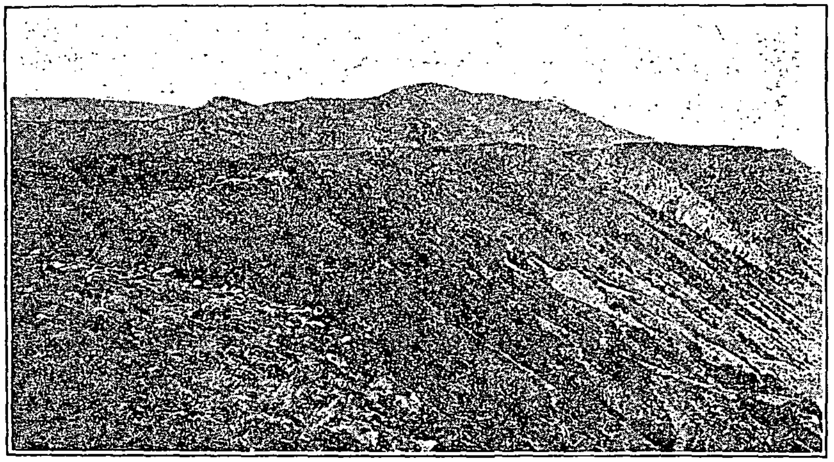

FIGURE 6.—*Terrace truncating the Park City Formation and the Weber Quartzite*

View taken westward, on the northeastern flank of the Uinta Mountain uplift. Upper canyon of Vermilion Creek in right foreground; Irish Canyon, through Mississippian limestone of Cold Spring Mountain, in center background; remnant of basal conglomerate of the Browns Park formation on edge of terrace in left foreground.

Relations of the Browns Park formation to the Uinta fault are ab-

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[18] A. R. Schultz: *Oil possibilities in and around Baxter basin, in the Rock Springs uplift, Sweetwater County, Wyoming.* U. S. Geol. Bull. 702, pl. 1, 1920.

normal. If correctly interpreted, these relations form an important link in the evidence for a graben. Powell[19] suggested that after Browns Park deposition a great reversal occurred along the line of the Uinta fault, by which the rocks on the south side fell 3,000 feet. With this conception the writer is in perfect accord, although part of Powell's reasoning was based on an erroneous identification of colored clay shale at the base of the Wasatch (north of the fault, in township 11 north, range 101 west) as "Flaming Gorge" (at least in part Morrison).[20] From this it may be concluded that the basal conglomerate of the Browns Park south of the fault and the Bishop conglomerate north of it were once a continuous layer, and that the present difference of elevation is due entirely to later movement. Proof of reversed movement on the Uinta fault is, therefore, very important.

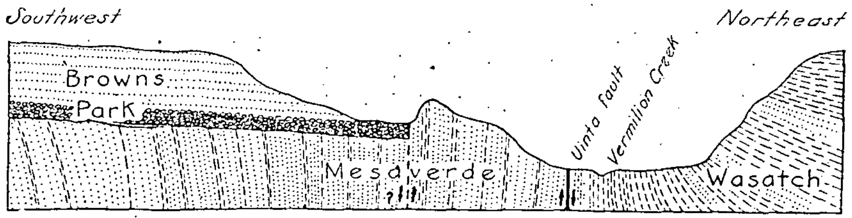

FIGURE 7.—*Sketch Section showing basal Conglomerate of Browns Park Formation resting on and ending laterally against steeply dipping Mesaverde Sandstones*

View is on Vermilion Creek, Colorado.

In section 1, township 10 north, range 101 west, the dip slope of the basal conglomerate of the Browns Park (already described as the northward extension of the terrace seen at Vermilion Creek) is covered with detached areas of the white sandstone. It dips gently northeastward and truncates the vertical Mancos and Mesaverde beds. Several hundred feet from the main Uinta fault, which is here concealed by alluvium of Vermilion Creek, the conglomerate stops abruptly against a low ridge of vertical Mesaverde sandstone. This curious relation, which is observable at intervals for a mile and a half to the northwest, is shown diagrammatically in figure 7. Overlap must be ruled out as a possible explanation, as the surface on which the conglomerate was laid down slopes evenly northeastward into the sandstone ridge. If the Mesaverde sandstones had existed as a hogback at the time of deposition, previous erosion would have taken the form of a strike valley on the mountainward side of the hogback, and the slope near the ridge would have been away from the ridge, not toward it. The surface of erosion was instead a sloping peneplain, and the abrupt ending of the Browns Park and of the old erosion surface on which it lies may be considered as proof of the reversed movement on the Uinta fault. The line of termination marks the plane of the reversed fault, which at this locality does not exactly coincide with the original fault-plane. The absence of drag in the Browns Park formation at this locality may be explained by its position over the edge of hard Mesaverde sandstone. As the new slipping must have occurred practically along the bedding of the Mesaverde, the hard layers would move as a block and overlying horizontal beds would not be subjected to twisting. Farther northwest the Browns Park near the fault lies on Mancos shale, which was much more distorted by the reversed movement. Here the Browns Park shows distinct drag, the southward dip in one case reaching 60 degrees.

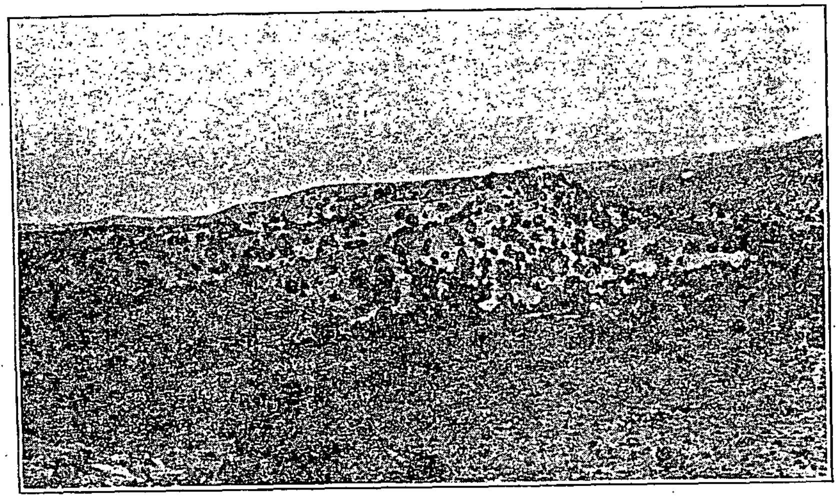

FIGURE 8.—*Intraformational Unconformity in the Browns Park Formation*

The view is northwest of Ladore Post Office, Colorado

At several localities west of Diamond Peak additional instances of drag caused by reversed movement have been noted by Powell[21] and Reeside.[22]

(7) Not all of the downward movement on this side of the graben took place on the Uinta fault. During the collapse of the arch there was distributive faulting and movement through the mass of "Uinta" quartz-

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[19] J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto, 1876, p. 205.

[20] Idem, p. 206.

[21] Idem, p. 206.

[22] J. B. Reeside, Jr.: Personal communication, 1923.

ite in Cold Spring Mountain. Some of these faults may be seen where they cross Bull Canyon, at the southeastern end of the mountain. Their throw must be to the south, as at several places on the southern slope of Cold Spring Mountain the quartzite dips distinctly southward, contrary to the normal dip on the flank of the Uinta Mountain arch. On the north side of Browns Park (valley), northwest of Ladore Post Office, the white sandstone of the Browns Park formation dips 25 degrees to the south, but flattens a short distance out in the valley. In sections 7 and 18, township 10 north, range 102 west, this tilting of the Browns Park formation may be resolved into two stages. The basal part of the formation, several hundred feet thick, containing much chert and chalcedony, dips 23 degrees to the south; the upper portion, consisting almost wholly of fine-grained white sandstones, dips only 7 degrees and truncates the lower portion (figure 8). This intraformational unconformity and the variation in lithology may be the reason why several earlier writers assigned all of the southward-dipping sandstones on the north side of Browns Park to the Green River. The unconformity, however, seems to be only local, as a mile southeastward along the outcrop no trace of it could be found. Moreover, at other places, especially on Little Snake River, the lower part of the Browns Park above the basal conglomerate contains similar layers of chert and chalcedony.

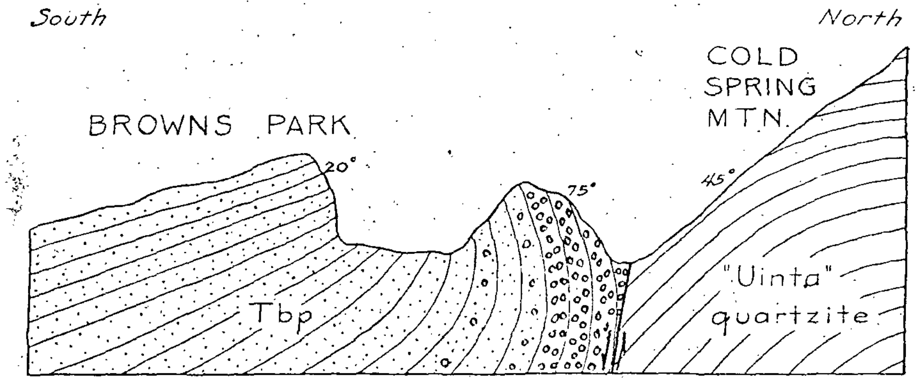

FIGURE 9.—*Sketch Section of a post-Browns Park Fault on the north Side of Browns Park near its upper End*

Tbp = Browns Park formation.

A fault on Cold Spring Mountain, with downthrow on the south, may also be seen at the upper end of Browns Park. The Browns Park beds have been dragged sharply upward, and the basal red conglomerate is exposed, as shown in figure 9.

(8) The present attitude of the Bishop conglomerate is in itself evidence for the collapse of the Uinta Mountain arch. From an elevation of nearly 10,000 feet on Diamond Peak the conglomerate slopes northward to an elevation of 7,000 feet near Aspen Mountain (shown diagrammatically in cross-section, figure 10). Granting that the conglomerate was laid down on an even peneplain sloping away from the Uinta Mountains, as suggested by Rich,[23] obviously this peneplain at the time of deposition must have extended southward and southwestward, with increasing elevation, to connect with outcrops of "Uinta" quartzite that were the source of material. If Cold Spring Mountain was the source, it must have stood at a higher elevation than Diamond Peak, so as to give the necessary gradient for transportation. If the main portion of the Uinta Mountains was the source, Cold Spring Mountain must have had an elevation intermediate between that of the main range and that of Diamond Peak, so as to form part of the slope down which the material was carried. Yet if the pre-Bishop surface is restored by projection southward from Diamond Peak, it is found to pass nearly 2,000 feet above the crest of Cold Spring Mountain, which has a maximum elevation of 8,500 feet. By what means has the present low elevation of its crest been caused? Erosion is dismissed without hesitation, for it is scarcely conceivable that nearly 2,000 feet of hard, cherty Mississippian limestones and red "Uinta" quartzite on Cold Spring Mountain could have been removed, while the soft Eocene beds of Diamond Peak, protected only by the cap of Bishop conglomerate, were practically untouched. In this statement the writer takes issue strongly with Rich,[24] who cites these differences of elevation to support his theory of the resistance of gravel to weathering. In his earlier paper[25] Rich admitted the possibility that the differences were due to downthrow

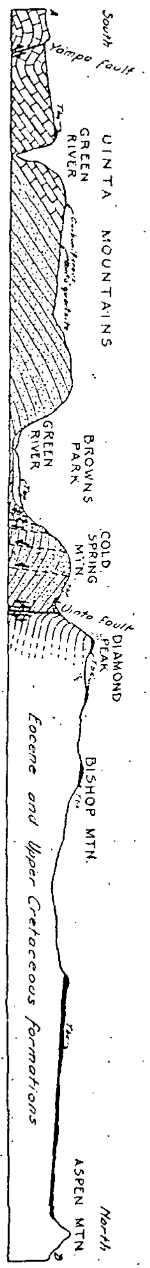

FIGURE 10.—*Geologic Cross-section from the Yampa Fault to Aspen Mountain.*

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[23] J. L. Rich: The physiography of the Bishop conglomerate, southwestern Wyoming. Jour. Geology, vol. 18, no. 7, 1910, pp. 608-613.

[24] J. L. Rich: Gravel as a resistant rock. Jour. Geology, vol. 19, no. 6, 1911, pp. 503-504.

[25] J. L. Rich: The physiography of the Bishop conglomerate, southwestern Wyoming. Jour. Geology, vol. 18, no. 7, 1910, pp. 622-624.

ward for two miles, until it turns once more and, joined by East Fork, crosses the whole series of Mesozoic and Paleozoic strata *against* the dip, finally reaching the Browns Park beds. Its course is marked by two canyons. The larger canyon, about 800 feet deep, is cut through the Park City formation and Weber quartzite. The upturned edges of these formations are truncated by the terrace already described, from which the basal conglomerate of the Browns Park apparently has only recently been partly eroded. The relative position of this terrace and of the Browns Park formation, which now rests on the older rocks on both sides

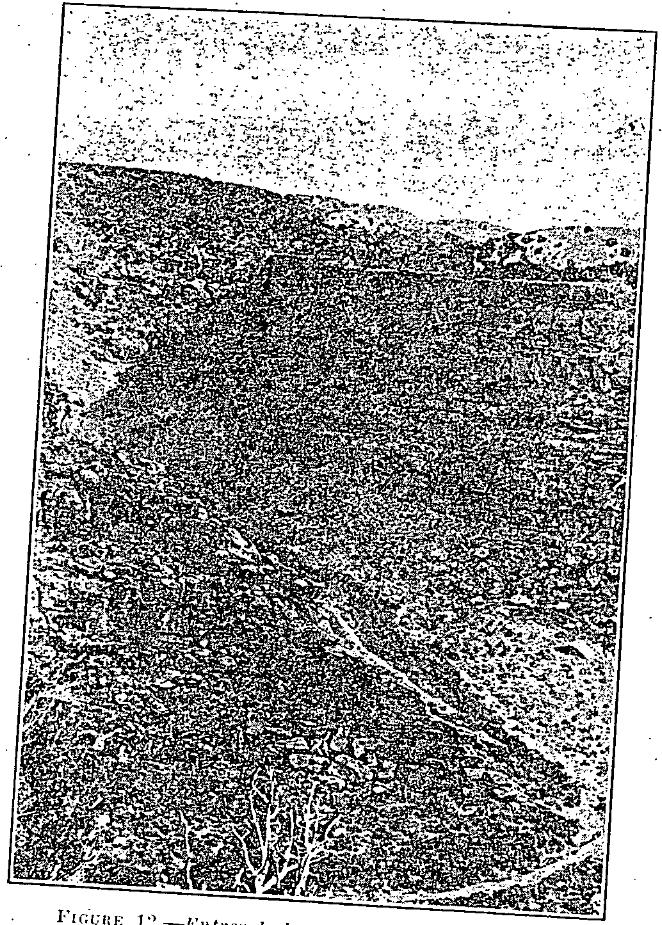

FIGURE 12.—*Entrenched Meanders in Bull Canyon*

The red "Uinta" quartzite is overlain unconformably by white sandstones of the Browns Park formation.

of Vermilion Creek, point unmistakably to a once continuous cover of Browns Park on which the stream first cut its channel.

Another interesting feature of the Vermilion Creek drainage is its illustration of stream piracy. The writer believes that at one time the main stream ran through Irish and Bull canyons, and that later it was beheaded by a branch of East Fork. The bottom of Bull Canyon is somewhat higher and Irish Canyon is several hundred feet higher than the bed of Vermilion Creek. The present channels in Irish Canyon are not those of streams which could carve such a type of valley, and the northern end of the canyon now drains into the interior basin around Irish Lake. Furthermore, Vermilion Creek in its course through the Wasatch heads straight for Irish Canyon, but turns aside where it meets harder rocks. Between this bend and Irish Canyon the position of the old channel is indicated by a wind gap and a reentrant in the conglomerate of the Browns Park formation. In this piracy post-Browns Park tilting was probably an important factor. This tilting was partly the movement shown by the slope of the terrace and partly an inclination toward the southeast, shown by local southeastward dips of the Browns Park between Irish and Bull canyons as compared with the normal southwestward dips elsewhere along its northern contact. Other factors, such as the northwest-southeast strike of the older rocks and the relations of hard and soft strata, helped to permit East Fork to lower its channel more rapidly and by headward erosion of a branch to tap Vermilion Creek above its entrance into the hard rocks.

SUMMARY OF GEOLOGIC HISTORY

The geologic history of the region, based chiefly on the evidence presented in the foregoing pages, may be summarized as follows:

Many thousand feet of sedimentary rocks were laid down with practical conformity through Paleozoic and Mesozoic time. After the close of the Cretaceous the Uinta Mountain arch was uplifted many thousand feet, partly by folding, partly by faulting. Vigorous erosion of the arch during and following the uplift supplied material for the extensive Eocene deposits which filled the Green River and Uinta basins, united around the eastern end of the Uinta Mountain arch, lapped over the outer edges of its flanks, and probably covered the somewhat eroded crest of the low Rock Springs anticline. At some time after the close of Eocene deposition the Uinta Mountain arch was further uplifted. This second movement, though probably of less displacement, covered a wider area, and the axis of the Uinta Mountain arch was continued far southeastward as the Axial Basin anticline. The Eocene strata, which, of course, shared in this movement, are now found dipping away from the folds. At this time or possibly a little later the Axial Basin anticline was further deformed by the sharp domes of Cross and Juniper Mountains.

A long period of quiescence followed, during which the eastern Uinta region was eroded to mature topography. Mountains and ridges were comparatively low and the total relief probably did not exceed 3,000 feet. Strata on the southern flank of the Uinta Mountain arch were beveled; on the opposite side a broad peneplain stretched northward from the eastern part of the arch and from the Axial Basin anticline, truncating Eocene and older rocks and perhaps merging with the peneplain on the southern flank of the Wind River Mountains, described by Blackwelder.[26] Owing to higher elevation or to fracturing, the crest of the Uinta Mountain arch was subject to more rapid erosion, and there began the carving of the great intermontane valley of which the lower part is now known as Browns Park. The headward extension of this valley far beyond the present limits of the park is indicated by the terrace above the canyons of Green River upstream from the park and by the westward continuation of the cliffs that mark its south wall. Browns Park valley opened eastward across the site of Dry Mountain and merged with the northward-sloping peneplain, from which it was separated farther west by a low range of hills. High on the south flank of the arch was a similar but lesser valley, the "Summit Valley" of Powell,[27] that drained eastward and probably turned southeastward along the line of the present Lodore Canyon. The Axial Basin anticline was deeply eroded and Cross and Juniper Mountains were left as isolated masses of much the same appearance as they have today.

Climatic changes or, more probably, regional uplift caused a rejuvenation of the streams, which began a vigorous attack on the red quartzite core of the Uintas. Some material was carried from the eastern part of the arch, and the Browns Park valley was greatly deepened; more was brought from the higher western part of the range. There resulted a great outpouring of red quartzite boulders, which were laid down as conglomerate eastward to Little Snake River and northward for many miles over the broad peneplain. On the south flank of the arch the hollows were filled and the beveled surface was partly covered. As time went on, streams lost some of their carrying power and brought white sand derived from the quartzite. Browns Park became filled with a great thickness of this sand, which spread up the valley by headward overlap beyond the earlier deposits of conglomerate. Overlap also gradually covered the slopes of the hills and mountains eastward to and including Cross and Juniper Mountains, until in all the eastern part of the Uinta Range only the highest remnants of the older rocks protruded above the cover of white sand.

If this period of deposition had been succeeded by further arching or by regional uplift, drainage would have followed the same directions if not the same channels, as before, and the conglomerate and sandstone would have been largely swept away by rejuvenation of the streams that made them. In Browns Park time, however, tilting on the south side of Cold Spring Mountain served as the forerunner of a new type of movement, and after deposition was complete the eastern end of the Uinta Mountain arch collapsed, forming a great graben. The collapse was caused by a single large fault on the south, by flexures and distributive faulting on the north, by tilting and some faulting on the east, and by tilting on the west. Along the margins of the graben the Browns Park formation was given an inward dip by upward drag on the faults. As far east as Cedar Mountain, the Browns Park formation was tilted westward toward the drag syncline which lies just north of the Yampa fault. Guided by this sloping surface and this syncline, the drainage of the Axial Basin anticline naturally formed a westward-flowing major stream—Yampa River. Its course over the covered portions of Cross and Juniper Mountains was accidental.

The eastern part of the Uinta Mountains had previously stood at a lower elevation than the western part. By collapse, this difference was greatly increased, and a vigorous stream, the young Green River, began its eastward course approximately above the old Browns Park valley. A northward turn was barred by Cold Spring Mountain and by fault-scarps on the north side of the graben. The river may have continued southeastward to the end of the arch, there turning southward in the syncline west of Cross Mountain to join the Yampa. In this case Lodore Canyon may be due to headward erosion and piracy by a stream which ran southward in the slight depression left after filling of the lower portion of Summit Valley. On the other hand, if the white sandstone was thick enough to cover the site of Lodore Canyon, Green River may have originally turned southward along this line, being diverted by the westward tilt of the Browns Park formation. The thickness of sandstone needed to cover Lodore Canyon seems to argue against the second possibility, but the entrenched meanders of Lodore Canyon and the topography in its vicinity point to superposition rather than to headward erosion.

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[26] Eliot Blackwelder: Post-Cretaceous history of the mountains of central western Wyoming. Jour. Geology, vol. 18, no. 3, 1915, pp. 193-207.

[27] J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto. Atlas, Map A, 1876.

North of the graben the streams flowed down a northward-sloping surface of Browns Park sandstone, in time cutting to the basal conglomerate of that formation, which covered the old peneplain. They may have drained into a river which skirted the edge of the peneplain in the low ground, where it merged with the peneplain on the southern flanks of the Wind River Mountains. Owing to low gradient and the fact that these streams were running on dip slopes, erosion was comparatively slow. On the other hand, tributaries of Green River, such as Vermilion Creek, had steep gradients into the graben and could attack and undermine the edges of the northward-dipping strata. By such rapid headward erosion Vermilion Creek succeeded in capturing a part of the northward drainage. By the same method Green River may have grown northward, capturing the major drainage of Green River basin and diverting it southward through Browns Park and Lodore Canyon. (This hypothesis is supported by the present course of Red, Sage, and Salt Wells creeks, which, as shown on figure 1, flow northward and then westward before joining Green River. Such courses suggest that these streams were originally tributaries of a river which did not flow southward to the Uinta Mountains. The absence of similar anomalies in the upper part of Vermilion Creek may be due to lateral planation during a period of temporary baselevel, when the lower part of the stream first cut down into hard rocks.) Meanders in Green and Yampa rivers that are now deeply entrenched may have developed during a period of temporary baselevel, caused, perhaps, when Green River cut through the overlying Browns Park formation and encountered the hard rocks of Split Mountain.

With the courses of the rivers once firmly established in the Browns Park beds, only time was needed to lower their channels and carve out their wonderful canyons.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 35, PP. 305-320 JUNE 30, 1924

IGNEOUS ROCKS OF ITHACA, NEW YORK, AND VICINITY[1]

BY J. H. C. MARTENS[2]

(Presented before the Society December 30, 1922)

CONTENTS

INTRODUCTION

Although dikes in the region about Ithaca have been known for many years, neither extended petrographic study of them nor reliable chemical analyses have been published. In view of the unusual nature of the rock and the isolation from other igneous intrusions, a somewhat more detailed investigation of the occurrence of these dikes and their chemical and mineral composition seemed desirable. The results of this investigation are presented in greater detail in a thesis deposited in the library of Cornell University.

REVIEW OF LITERATURE

The first known record of the igneous intrusions in the small area under consideration is that by Vanuxem[35, 36] concerning the dikes at Ludlowville. The dikes at Syracuse and in East Canada Creek, near Manheim, were noted at about the same time.

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[1] Manuscript received by the Secretary of the Society June 27, 1923.

[2] Introduced by A. C. Gill.

W Lee Stokes

CRETACEOUS STRATIGRAPHY AND FACIES PATTERNS — NORTHEASTERN UTAH AND ADJACENT AREAS

LYLE A. HALE and
FRED R. VAN DE GRAAFF

INTRODUCTION

The Cretaceous rocks of northeastern Utah and adjacent areas were deposited along the west-central margin of a large sedimentary basin that extended from the Gulf of Mexico to the Arctic Ocean and eastward to the central plains. At the present time these deposits are preserved within the various deep synclinal basins, typically the Uinta Basin of northeastern Utah and the Green River Basin of southwestern Wyoming, that were formed along adjacent mountain uplifts during the Laramide orogeny. Anticlinal uplifts for the most part have been eroded into Cretaceous or older rocks leaving on their flanks excellent although discontinuous exposures for study.

These isolated outcrop areas have been thoroughly studied and described by many authors since the territorial surveys. Consequently, a complex stratigraphic nomenclature has evolved as type locality names were applied by the various geologists in their particular areas of study. Only in recent years has subsurface and faunal control become sufficient to portray with reasonable accuracy the regional stratigraphic framework and paleogeographic conditions.

LYLE A. HALE is presently employed as a staff geologist by Mountain Fuel Supply Company. His academic training in geology was received at Utah State University where he was graduated with a B.S. degree in 1948. He continued his geologic studies at the University of Wyoming and was awarded his M.S. degree from this school in 1950. Throughout the latter portion and immediately following his academic training the author worked part-time as a geological assistant for the U. S. Geological Survey and as a field geologist for Amerada Petroleum Corporation. In 1951 he became associated with Mountain Fuel Supply Company. The writer is well known in the Rocky Mountains through six previous publications dealing with Upper Cretaceous stratigraphy. These papers have appeared in guidebooks of the Wyoming Geological Society and the Rocky Mountain Association of Geologists. He also coedited the 1961 guidebook for the Wyoming Geological Society. Mr. Hale resides in Bountiful, Utah, and is affiliated with the American Association of Petroleum Geologists, Wyoming Geological Society, Rocky Mountain Oil & Gas Association, and the Intermountain Association of Petroleum Geologists (President, 1963; First Vice-President, 1962).

FRED R. VAN DE GRAAFF is a geologist employed by Mountain Fuel Supply Company. He received his geologic training at Utah State University. He was graduated from this institution with a B.S. degree in 1959 and an M.S. degree in 1962. While in graduate school he worked for Mountain Fuel Supply Company as a geologist during the summers. Upon receiving his M.S. degree he became employed full-time by Mountain Fuel. The writer has published a previous paper dealing with Upper Cretaceous stratigraphy which appeared in the 1961 guidebook of the Intermountain Association of Petroleum Geologists. Mr. Van De Graaff presently resides in Vernal, Utah.

The primary purposes of this paper are to: (1) show the relationship between basinal and provenance tectonisms and sedimentary facies patterns, (2) illustrate and briefly describe the paleogeography and stratigraphic framework of this part of the Cretaceous sedimentary basin, and (3) demonstrate basin to basin continuity of lithogenetic units by strandline correlations and faunal control. Figure 1 is an index map of the subject area showing the major tectonic features, the Cretaceous outcrop areas in key section localities and their location with respect to major towns and other reference points. The approximate Mesaverde-Mancos facies boundary is indicated by a dashed line.

METHODS OF ILLUSTRATION

In this study five different facies and corresponding depositional environments are recognized, as modified after Spieker (1949). Symbols as shown on figure 2, have been used in construction of the lithofacies maps and restored sections that correspond to the dominant lithology in a particular formation or facies. Nine significant transgressions and regressions of the shoreline are designated from oldest to youngest T_1 through T_9; R_1 through R_9 adopted after Weimer (1960).

The restored sections were constructed from an integration of all electrical log data in basinal areas which were tied to faunally controlled stratigraphic sections in key outcrop areas. In each case, the youngest or best controlled marine transgression was used as a reference plane. Except for slight vertical exaggeration of significant thin beds, the sections above and below the datums were plotted to scale. The Cretaceous-Tertiary boundary is difficult to define especially in the subsurface. Therefore, the remaining thickness of the Cretaceous section below the boundary is arbitrary in some areas. Detailed formational descriptions are beyond the scope of this paper. Rather, the authors have attempted to demonstrate only the gross facies

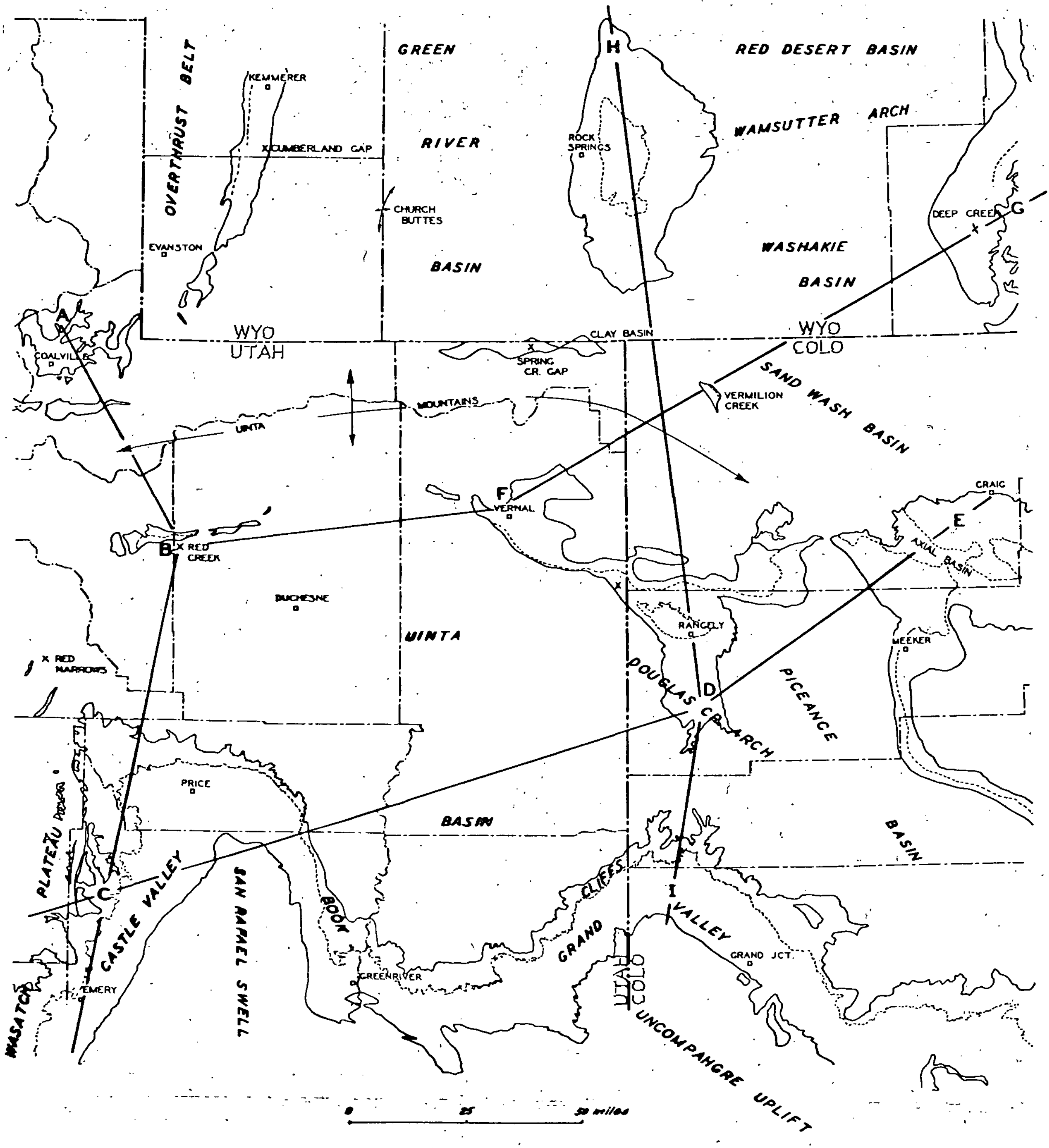


FIGURE 1.—Index map Uinta Basin and adjacent areas showing Cretaceous outcrop areas and positions of restored stratigraphic sections.

relationships and salient features of the depositional history and reference is made at appropriate times to the wealth of detailed published information. The Wasatch Plateau-Book Cliffs area is the focal point of the discussions. With a few exceptions the stratigraphic nomenclature in these areas will be used and then related to lithogenetic equivalents elsewhere. In discussing geologic ages, American provincial nomenclature will be used. Their equivalent European provincial ages may be noted by referring to figure 3.

REGIONAL STRATIGRAPHIC SETTING AND FRAMEWORK

During deposition of Cretaceous sediments, the subject area (fig. 1) was a part of the marginal depositional site on the western border of the shallow sea. Throughout the Cretaceous a principal tectonically active provenance encroached eastward across north-central Utah as an allochthonous feature or a series of wavelike folds and imbricate thrusts. This feature has been described by Eardley (1934), Baker (1947), and Bissell (1952). Its final basinward surge along the Deer Creek and Strawberry thrusts carried this feature to the western margin of the map area in Late Cretaceous time. The periodic uplifts and eastward movements of this provenance was a major factor in the development and configuration of facies patterns in the depositional basin to the east. A thick varied sequence of coarse clastic rocks was deposited in a foredeep parallel to the provenance. Finer clastics were then carried eastward across alluvial fans, floodplains, and swamps by stream systems that discharged their sediments into the shallow epicontinental sea. Periodic pulses of subsidence in a continually downwarping depositional site, not only provided space for deposition and preservation of sediments but triggered widespread transgressions of the sea over bordering lowlands. These opposing crustal movements (uplift of the source areas and downwarping of the basin) were the primary forces responsible for the intricate intertonguing framework of the Cretaceous rocks. In general, during the early part of Cretaceous time the dominant sedimentary trend was transgression of the sea as reflected by the progressive westward shift of the shoreline and associated environments. In the middle Late Cretaceous, the cycle reversed with regressive, eastward movements predominating until the close of the Cretaceous. This general pattern was interrupted frequently by minor but

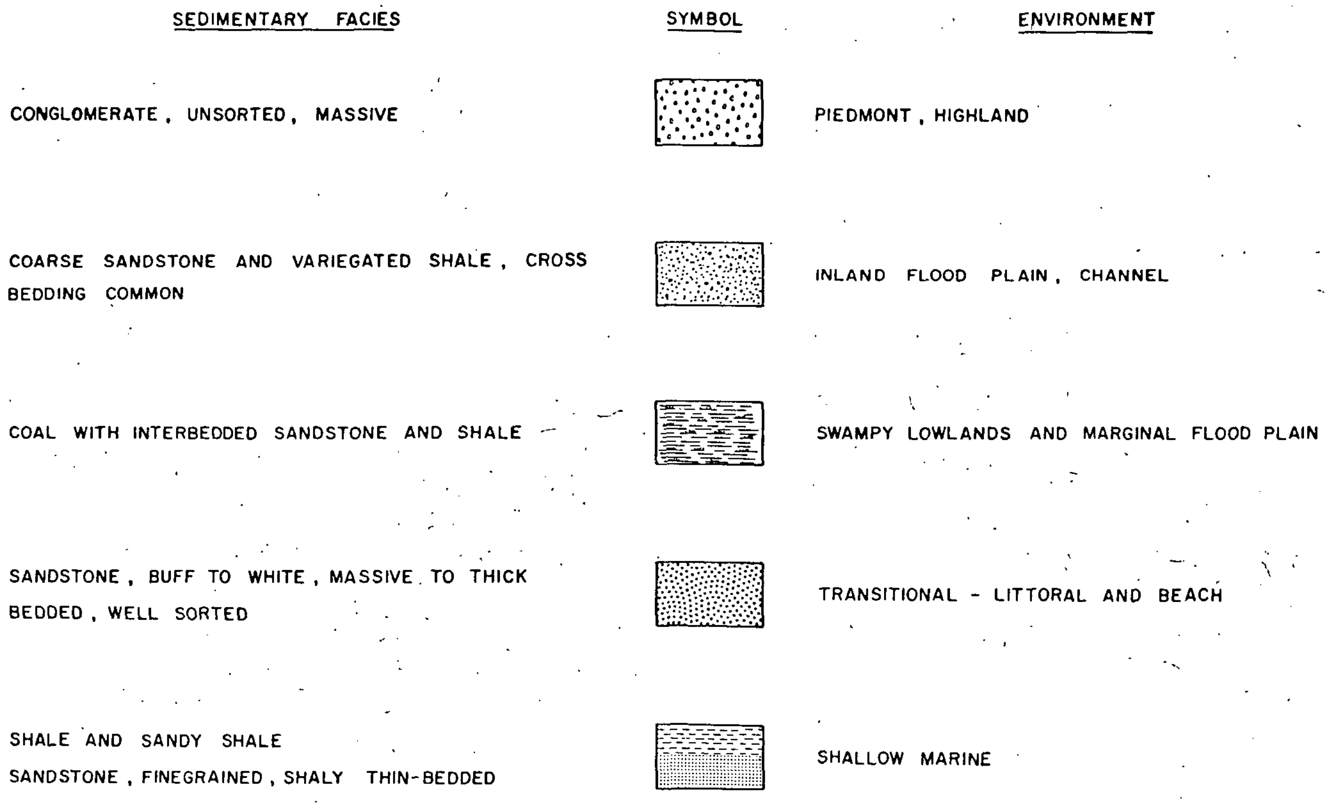
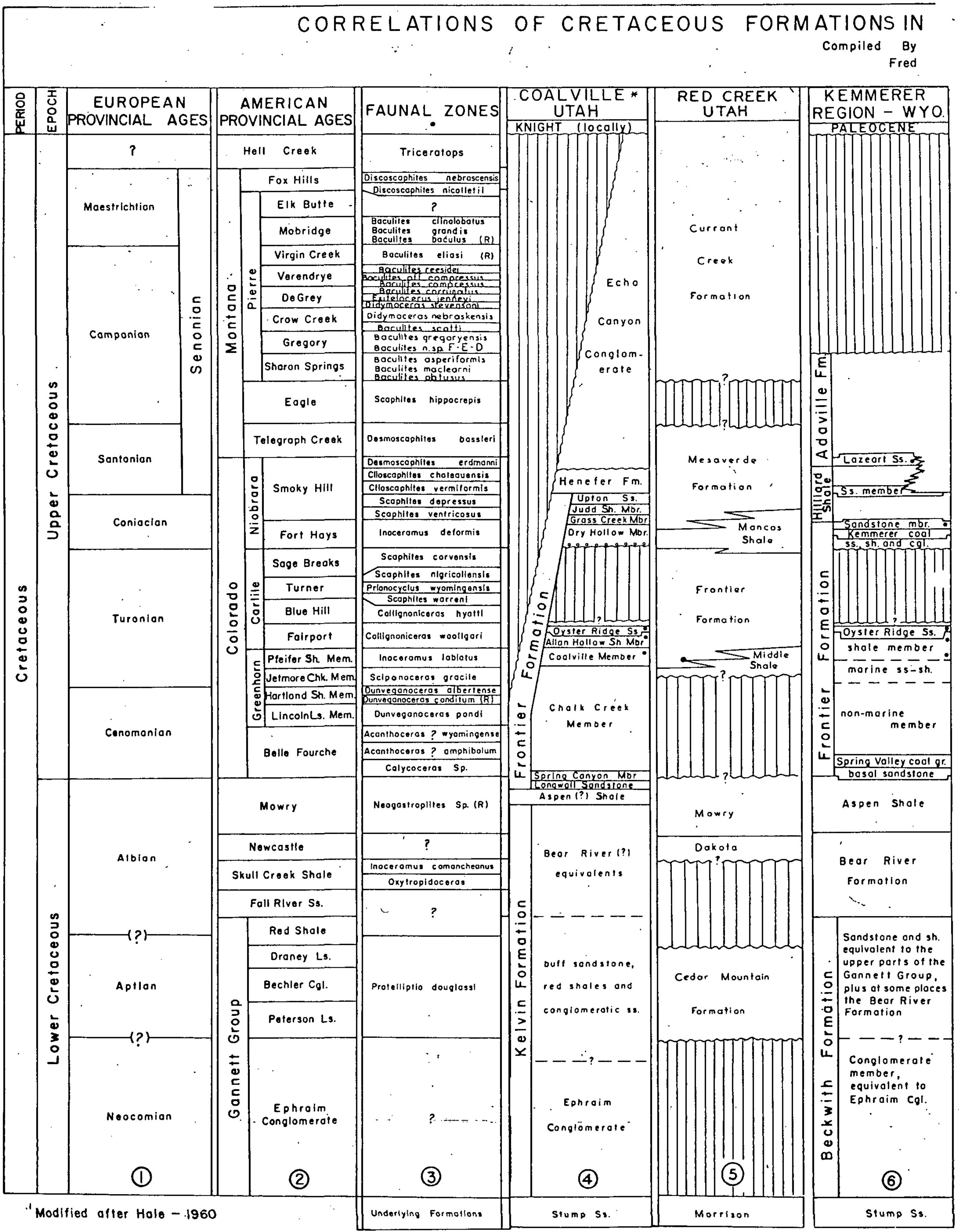


FIGURE 2.—Legend showing facies symbols used on all maps and cross sections.



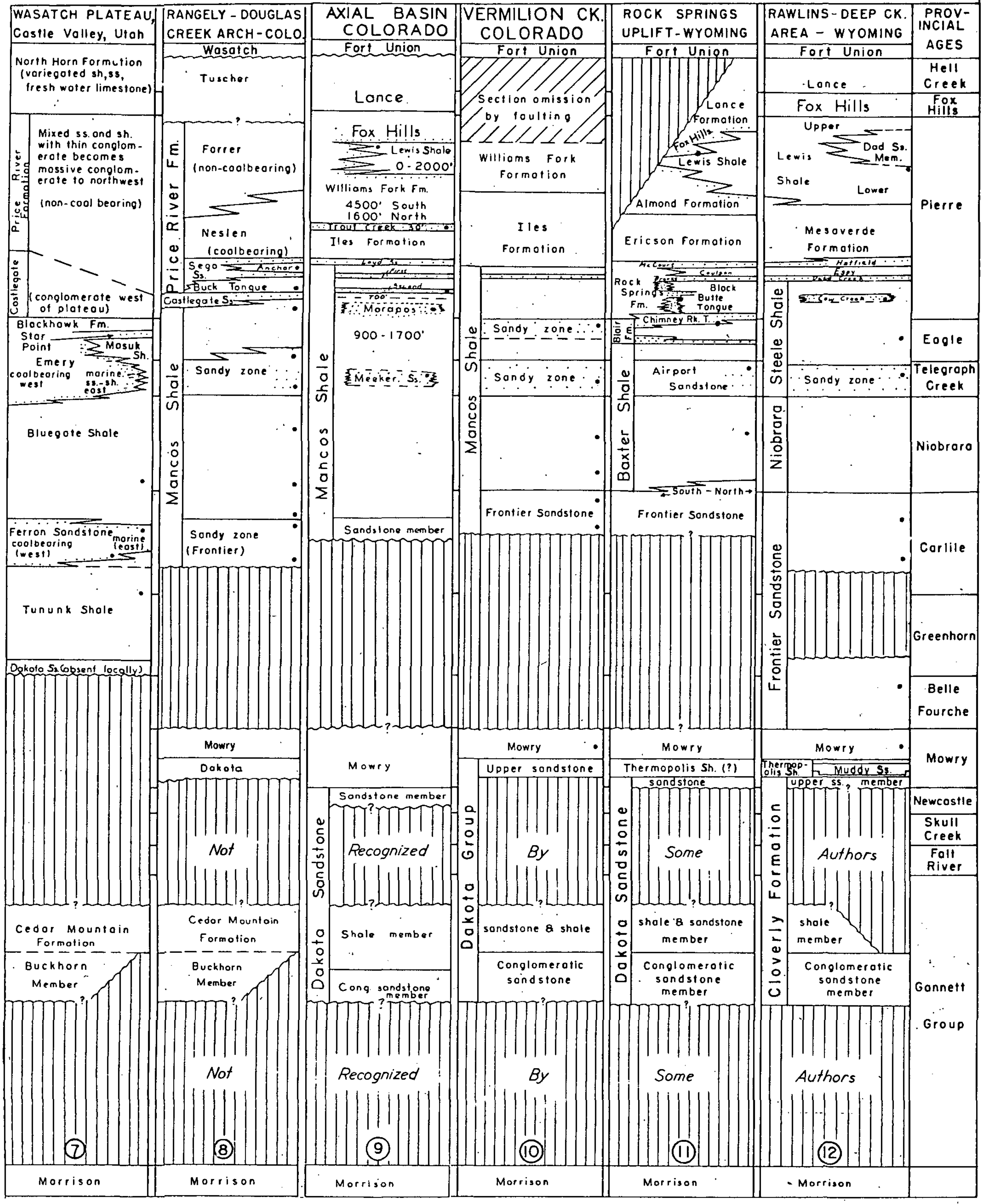
¹ Modified after Hale – 1960

* For detail refer to Hale (1960-62)

FIGURE 3.—Correlations of Cretaceous formations in adjoining areas of Wyoming, Utah, and Colorado.

ADJOINING AREAS OF WYOMING UTAH AND COLORADO PLATE I

L. A. Hale
Van De Graaff



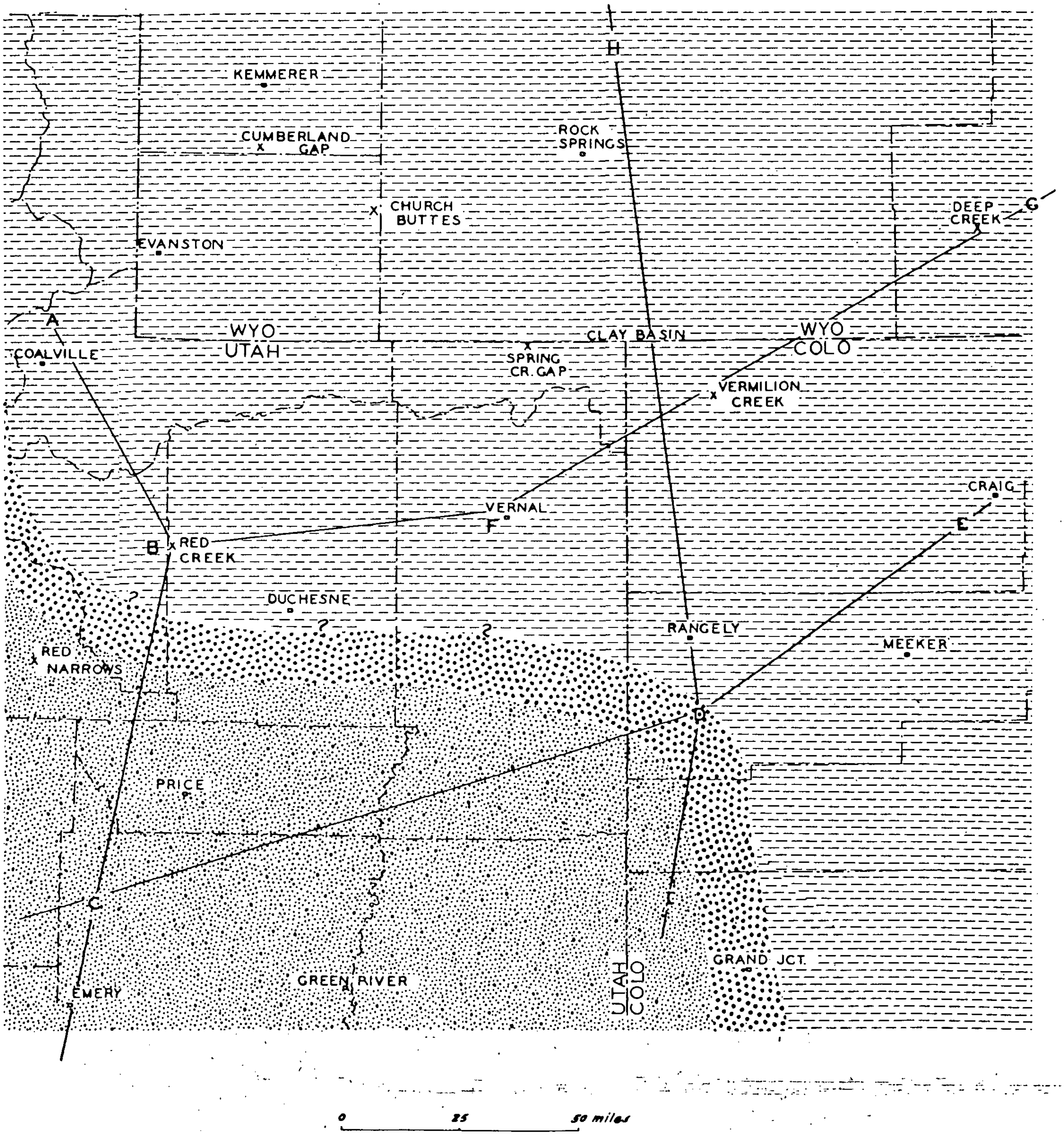


FIGURE 4.—Lithofacies map of Mowry-Aspen transgression T1.

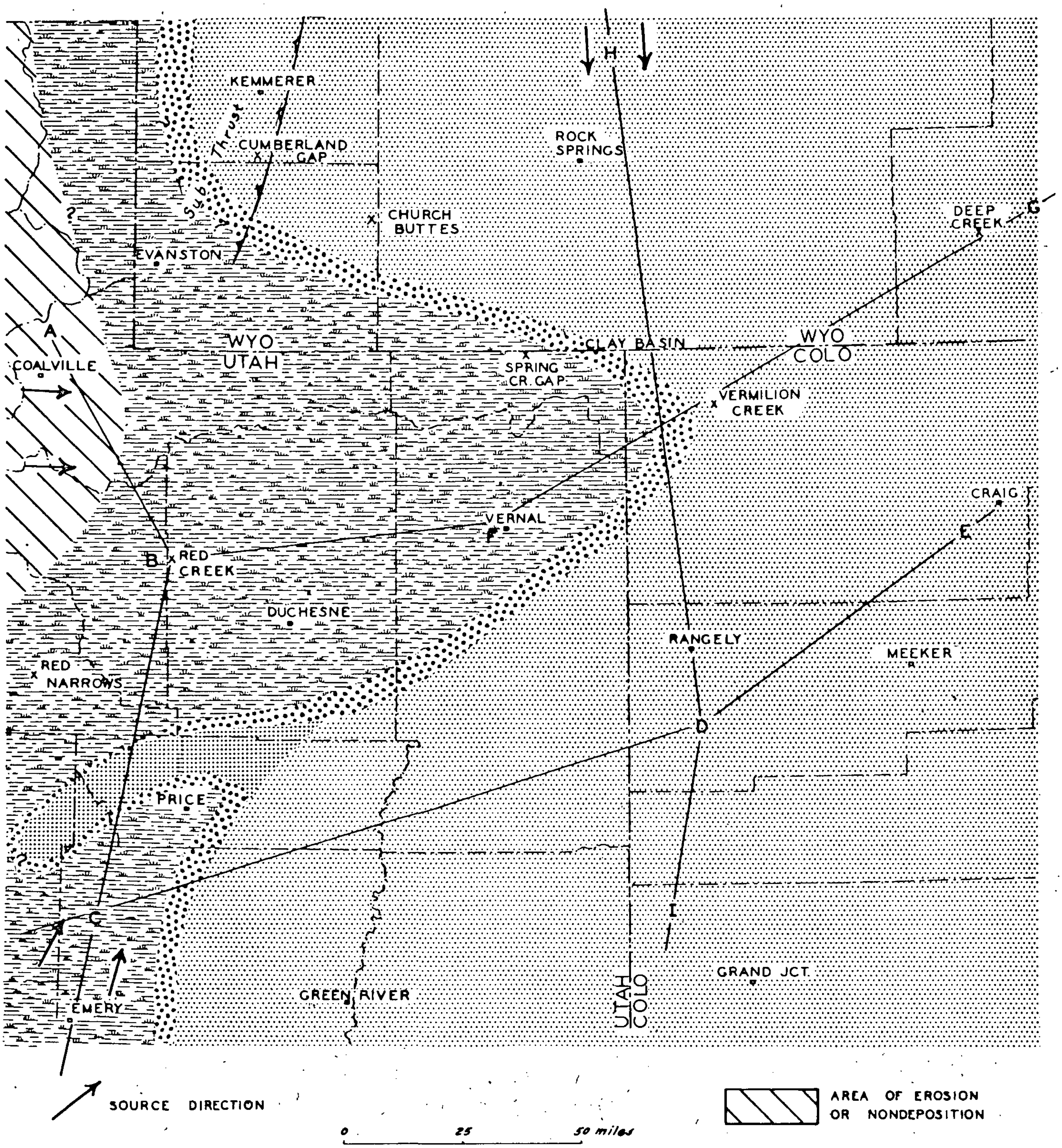
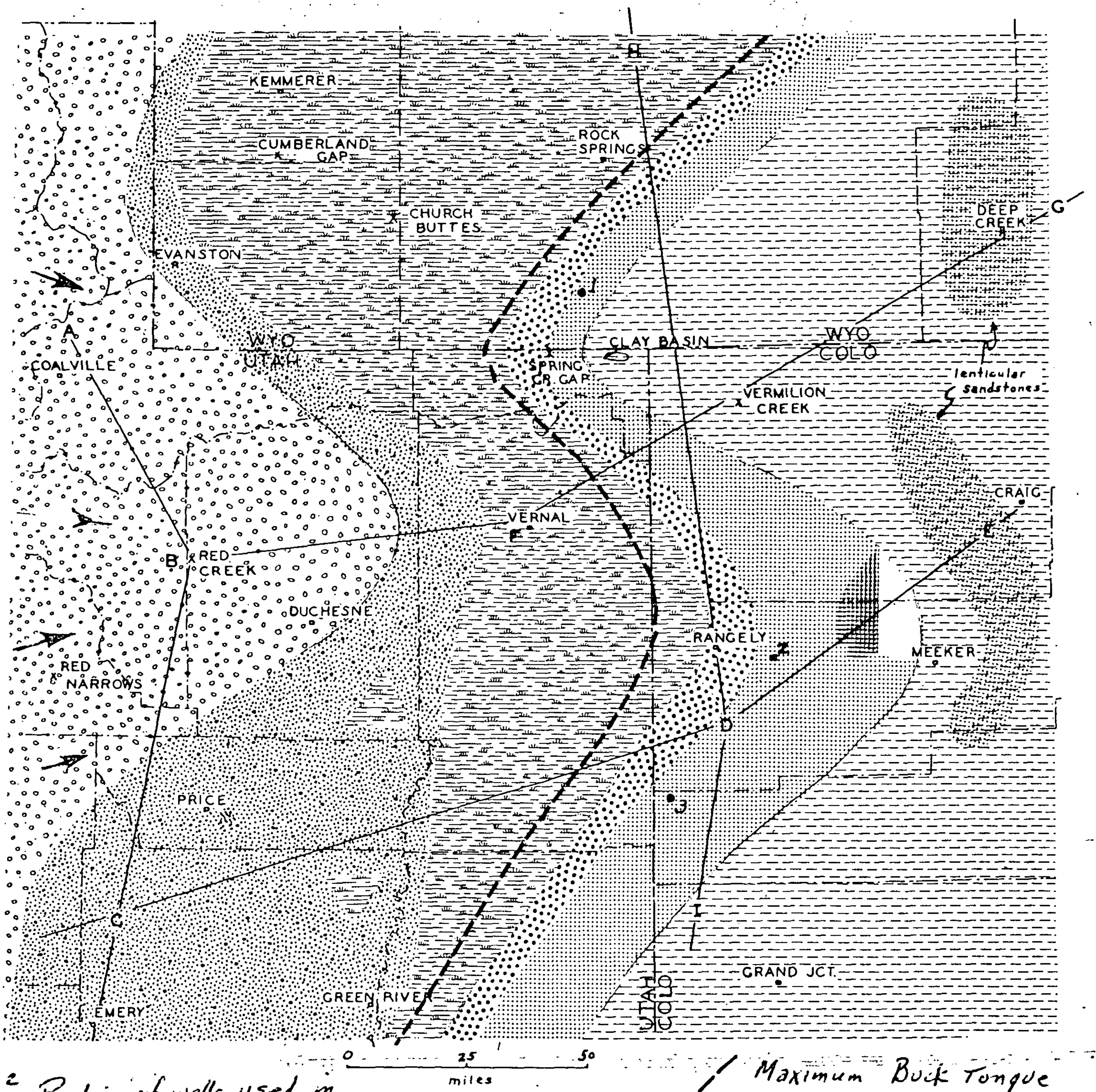


FIGURE 5.—Lithofacies map of Frontier-Ferron regression R2.



•² Position of wells used in Correlation Fig. 12

/ / Maximum Buck Tongue Transgression

FIGURE 6.—Lithofacies map of Castlegate Sandstone and equivalents.

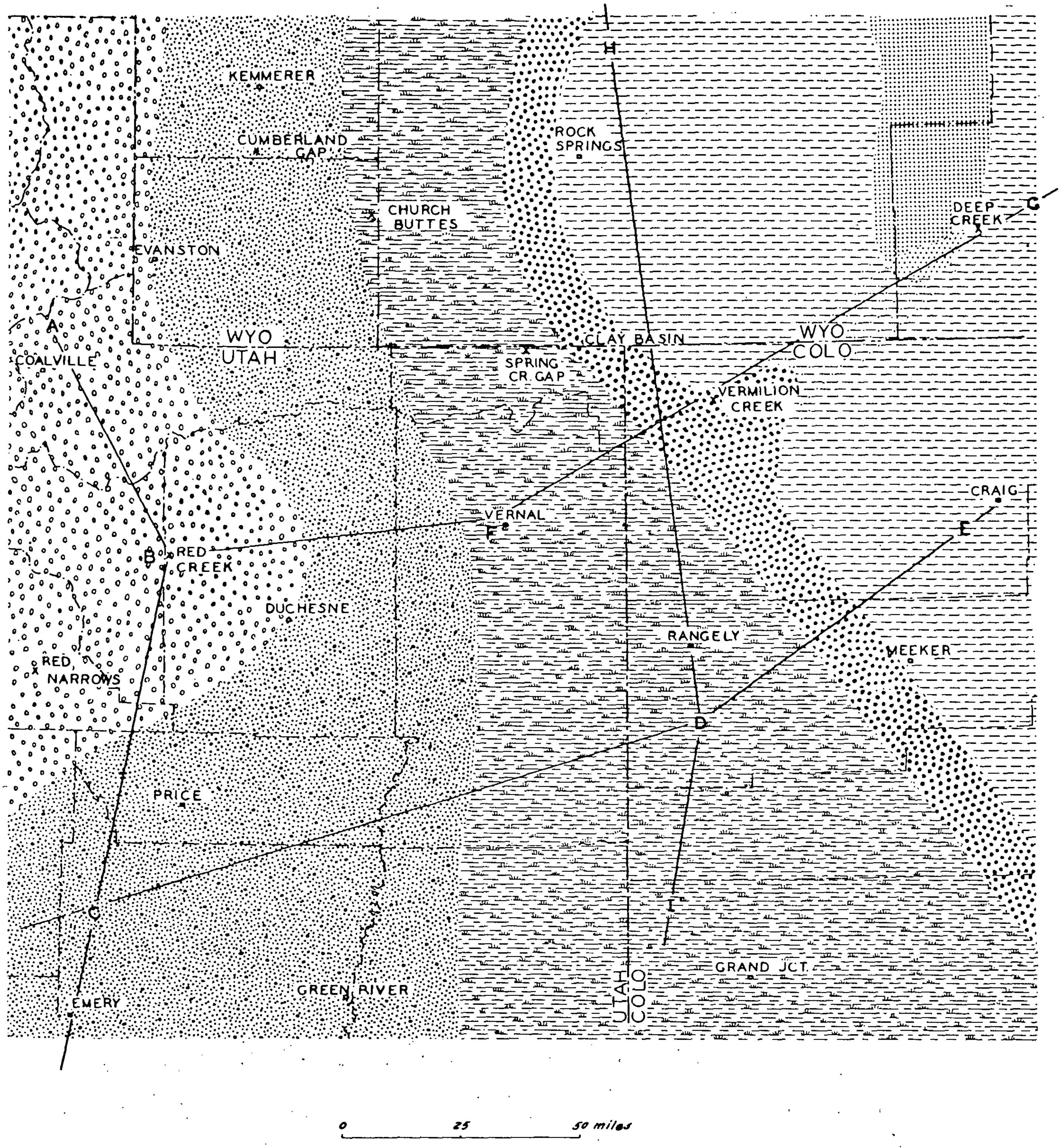
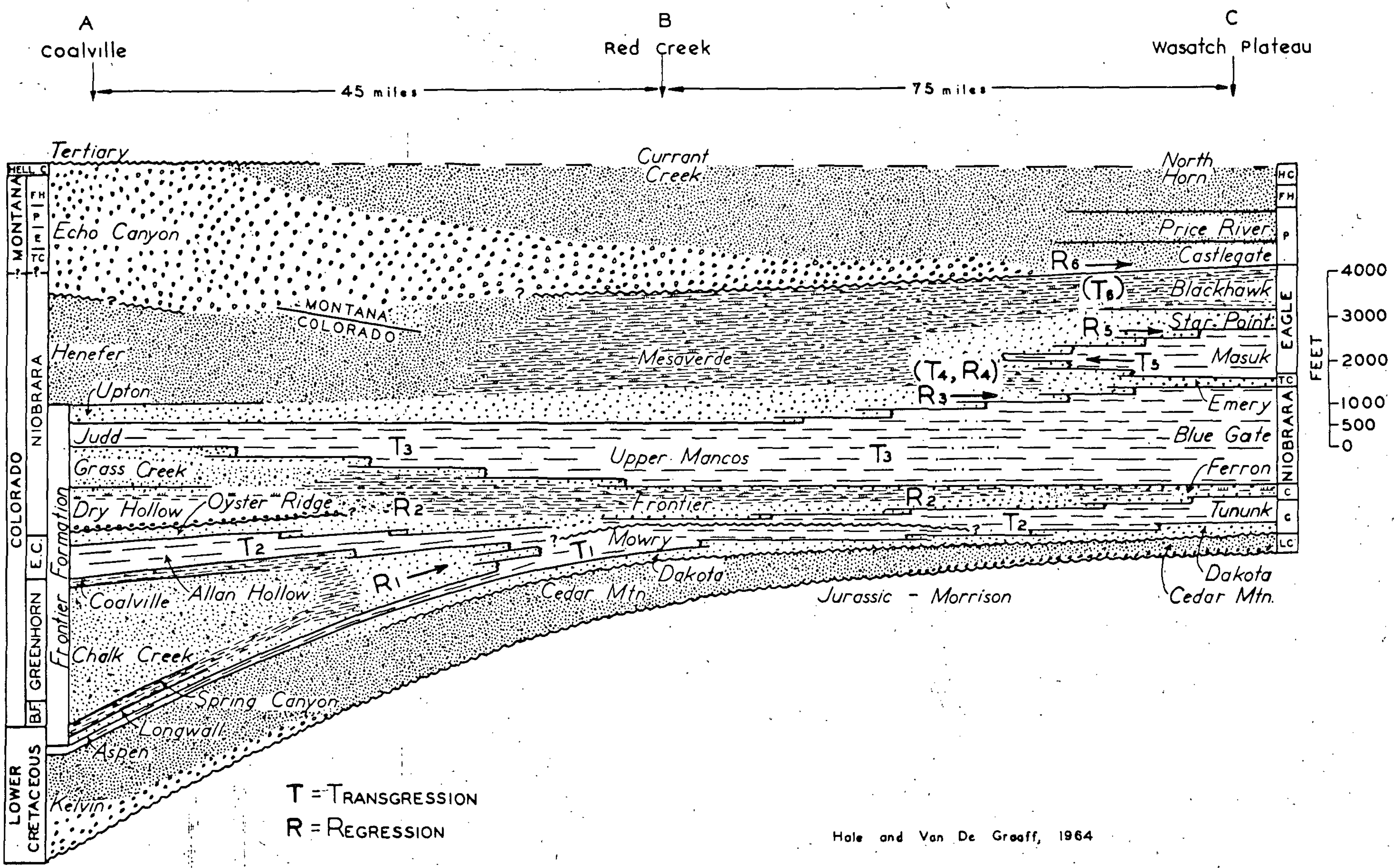


FIGURE 7.—Lithofacies map of Lewis Shale and equivalents, trangression T9.



Hale and Van De Graaff, 1964

FIGURE 8.—Diagrammatic restored section of Cretaceous rocks, Coalville to Wasatch Plateau, Utah.

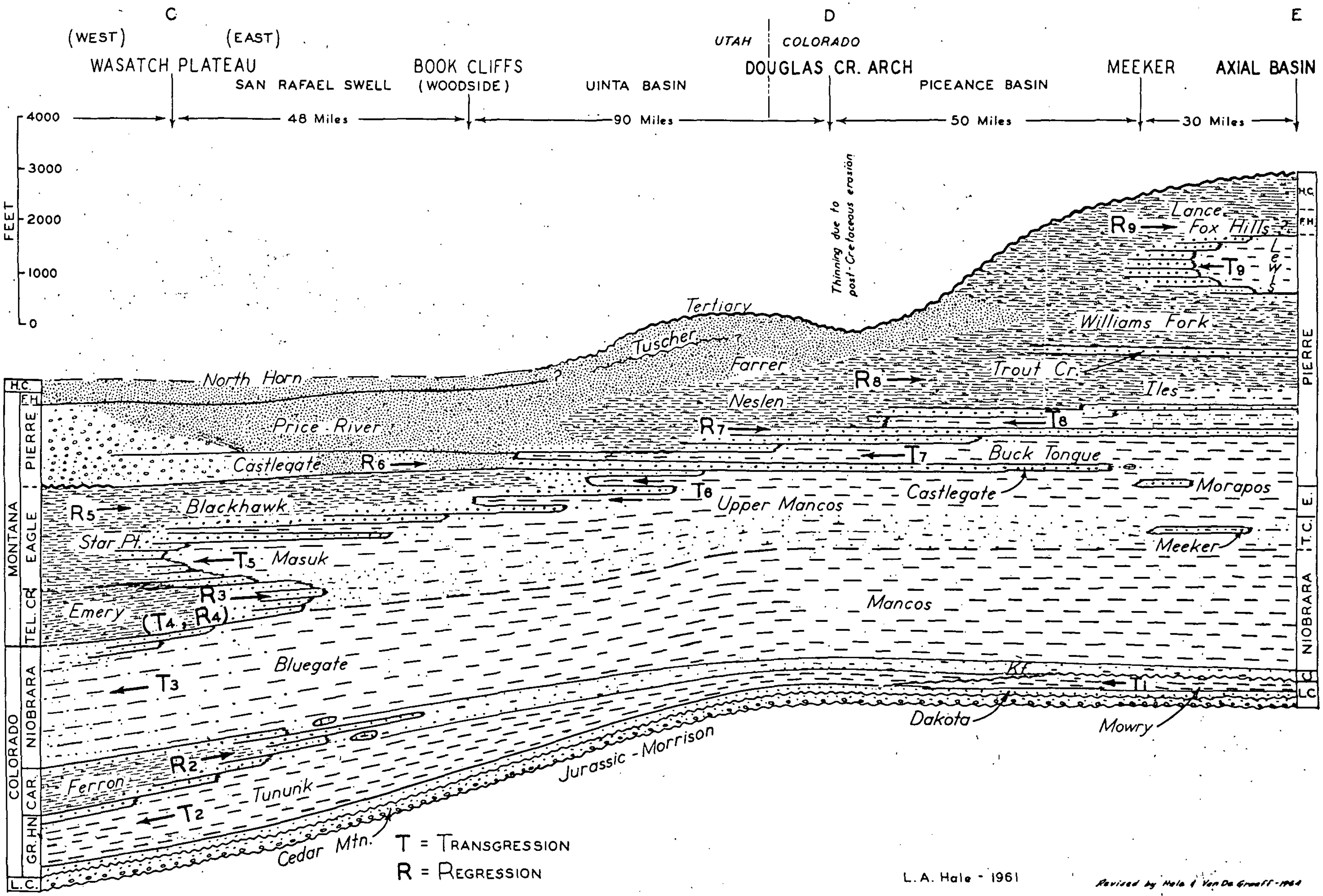
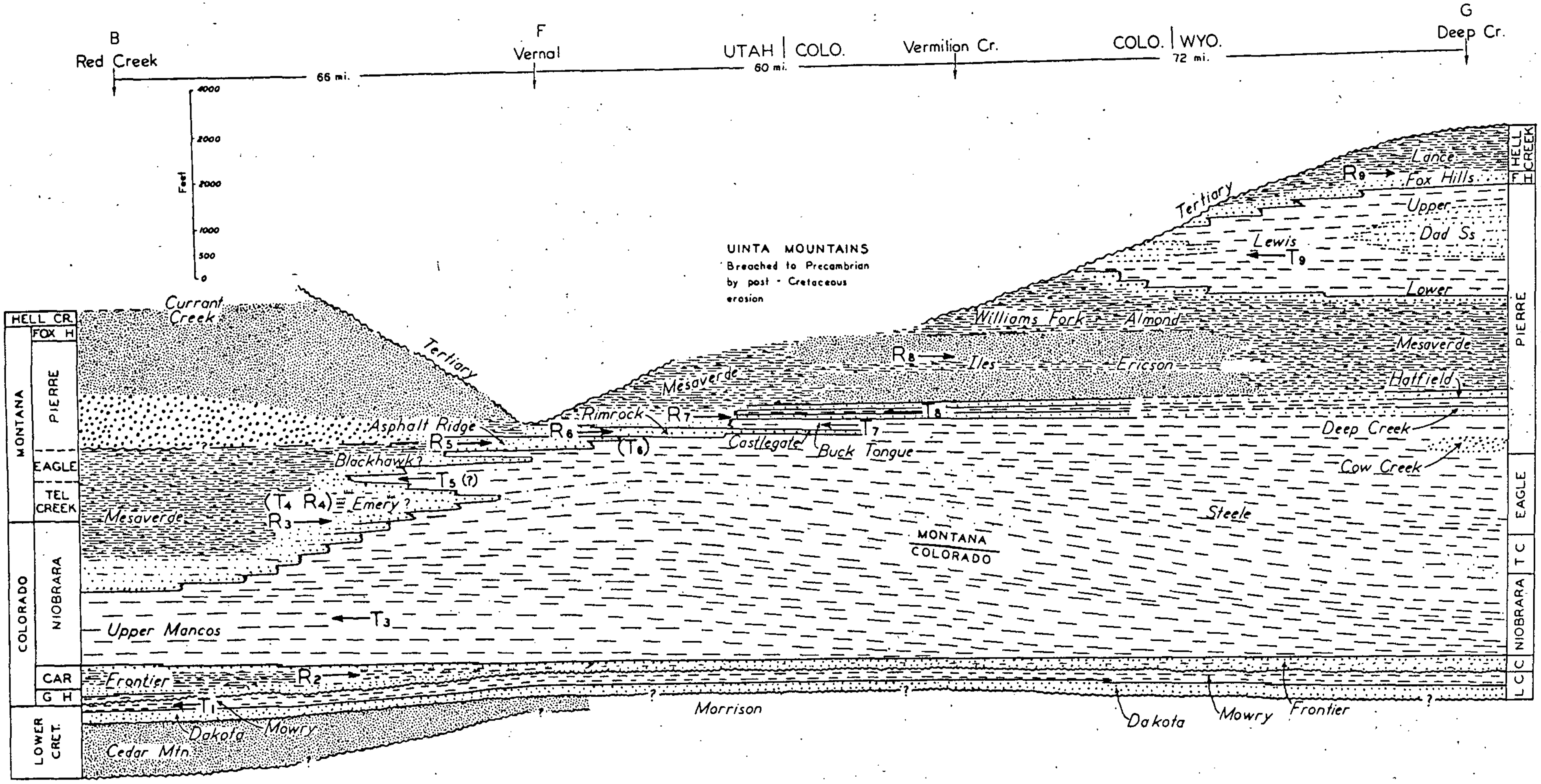


FIGURE 9.—Diagrammatic restored section of Cretaceous rocks, Wasatch Plateau, Utah to Axial basin, Colorado.



T = Transgression
R = Regression

Hale and Van De Graaff, 1964

FIGURE 10.—Diagrammatic restored section of Cretaceous rocks, Red Creek, Utah to Deep Creek, Wyoming.

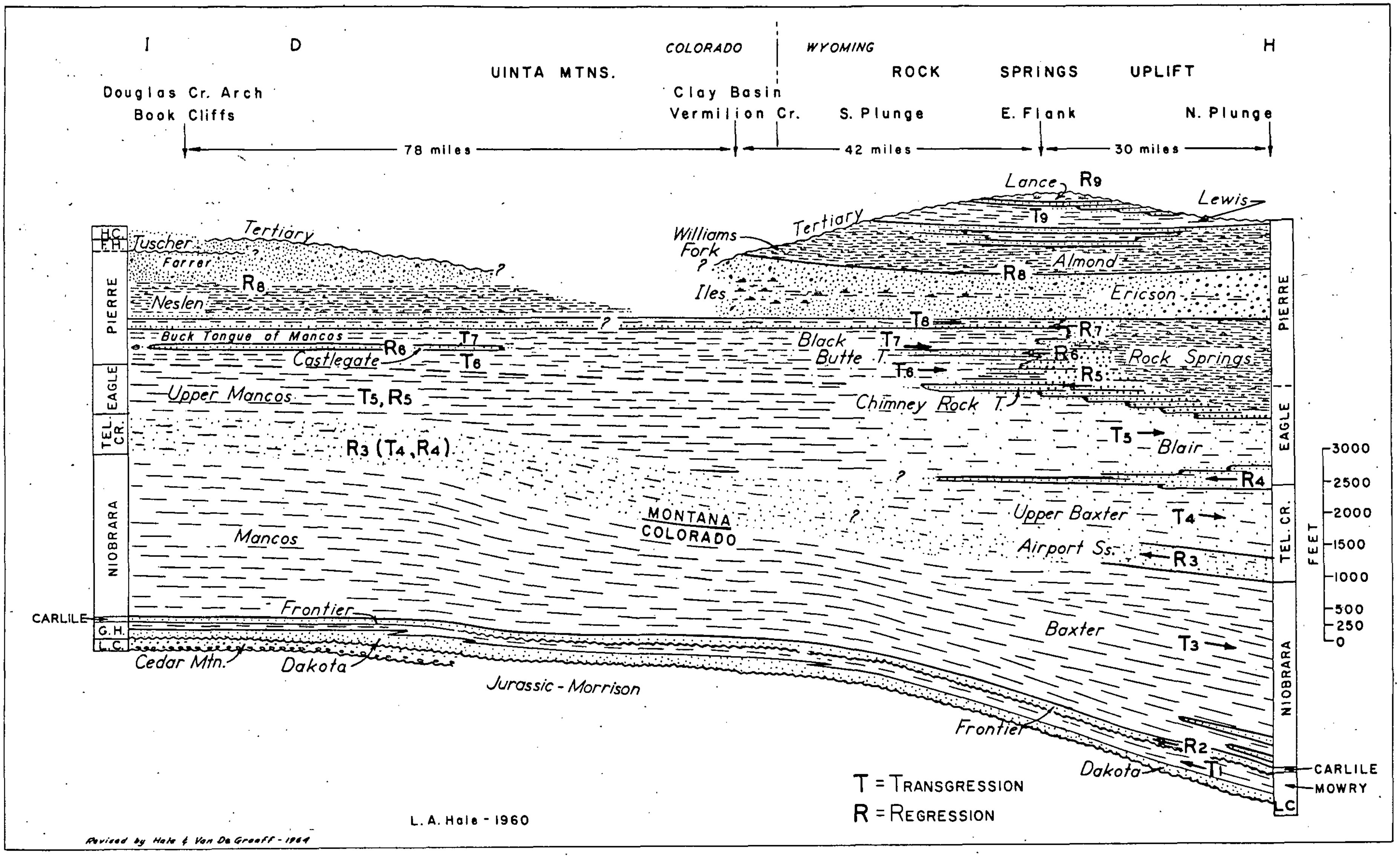


FIGURE 11.—Diagrammatic restored section of Cretaceous rocks, Douglas Creek arch, Colorado to Rock Springs uplift, Wyoming.

significant transgressions and regressions of the shoreline. Actual separation of the area into the present tectonic framework did not occur until the Laramide (post-Cretaceous) orogeny, although embryonic growth of the Uinta Mountain and Douglas Creek arches, and renewed movements of the Uncompahgre uplift can be detected by isopachous mapping.

LOWER CRETACEOUS

General Statement.—The Early Cretaceous history of the region is recorded by a relatively thin sequence of rocks. Considerable controversy exists in present literature regarding depositional history and particularly in regard to the Jurassic-Cretaceous boundary. Stokes (1944, p. 951) first defined a fluviatile bed-red sequence in east central Utah (formerly assigned to the Morrison Formation of Jurassic age) to the Lower Cretaceous and named these rocks the Cedar Mountain Formation (with a basal Buckhorn Conglomerate Member). He recognized these rocks at nearly every outcrop locality in the map area and correlated them (in part) with the thick Kelvin Formation at Coalville. Other authors (Haun, 1959, and Weimer, 1962) demonstrate a south-southwestward intertonguing relationship between the Dakota-Mowry sequence and beds in the upper Morrison of Lower Cretaceous age. Without reviewing all the detailed interpretations and evolution of stratigraphic nomenclature, the interpretation most logical to the writers is as follows:

Mowry Shale.—At the beginning of Early Cretaceous time, the map region was dominantly a land area of fluviatile red-bed deposition which persisted with some local hiatuses until late Mowry. The invasion of the Early Cretaceous sea (T_1) transgressed across southern Wyoming and northwestern Colorado and reached its maximum extent at the Douglas Creek arch and central Uinta Basin in latest Mowry (fig 4). The transgressive shoreline deposit is the Dakota Sandstone. Its relationship to the underlying red beds probably varies locally from reworked and intertonguing to depositional onlap. The zero position of the Mowry is well controled in northwest Colorado but due to depth of burial cannot be delineated across northern Utah. Figure 4 depicts the largely inferred paleogeographic setting and facies patterns during Mowry deposition. The Mowry thickens gradually to the east and northeast into Colorado and Wyoming but the main axis of deposition was in southwestern Wyoming, where equivalent shales, called the Aspen, attain a thickness of 2,000 ft. Over most of the map area a significant unconformity separates the Mowry from the overlying Frontier (fig. 3).

The environment of the Mowry sea was conducive to abundant marine life. Characteristic fauna *Neogastroplites* and others accurately date these rocks.

UPPER CRETACEOUS

General Statement.—Earliest Upper Cretaceous rocks are apparently represented only in the western parts of the region. The initial regressive cycle recorded in the Upper Cretaceous probably began in latest Mowry as fluviatile deposition of the lower Frontier (R_1) at Coalville, Utah, and at Cumberland Gap, Wyoming (Hale, 1963), and extends through the Belle Fourche epoch (fig. 3). Except for isolated localities at Grand Junction, Colorado, and Rawlins, Wyoming, rocks equivalent to this age are probably missing.

In Greenhorn and early Carlile time the second marine transgression inundated the region. This transgression marked the beginning of a long period of sustained marine shale deposition in the eastern part of the area that makes up the main body of the Mancos Shale. Its thickness ranges up to 5,000 ft. and spans all of Colorado and lower half of Montanan time. Westward and northwestward the Mancos marine shale faciès intertongues with wedges of nonmarine and marine sandstone facies. These units have all been assigned local formation (or facies) names as indicated on the restored sections (figs. 8 and 11). Still farther west, these nearshore facies thicken in the foredeep area and grade to a fluviatile sandstone and conglomerate facies.

Tununk Shale.—The thickest and most complete record of the second transgression (T_2) is the Tununk Shale of the Wasatch Plateau area. The Tununk is recognizable in the subsurface as far west as Sanpete Valley in central Utah. It is represented by the Allan Hollow Shale Member at Coalville and an equivalent shale member in the Frontier at Cumberland Gap. The Tununk thins rapidly eastward along the Book Cliffs but equivalent shales are recognizable as far east as Grand Junction. Elsewhere in the region Greenhorn rocks were either not deposited or were removed by post-depositional erosion. The Tununk and equivalent shales are accurately dated by the distinctive fauna *Inoceramus labiatus* (Greenhorn) and *Collignoniceras woollgari* (early Carlile).

FERRON FORMATION.—The first regressive (R_2) cycle of major proportions which occurred in Carlile time is recorded by the Ferron Formation (and its equivalent the Frontier). The Frontier was deposited in response to the second uplift of the provenance that shed sediments eastward in a broad fan-shaped pattern in northeastern Utah. The equivalent paludal and transitional facies of this regression formed the initial phase of an eastward bulging deltalike feature that persisted in the northern Uinta Basin area until early Pierre time. The general facies patterns during late Carlile time are schematically portrayed on figure 5. This feature has been somewhat arbitrarily termed the "Vernal delta." At approximately the same time another provenance became active in south central Utah and shed a wedge of deltaic-type sediments (Ferron) northeastward into the Castle Valley area (Katich, 1954). The Ferron is a thick (780 ft.) sequence of coal-bearing sandstones and shales in the southern Wasatch Plateau but changes rapidly eastward to a thin-bedded marine sandstone and shale facies (fig. 9). A narrow marine embayment apparently existed in the Clear Creek area that isolated a northeast-projecting tongue of deltaic sediment in the type Ferron area. Similarly the Frontier Formation at Red Creek is a comparatively thick (760 ft.) sequence of coal-bearing and associated transitional rocks. The formation thins eastward, and coal beds persist as far east as the Vernal area (fig. 10) before disappearing by facies change to dominantly thin marine sandstones and shale. During latest Carlile the thrust belt to the west became active and the late Carlile portions of the Frontier at Coalville and Cumberland Gap (representative of most of the eastward facies of Frontier and Ferron) were removed by erosion. The coal-bearing strata of the Frontier and Ferron grade both upward and downward into marine rocks indicating a complete though slightly asymmetrical cycle of deposition. However, overlying transitional rocks are much thinner, indicating the transgressive phase (T_3 Niobrara) was much more rapid than the (R_2) regressive phase.

Unconformable relationships.—The closely controlled faunal record of the Carlile epoch indicate the existence of a significant and widespread unconformity between the basinward facies of the Frontier and underlying Mowry Shale (fig. 3). Omissions in the faunal assemblages, which embrace early Carlile to Early Cretaceous, were noted by Reeside (1955) at Vermilion Creek and in the Vernal region (Blue Mountain locality) by Cobban and Reeside (1952). Recent detailed work by Weimer (1962) presents evidence that the hiatus is attributable to post-depositional growth of an embryonic Uinta Mountain arch. Correlations by Hale (1960) indicate the temporarily positive area may also have included the southwestern part of Wyoming (exclusive of the thrust belt).

BLUE GATE SHALE.—Following the Frontier regression the third and most sustained marine transgression occurred in Niobrara time. The sea rapidly inundated the swamps and adjacent fringe areas of the Vernal and Ferron "deltas." The initial transgression (T_3) intertongued westward with coarser clastics of the upper Frontier at Coalville and Cumberland Gap and reached its maximum advance an unknown distance west of these localities. In the southwest the shales of this transgression (Blue Gate) reach a thickness of 2,000 ft. and have been identified as far west as Sanpete Valley (subsurface) west of the Wasatch Plateau. About 1,500 ft. of equivalent shales are present at Red Creek. In the north, sandstone tongues associated with a separate northern provenance appear in the lower Baxter Shale on the north plunge of the Rock Spring uplift (fig. 11). These sandstones, which produce gas at the Nitchie Gulch field, are of marine origin and are assigned to the upper Frontier Formation.

EMERY SANDSTONE.—Still in early Niobrara the sea began a fluctuating but inexorable retreat from the area. The next regression (R_3) is recorded by the Mesaverde (undivided) at Red Creek and the Emery Sandstone at the Wasatch Plateau. The character and distribution of the Emery (like the Ferron) is well known from an abundance of subsurface data in the Wasatch Plateau area (Hale, 1959). The Emery is dominantly a marine sandstone facies along the east front of the Plateau but thickens westward and changes rapidly to a coal-bearing facies beneath the Plateau area. Facies strike in this area is about north-south and the juxtaposition of the coal-bearing marine interface indicates a long period of shoreline stability. Control for the facies strike northward across the west side of Uinta Basin is practically nil. However, a critical subsurface control point south of Soldier Summit, between Price and the Red Narrows, indicate a definite eastward swing in facies strike of the Emery (and other Mancos equivalent) in the direction of Duchesne. This change in facies strike corresponds to the southeast fringe of the Vernal "delta" which built eastward along a main axis of deposition between Red Creek and Vernal. At Red Creek, equivalent and slightly older rocks of the Mesaverde thin eastward by intertonguing with the Mancos Shale and change almost completely to a marine shale facies before reaching the Vernal outcrop area (fig. 10). Due to total lack of control, the intervening facies patterns must be inferred. Equivalent rocks on the north flank of the Uinta Mountains are represented by upper marine shale in the Spring Creek-Manila outcrop area and presumably also the upper (subthrust) Hilliard Shale of southwestern Wyoming. In the overthrust area, equivalents appear to be the lower Adaville and lower Echo Canyon Conglomerate in the Coalville area. Throughout the eastern half of the map area there is a widespread sandy shale facies that is believed to be the lithogenetic equivalent of the Emery. Locally well-developed sandstone facies occur over the Douglas Creek arch and Axial basin areas are called the Emery (?) or "B" zone and Meeker Sandstone. Both local developments are believed attributable to winnowing action in a shallow marine (shoal) environment during embryonic growth of the Douglas Creek and Axial basin anticlines since isopachous studies indicate optimum development over these features. Kopper (1962) believes the "B" zone sands were derived from a delta that projected south from the Rangely area.

The Emery Sandstone and equivalents are dated as Telegraph Creek and in part Eagle. In the Grand Junction area Katich (1956) found fossils of both ages in a sandy shale zone 800 ft. below the Mesaverde which he considers the probable equivalent to the Emery Sandstone. At Vermilion Creek Reeside (1955) reports a Telegraph Creek fauna in a sandy zone in the Mancos 2,470 ft. below the top and Eagle fossils 1,324 ft. below the top. Still farther north at the Rock Springs uplift in Wyoming, Telegraph Creek fossils are reported in the Airport Sandstone by Hale (1950). Eagle fossils are found in the upper Blair Formation by Smith (1961). These age relations are indicated on the north to south restored diagram (fig. 10). Significantly, the increase in range of these fossil zones is indicative of northward thickening of contemporaneous deposition toward Wyoming. Based on the interpretation, regression R_3 (Airport Sandstone), transgression T_4 (upper Baxter), and regression R_4 (basal Blair Sandstone) are believed to have occurred contemporaneously with the Emery regression in Utah.

MASUK SHALE.—Following the Emery regression a *fifth transgression* (T_5) *occurred* in Eagle time as recorded by the Masuk Shale in Wasatch Plateau area. The Masuk, a distinct marine shale along the east front of the Plateau, changes facies rapidly westward (in the subsurface) and blends with the Emery and Blackhawk-Star Point as a dominantly coal-bearing sequence. Consequently, the Mesaverde facies boundary is placed at the base of the Emery west of the Plateau. No subsurface data exists for control to the north across the Uinta Basin; however, at Soldier Summit a definite swing in facies strike from essentially north-south to a northeasterly strike is evident from well data. Equivalent rocks at Red Creek are either missing due to an unconformity or are represented in the upper Mesaverde. Tentatively, the Masuk is correlated with the middle Blair transgression (T_5) in the Rock Springs uplift (fig. 11). Elsewhere time equivalent rocks are in the upper part of the Mancos and Steele Shales. A convergence of time lines is evident from stratigraphic thinning over the Douglas Creek arch and adjacent Book Cliffs (fig. 9).

BLACKHAWK FORMATION.—The major coal-bearing formation of the Mesaverde Group in the Wasatch Plateau-western Book Cliffs area is the Blackhawk Formation. It is underlain by a series of regressive marine sandstones, the Star Point Formation. The Blackhawk Formation is subdivided into five members named for coal mines in the Price-Sunnyside area (Clark, 1928). Each member consists of coal beds at the top with an underlying prominent littoral marine sandstone. The Blackhawk represents the first regressive phase of the Mesaverde as defined in this area but actually is the fifth major regression (R_5) in the total Cretaceous sequence (fig. 9). The Blackhawk is tentatively assigned to upper Eagle based on correlations with better controlled sections elsewhere.

The coals of the Blackhawk disappear to the southeast by facies change as the formation splits into eastward-pointing marine sandstone beds which in turn intertongue with the Mancos Shale as schematically portrayed on figure 9. Young (1955) describes in detail the intertonguing relationships of the Mancos and Mesaverde Groups along the Book Cliffs outcrops. Marine sandstones of the Blackhawk are recognizable in deep wells in the central Uinta Basin, but sparse control serves only to establish a general northeasterly facies strike. At Coalville the Blackhawk is tentatively correlated with the lower Echo Canyon Conglomerate. Equivalent rocks at Red Creek are presumed to be missing due to post-depositional uplift and erosion of upper Mesaverde rocks (fig. 3, column 5). Eastward at Vernal, the uppermost Mancos and part of the Asphalt Ridge Sandstone is correlated with the Blackhawk (fig. 10). Equivalent rocks elsewhere in Utah and Colorado are upper Mancos Shale. In the Rock Springs area, formations tentatively correlated with the Blackhawk are the upper Blair including the Chimney Rock Tongue which carries an Eagle fauna (Smith, 1961).

CASTLEGATE SANDSTONE.—Following deposition of the Blackhawk, about the beginning of the Pierre epoch, a pronounced orogenic uplift occurred in the central Utah provenance. As a result, thick massive conglomerates accumulated in the foredeep and spread eastward as a broad alluvial fan. The names applied to the coarse clastics are the Echo Canyon at Coalville, the Currant Creek at Red Creek, and the Price River conglomerates as exposed west of Price (fig. 8). At all three localities the conglomerates rest unconformably on older Cretaceous rocks. The accelerated rate of erosion and sedimentation had a pronounced effect on the basinward depositional patterns. As the incoming sediments exceeded available space the shoreline rapidly regressed to the east. The initial regressive sandstone (R_6), the Castlegate Sandstone, rapidly buried the swamps and floodplains of the Blackhawk and spread far to the east across Utah and into Colorado. An apparent lag in sedimentation in the present Uinta Mountain area developed a conspicuous "S" pattern in the facies strike (fig. 6). This configuration contrasts with a prevailing northeasterly strandline strike as interpreted by Zapp and Cobban (1960, 1962), and others.

Between Price and Green River the Castlegate is a poorly sorted, in part conglomeratic, sandstone of fluviatile (inland) origin. East of Green River it is associated with a thin narrow belt of lagoonal deposits, then it grades to a tongue of littoral and shallow marine sandstone which wedges out near the Colorado border. The Castlegate Sandstone is easily recognizable in the subsurface in the eastern Uinta Basin and adjacent Douglas Creek arch. Extensive drilling for natural gas in the Castlegate since its discovery at Rabbit Mountain (west side of Douglas Creek arch) in 1951 has provided good correlation control with outcrops at Rangely. In this area the Castlegate is correlated with the Rim Rock sandstone as restricted by Hale 1959, plate II). Thin coals and associated lagoonal beds appear near Rangely. The sandstone thickens westward by intertonguing with the underlying Mancos. Near the state line the overlying shale (Buck Tongue) grades to a coal facies and the Castlegate, or in this area Rim Rock sandstone of Walton (1944), becomes the base of the undivided Mesaverde Group in Utah. Near the Vernal area the Rim Rock overlies the Asphalt Ridge Sandstone of Walton (1944). From Rangely eastward the Castlegate grades from littoral to shallow neritic. It is a prominent marine sandstone tongue that persists as far east as Wilson Creek near Meeker before grading into Mancos Shale (fig. 6).

No direct correlations can be made northward into Wyoming because of complete erosion of the section from the Uinta Mountain arch. Excellent Cretaceous exposures on the north flank of the Uinta arch in the Spring Creek Gap area between the new Flaming Gorge Reservoir and Clay Basin have been examined and correlatives, not only of the Castlegate Sandstone, but also of overlying units, have been recognized. In this area a prominent hogback-forming sandstone the Race Track sandstone (of local usage) splits from the undivided Mesaverde near the Green River. It projects eastward, gradually thins by gradation to shale at the base, and changes into an indistinct sandy shale zone at Clay Basin. The Race Track sandstone was initially correlated to the northeast with the Chimney Rock Sandstone in the Rock Springs uplift by Hale (1955). However, subsequent well data establishes that the Chimney Rock Sandstone is missing by reason of facies changes in the Spring Creek Gap outcrop and that the Race Track sandstone correlates with a sandstone in the middle Black Butte Tongue of Hale (1950) of the Mancos Shale (see fig. 12).

The Race Track sandstone is equivalent to the upper Mancos Shale at Vermilion Creek outcrop and also in wells drilled in the Vermilion Creek basin to the northeast. The Morapos Sandstone of the Axial basin area has been interpreted as an offshore bar development equivalent to the Castlegate. However, recent work by Zapp and Cobban (1960) indicates the Morapos is slightly older. Tentatively, the Cow Creek Sandstone in the Deep Creek area (Hale, 1961) is considered an offshore bar development roughly equivalent to the Race Track-Castlegate interval (fig. 10).

Fossil evidence tends to support the foregoing regional correlations. The index fossil *Baculites asperiformis* has been reported in association with the Castlegate Sandstone by Zapp and Cobban (1960) and others. Smith (personal communication) has found the same fossil in the middle of the Rock Springs Formation on the west flank of the Rock Springs uplift and just above the Cow

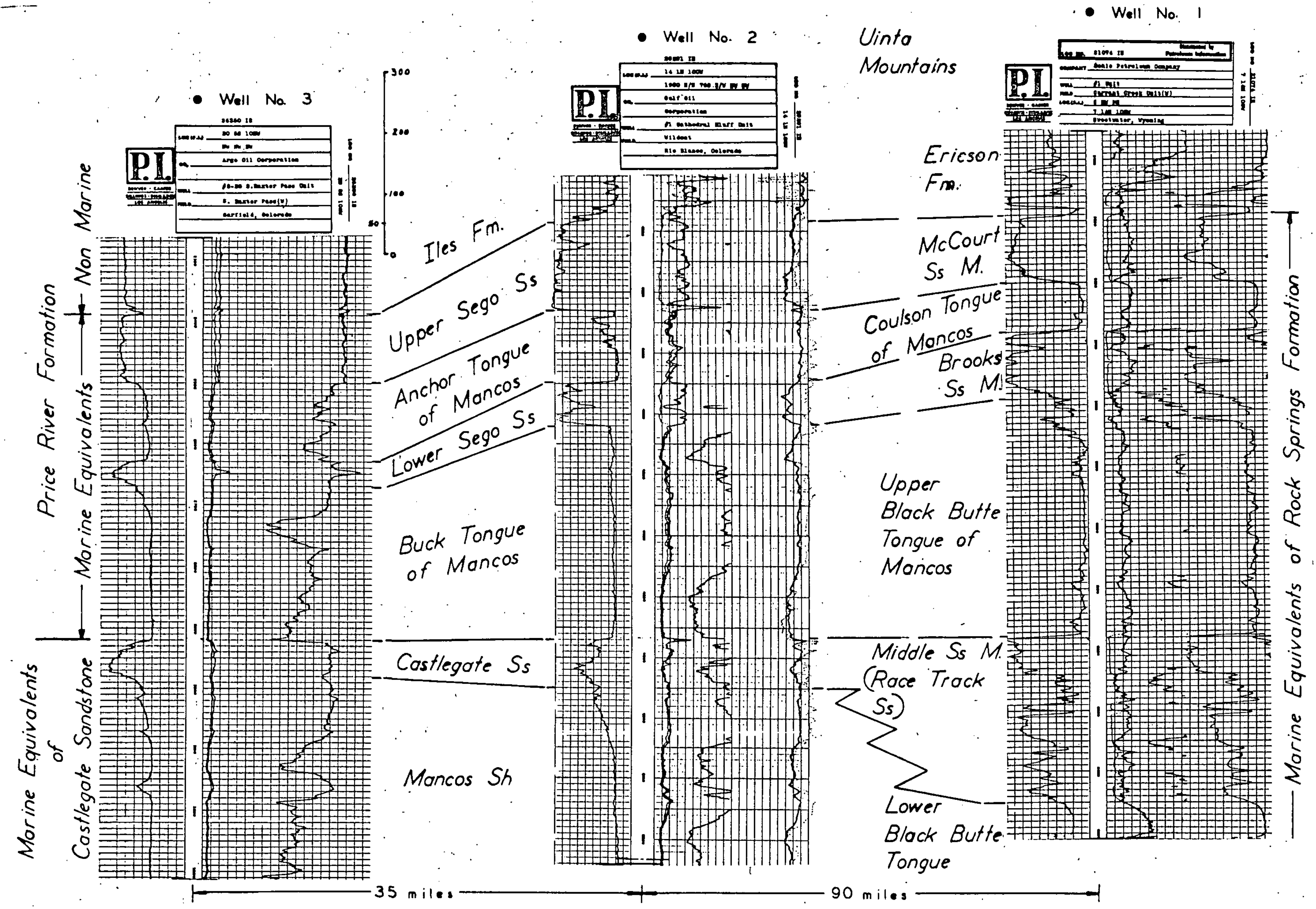


FIGURE 12.—Strandline correlation of time-stratigraphic equivalents, upper Mancos transition zone, Wyoming and Colorado.

Creek Sandstone south of Rawlins since publication of his 1961 paper.

PRICE RIVER FORMATION.—Following the initial flood of coarse Castlgate conglomerate, sedimentation rate waned slightly but maintained a dominant regressive (inland) character through deposition of the overlying Price River Formation (R_7). The Price River which formerly included the Castlegate as a lower member is a sequence of coarse lenticular sandstone and shale about 900 ft. thick in Price River Canyon. Westward the Price River merges with Castlegate equivalents as a continuous massive conglomerate facies. The lithogenetic relationship with the Currant Creek and Echo Canyon conglomerates is indicated on figure 8. Eastward from these areas the conglomerate facies gradually changes to a coarse sandstone and shale. These rocks in turn change to a coal-bearing facies and at the base intertongues with the marine Mancos Shale as indicated on the restored sections. Two significant marine transgressions occurred during early Price River deposition. Although the resulting shale deposits are facies of the marine Mancos they are discussed as depositional events during Price River time.

Buck Tongue of Mancos Shale.—Concomitantly with the regressive depositon of the early Price River Formation, relatively sudden downwarping of the Cretaceous basin triggered a widespread inundation (T_7) of the shoreline and bordering swamps and lowland area. The maximum westward advance of the shoreline, which has been recognized at nearly every outcrop, has been superimposed on the lithofacies map of the Castlegate as a dashed line (fig. 6). Marine shales, deposited as a result of this transgression and the ensuing regression, are called the Buck Tongue of the Mancos in the Book Cliffs. Equivalent shale units have been recognized east of Vernal between the state line and Meeker, Colorado. Time stratigraphic equivalents in Wyoming are the marine shales and sandstones of the upper Black Butte Tongue as defined by Hale (1950, 1955). In contrast to the slow regression of the Buck Tongue-Sego Sandstone, the Black Butte was deposited during a period of stable shoreline conditions. At Spring Creek Gap these equivalent rocks form a conspicuous strike valley between the Race Track sandstone and the Ericson escarpment to the north. Marine shales of the Buck Tongue and equivalents rest in sharp contact with the underlying regressive deposits. At the point where these rocks pinch out the overlying shales merge with the main body of the Mancos.

The Castlegate-Buck Tongue interval constitutes a typical asymmetrical cycle of deposition, as defined by Weller (1960) in that no transitional or gradational boundary exists between the two units. Basically the asymmetry is caused by (1) a gradual regression as sediment supply exceeded space, resulting in an upward gradation from shale to sandstone, and (2) epeirogenic downwarping of the depositional site followed by a rapid inundation and shoreward shift of all depositional environments. This results in a sharp contact between littoral and lagoonal type deposits and marine shale. This is in contrast to both regressive and transgressive deposits recorded in the Ferron and Emery members to the west.

Lower Sego Sandstone.—The stratigraphic record of the Price River and equivalents indicates continued regressive deposition during and subsequent to the Buck Tongue transgression. After the sea had reached its new position over the Castlegate it began a slow retreat (R_7) as recorded by the regressive sandstone of the Price River (and Neslen) Formation called the Sego Sandstone (fig. 3). This is attested to by the intertonguing relationship of basal Sego and Buck Tongue shale and eastward stratigraphic rise of the facies boundary in the eastern Book Cliffs-Rangely area.

In contrast, the Rock Springs uplift area received thicker contemporaneous deposits and was a locality of stable shoreline conditions as indicated by the rapid facies change of the upper Rock Springs Formation. In general, dominantly coal-bearing rocks intertongue to the southeast with a dominantly littoral marine sandstone facies then abruptly change to marine sandy shales and sandstones of the upper Black Butte Tongue (Hale, 1950, 1955) and shown on (fig. 11). An overlying regressive sandstone tongue, the Brooks Sandstone (Smith, 1961) is correlated with the lower Sego (fig. 3). The section at Spring Creek Gap, along a facies strike of about N. 40 E., exhibits the same stratigraphic sequence and general facies relationships.

An offshore bar relationship is indicated in the eastern Book Cliffs near Grand Junction (Young, 1955, pl. 3). The lower Sego had previously been correlated and identified with the Morapos Sandstone of the Axial basin area (Hale, 1959, pl. 2). New well control and faunal data reveals this correlation is incorrect. As indicated previously, the correct stratigraphic position of the Morapos based on faunal evidence is just beneath the Castlegate. The occurrence of the fossil *Baculites scotti* Cobban (reported by Cobban, 1958) dates the Sego as middle Campanian (Crow Creek level of the Pierre Shale). Fossils collected from the Brooks Sandstone by Smith (1961) and identified by Cobban reveal an age of "not younger than basal Parkman" or approximately equivalent to the Sego.

Anchor Tongue of Mancos Shale.—During the initial regressive phase of the lower Sego another pulse of subsidence (epeirogenic downwarping) occurred. Again the shore and inland areas were inundated by a more limited transgression (T_8). The new shoreline position is not accurately controled but appears to have the same general configuration as T_7. The maximum landward advance reached the west plunge of the Rangely anticline. From this locality the zero line extends about S. 40-45° W. to a point in the Book Cliffs due north of Crescent Junction. Inundation of coal swamps is evident in the eastern Book Cliffs (Young, 1955, pl. 3) but elsewhere the general effect was one of deepening the marine environment and superimposing neritic shales in sharp contact with littoral and beach sandstones. Thickness ranges from 0-200 ft.

In the Rock Springs area, the Coulson Shale (Smith, 1961) is believed to be the direct time-stratigraphic equivalent of the Anchor Tongue (fig. 12).

Upper Sego Sandstone.—After the rapid Anchor Tongue transgression, deposition of Price River age rocks continued with a final retreat (R_8) of the sea from northeastern Utah being recorded by the upper Sego Sandstone. The upper Sego is a typical light-gray, littoral, marine sandstone. Generally, it is overlain by a coal or carbonaceous shale that marks the base of the Neslen in the eastern Book Cliffs east of the wedge-edge of the subjacent Anchor Tongue. Minor transgressions, similar in scope and duration to the Anchor Tongue, continued to occur in the Book Cliffs north and east of Grand Junction as observed by Young (1955), but the dominant sedimentary trend was rapid regression and a subsequent long period of continental deposition. An equivalent sandstone marks the base of the main body of the coal-bearing Mesaverde rocks in the Rangely area (Hale, 1959). However, the Sego of the Rangely area was erroneously correlated eastward with the Morapos Sandstone by Hale (1959, pl. 1). Subsurface control is still not sufficient for accurate correlation but tentatively the upper Sego is approximately equivalent to either the Loyd Sandstone of Konishi (1959) or his first sandstone about 100 feet below the Loyd. Correlations essentially along facies strike indicate the upper Sego is approximately the time-stratigraphic equivalent of the McCourt Sandstone as defined by Smith (1961) in the south Rock Springs uplift (fig. 12). In this area the McCourt, 105 ft. thick, marks the base of the Ericson Formation. It has been correlated in the subsurface along a facies strike of about N. 40° E. and tied with the outcrop both at Spring Creek Gap and Clay Basin. A similar sandstone in the same stratigraphic position has been recognized at the base of the Iles at Vermilion Creek. The McCourt Sandstone is apparently equivalent to the Hatfield Sandstone of the Deep Creek area as defined by Hale (1961).

Neslen facies.—During middle and late Pierre (Price River) time continental deposition predominated over the region except for minor marine invasions in the eastern Axial basin area (see fig. 1). The provenance to the west continued to shed coarse detritus into the foredeep areas at Coalville, Red Creek, and Red Narrows. Finer clastics were carried eastward into the inland floodplain areas. The bulk of these sediments appears to have bypassed these areas and accumulated in the downwarping basinal area to the east. Thus, relatively thin fluviatile rocks (typically the Price River) are represented by thicker contemporaneous deposits farther east. Correlations of time-stratigraphic units eastward reveal the typical basinward shift of environments and stratigraphic rise of facies boundaries.

The fluviatile rocks of the lower Price River gradually give way eastward to a coal-bearing facies in the eastern part of the Book Cliffs. Young (1955) named this 100-1,000 ft. section the Neslen coal-bearing facies of the Price River to replace the Mount Garfield Formation (Erdmann, 1934) in the Grand Junction area. The same coal-bearing sequence was recognized by Gale (1910) in the Vernal-Rangely area and along the Douglas Creek arch. Later the name Iles Formation was applied from Axial basin terminology. However, the writers believe the Book Cliffs terminology is more appropriate to the Mesaverde rocks in these areas because of the basic similarities in lithology and facies relationships. The coal-bearing character of the Neslen persists eastward into the Axial basin although interbedded light gray littoral sandstones appear in the Meeker area. This sequence of beds is called the Iles Formation. Marine rocks become increasingly common eastward and shale tongues appear in the Pagoda area (Zapp and Cobban, 1960).

Equivalent rocks in the Rock Springs area consist of 350-800 ft. of coarse poorly sorted conglomerates and coarse sandstone of the Ericson Formation. The general character of this formation indicates a separate provenance located in northwestern Wyoming. If properly correlated, the orogeny of the Ericson provenance corresponds in time to later phase of the central Utah orogeny, younger than Castlegate. The flood of coarse sediments rapidly buried the swamps that typified the Rock Springs Formation and shifted the various depositional environments to the southeast and east. The depositional strike appears to conform generally with the facies strike (N. 40° E.) of the underlying Rock Springs as evident from correlations with the section at Spring Creek Gap. Abrupt thickening occurs to the southeast in the Vermilion basin area (Douglas and Blazzard, 1961, fig. 4) and coal beds begin to appear first in the middle of the formation. At Vermilion Creek, the section is dominantly sandstone, but contains several coal beds in the middle part of the formation. This led Sears (1924) to name the sequence the Iles Formation. In the Deep Creek area the Ericson and Iles are equivalent to most of the undivided Mesaverde (Hale, 1961).

Support for this correlation is the observation, both at the outcrop and in the subsurface, that the regression of the Ericson-Iles was comparatively rapid with little, if any, significant stratigraphic rise of facies boundary. Interpreted in this manner the Ericson-Iles and Mancos boundary is nearly a stratigraphic plane over wide areas in south-central Wyoming and northwestern Colorado. These dominantly continental and coal-bearing rocks intertongue extensively with dominantly marine rocks in the Oak Creek area (Zapp and Cobban, 1960). The above facies relationship is also apparent east of the Deep Creek area in Wyoming.

Farrer facies.—This name was applied by Young (1955) to all non-coal-bearing strata of the Price River Formation in the western Book Cliffs area. Thus, the Farrer as a facies unit includes stratigraphic equivalent of the Neslen east of Woodside. Consequently, as Young pointed out, the contact between the two facies rises stratigraphically to the east. This rise should normally decrease the thickness of the Farrer facies but instead it thickens to about 1,200 ft. near Grand Junction, Colorado. This is interpreted as thicker contemporaneous deposition. Gale (1910) noted a similar non-coal-bearing sequence comprising the upper Mesaverde at Rangely. Continued eastward facies changes and stratigraphic rise of the barren and coal-bearing facies boundaries is apparent. At Axial basin an equivalent coal-bearing sequence 1,700 ft. thick is called the Williams Fork Formation. In this area the Williams Fork is separated from the Iles Formation by a prominant, white (littoral or beach) sandstone called the Trout Creek. Southwest of Meeker the Williams Fork includes continental equivalents of the Lewis Shale. At Vermilion Creek only a thin section of the Williams Fork is preserved beneath the Tertiary unconformity (fig. 10). In adjacent Wyoming, the Almond Formation, 600-800 ft. thick in the Rock Springs uplift, is correlated with the Williams Fork Formation. The contrast in thickness between these two formations is believed to be due to either intertonguing with the overlying Lewis or thicker contemporaneous deposition or a combination of these.

LEWIS SHALE.—While continental rocks of the Price River and related formations were being deposited, the ninth and final marine transgression (T_9) occurred in northwestern Colorado and south-central Wyoming. This transgression, recorded by marine rocks of the Lewis Shale, was apparently rapid as evidenced by thin, basal, transgressive, marine sandstones. The sea transgressed the region from the northeast, inundating the swamp and floodplain deposits of the Williams Fork and Almond Formations. Significant pauses in the transgression permitted shoreline and offshore sand buildups most notably in the Wamsutter arch area (Patrick Draw field) east of Rock Springs, Wyoming. The Lewis sea reached its maximum advance during the Mobridge epoch of the Pierre along a northwest-southeast line between Rock Springs, Clay basin, and Meeker, Colorado, as depicted on figure 7. The ensuing regression (R_9) was slow as indicated by extensive intertonguing with the continental Lance and its regressive marine sandstone the Fox Hills (fig. 10). During this retreat a maximum of about 2,600 ft. of marine shale and sandstones accumulated in the downwarping basinal area to the east. Two prominent equivalent sandstone facies are developed in the Lewis Shale. Haun (1959) described a fine sandstone facies that projects from the Maybell-Vermilion Creek area northeastward across the Sand Wash basin into Wyoming (fig. 7). His isopachs indicate a northeast-trending axis of deposition. This facies correlates with the Dad Sandstone Member of Hale (1961) of the Lewis Shale, 1,000 ft. thick in the Deep Creek area. Both deposits, interpreted as separate marine delta-fringe deposits, divide the Lewis into upper and lower units.

Fossils in the Lewis Shale indicate an age range of late Pierre (Virgin Creek to possibly lower Elk Butte epochs).

North Horn Formation.—Cretaceous history in the Wasatch Plateau area ended as it began with deposition of fluviatile red beds. The North Horn Formation consists of variegated clastics and lacustrine limestones about 2,200 ft. thick. Its lower contact is gradational with the Price River but the comparative features, particularly color, are a sharp contrast. Another significant contrast is the reverse direction of thickness change. The North Horn thins eastward and its lower part is correlated with the Tuscher Formation, 200 ft. thick. In the central and eastern Book Cliffs the Tuscher rest unconformably on the Farrer.

A unique feature of the North Horn is the apparrent fact that the Cretaceous-Tertiary boundary is located within the formation with no apparent hiatus. Spieker (1946) reports dinosaurian remains of late Montanan (Maestrichtian) age in the lower part. The middle part is barren but the upper beds contain Paleocene mammal remains.

Since the Currant Creek Formation may include Tertiary- and Cretaceaus-age rocks, the North Horn is apparently equivalent to the upper part. Tentatively, the North Horn is correlated with uppermost Echo Conglomerate and part of the Knight Formation at Coalville.

Lance Formation.—While red beds were being deposited in central Utah in the closing stages of the Cretaceous, thick floodplain and paludal sediments were deposited in the downwarping basin to the east. These sediments which comprise the Lance Formation, represent the final regression (R_0) in the region. The underlying Fox Hills is its regressive marine sandstone. Thicknesses of the Lance range from zero feet in the west, due to post-Cretaceous erosion, to 1,000-1,400 ft. to the east. It appears likely that local source areas emerged as a result of embryonic folding of the Douglas Creek arch, Sierra Madres and possibly others. However, it is evident that major folding and development of the present tectonic framework did not occur until the close of Cretaceous time.

CRETACEOUS-TERTIARY UNCONFORMITY

The unconformable relationship between the Cretaceous- and Tertiary-age rocks, particularly the Lance-Fort Union, is not fully known, because of similar lithologic character and resulting difficulty in picking the boundary. However, on a regional basis the unconformity cuts downward into progressively older beds in an east to west direction. Significantly, the unconformity can be traced in the subsurface from the Vermilion basin southwest toward the Uinta Mountain uplift. As the uplift is approached the unconformity cuts progressively downward through the Lance and Lewis and at the Vermilion Creek section the Tertiary rocks rest on the lower Williams Fork Formation (figs. 10 and 11). It is apparent, therefore, that except for embryonic growth in Carlile time the Uinta Mountain uplift did not develop until early Tertiary except for some apparent folding in the western part of the range (Bissell, 1952) and others.

SUMMARY AND CONCLUSIONS

The following significant conclusions can be made relative to the Cretaceous depositional history of the subject area.

(1) The primary source area of Cretaceous sediments was eastern Nevada and western Utah. It gradually moved eastward across Utah as a series of wave-like folds or imbricate thrusts and reached the map area (fig. 1) in latest Cretaceous.

(2) Periodic tectonisms of the provenance accelerated sedimentation and, along the basinal downwarping, were the principal factors influencing sedimentary facies pattern.

(3) Nine principal transgressions and regressions occurred during the Cretaceous.

(4) The initial marine transgression occurred in late Mowry with deposition of Mowry Shale. Transgressive marine deposition predominated until middle Niobrara when the trend reversed to dominantly regressive deposition.

(5) Marine deposition prevailed over the eastern area from Early Cretaceous (Mowry) to Pierre and in excess of 5,000 ft. of Mancos Shale accumulated. Traced westward and northwestward the Mancos intertongues extensively with continental and associated marine rocks.

(6) In middle Montanan time a pronounced uplift of the provenance shed coarse clastics eastward and accelerated-regressive deposition.

(7) During this rapid regression three sharp basinal subsidences caused widespread inundation of beach and marginal swamp areas in northeast Utah and adjacent Wyoming and deposited west-pointing (transgressive) shale tongues.

(8) While about 2,100 ft. of coarse fluviatile sediments (Castlegate to lower North Horn) were being deposited, the downwarping basin to the east received about 6,300 ft. of contemporaneous beds (upper Mancos through Lance).

(9) Development of the present tectonic framework did not occur until early Tertiary time, although embryonic growth of the Uinta Mountains (Carlile) and Douglas Creek arch (Niobrara) and renewed movements of the Uncompahgre uplift are apparent from isopachous mapping.

(10) Finally, correlations and interpolations of stratigraphic data between the Green River and Uinta Basins indicates the Uinta Mountains did not affect the development of post-Frontier facies patterns.

ACKNOWLEDGMENT

The writers express their appreciation to Mr. L. W. Folsom, Manager of Exploration, and Mr. W. W. Skeeters, Chief Geologist, Mountain Fuel Supply Company, for permission to prepare and publish this information and for critically reading the manuscript.

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Smith

UTAH POWER & LIGHT COMPANY
1407 WEST NORTH TEMPLE STREET
P. O. BOX 899
SALT LAKE CITY, UTAH 84110

August 22, 1974

UNIVERSITY OF UTAH
RESEARCH INSTITUTE
EARTH SCIENCE LAB

Professor Wayne Brown, Dean
College of Engineering
University of Utah
Salt Lake City, Utah 84112

Dear Wayne:

Enclosed is a copy of my short status report. Please destroy the handwritten copy since I located a few errors in proofing the final copy.

Sincerely,

Val A Finlayson

er

Enclosure

cc: Taylor Abegg
Stanley Ward ✓

UTAH POWER & LIGHT COMPANY
REQUIRED GENERATING CAPACITY

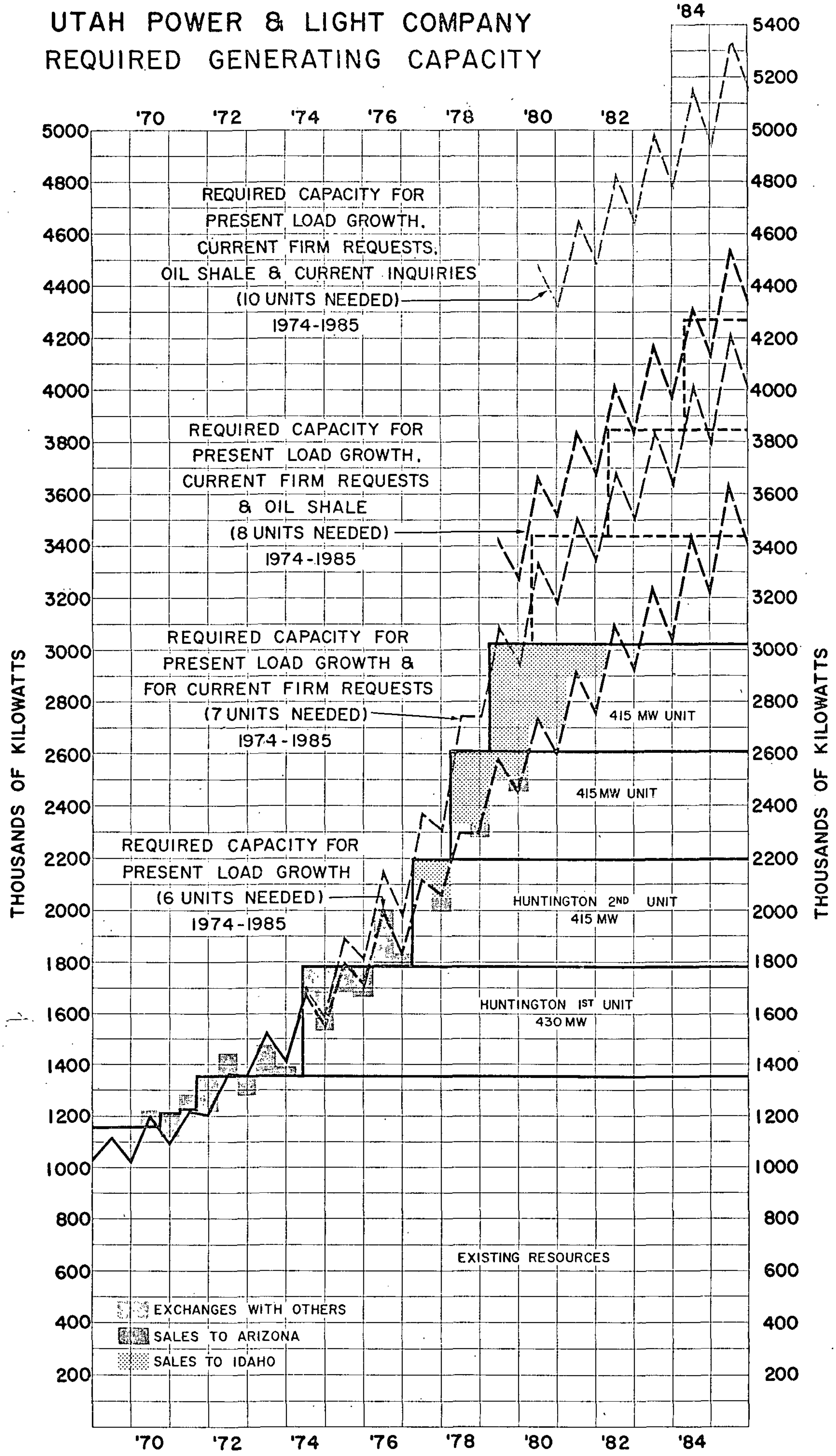

FIGURE NO. 2

APRIL 1974

V A Finlayson/er
August 20, 1974

UTAH GEOTHERMAL REVIEW

Since January 1972, Geothermal Kinetics Inc. (GKI) with assistance from Utah Power & Light Company has conducted numerous geological geophysical, and geochemical studies in Utah and surveys continue in Utah and Idaho.

A. Exploration

(1) Aerial photography from high altitude or satellites were used to outline major buried batholiths or volcanic intrusive centers.

(2) Geochemical analysis of the hot springs in these major areas of interest were made by GKI and checked independently by Professor Helgesen of Berkeley. Using SiO_2 and the sodium potassium or sodium potassium calcium ratios as thermometers, minimum reservoir temperatures of 375°F to 400°F were indicated for the site in Box Elder County, Utah.

(3) Ground noise surveys were conducted. Seismic noise studies are commonly made by all exploration groups including the USGS and major oil companies. By use of computers, the noise signals are Fourier analyzed and frequency profile maps produced. The generating force for seismic noise anomalies is not well understood.

(4) Deep Resistivity surveys were conducted by Dr Keller and his staff at Group Seven, a wholly owned subsidiary of GKI. At the time the studies were made during the winter of 1972 and early summer of 1973, Group Seven was the only company doing deep resistivity surveys with a penetration of over 5000 feet. Usable values as deep as 15,000 feet have been obtained. At the Box Elder County Anomaly, conductances ranged from 1000 to 4000 mhos.

(5) Time-domain electromagnetic soundings were made to gain more information about the depth of the anomaly.

(6) Pole-Dipole Resistivity Sections were also made to obtain depth information.

(7) Rotating dipole resistivity surveys and ultra-deep electromagnetic surveys were then carried out. Dr Keller's final conclusion from all of the studies predicted temperatures of 320°F to 360°F with a goethermal potential as great as 25,000 to 50,000 megawatt-years for the Box Elder-Cache Valley Sites combined.

(8) Active Seismic surveys were conducted by Petty-Ray Company utilizing the Vibroseis technique. This study was to gain better information on the Box Elder site prior to drilling of any wells so that the stratigraphy might be deduced. No deep wells exist in the area.

B. Leasing

With the information from the exploration program, three areas were leased in Utah;

1. Box Elder County Site (25,000 acres)
2. Cache County Site (25,000 acres)
3. Iron County Site (50,000 acres)

Utah Power & Light Company and GKI filed on water rights within the areas. Utah Power & Light Company also holds an exclusive agreement with the Shoshone Bannock Tribe to develop geothermal resources at Fort Hall in Idaho and resistivity studies are now being conducted on that site.

C. Utah Steam Venture

On December 26, 1973 Utah Power & Light Company and GKI entered into an agreement to develop geothermal resources at the Utah and Idaho sites. On February 20, 1974 well drilling commenced at the Box Elder County Site about seven miles north of Brigham City in Section 16, Township 10N. Range 2 West. A 13-3/8 inch casing was installed to 3,232 feet, a 9-5/8 inch casing installed to 8,973 feet, and a 7 inch liner installed to 10,388 feet. The total depth of 11,005 feet was reached on June 21, 1974. The following corporations were involved during the drilling:

(1) Geo Drilling Company, a subsidiary of GKI, conducted the drilling.

(2) Baroid supplied mud materials and a 24 hour service for mud logging, including gas in the mud, mud termperature, and drilling rate. Microscopic examination of drilling cuttings was performed.

(3) Dresser Atlas performed a number of downhole logs including temperature, neutron lifetime, resistivity, and porosity.

(4) Halliburton Services cemented the casings and ran drill stem tests.

(5) Air Equipment and Drilling, Inc. supplied air for latter drilling.

The following consultants examined the data from the well:

(1) J H Smith, geothermal engineer from KRTA, Auckland, New Zealand.

(2) Galen Haugh, a petrologist from Brigham Young University examined drill cuttings from samples taken every 10 feet.

(3) Greg Francis, a geologist from Mountain Fuel Supply Company examined the cuttings to help identify the lithology.

(4) James Kuwada, Vice President of Rogers Engineering Company is advising the Utah Steam Venture on well chemistry and power generation feasibility.

C. Present Status

The drilling has pinpointed a potentially important geothermal zone of alteration. Three major normal faults and two major thrust faults were encountered. The well encountered 438 feet of fracture permeability in the geothermal alteration zone (10,354 to 10,792 feet). It is believed that a test 3,930 feet to the east of the present well (Davis #1) could have encountered up to 6,500 feet of geothermal reservoir with the top of the reservoir at 6,000 feet. A logical question is why was this second location not drilled first, especially since the Group Seven resistivity anomaly was centered east of the Davis #1 drill site. The reason was that accepted geological theory for the area predicted that a well 3,930 feet to the east of Davis #1 would have been in pre-Cambrian igneous and metamorphics at 6,000 feet without the concealed first thrust fault. The well proved accepted theory false and shows that the Wellsville Mountains to the east are a remnant of at least two thrust sheets and have no roots.

The following tests have been made or are continuing at present:

(1) Water samples collected from the geothermal zone by means of a drill stem test produced results of about 85,000 ppm total dissolved solids with 51,000 ppm chlorides, 30,157 ppm sodium, 1,720 ppm calcium, 2,396 ppm potassium and 315 ppm SiO_2. From the samples, a final equilibrium temperature between 400°F and 500°F is predicted.

(2) The drill stem test by Haliburton gave fluid flow rates of 339 gal/min at 4,000 feet in depth, 1,000 gal/min at 7,450 feet and a fluid flow rate greater than 3,000 gal/min at total depth. Flow rates to the surface range from 3 to 7 gallons/minute.

James Kuwada estimates that for a well of this depth, a flow rate of more than 1,000 gallons/minute at a temperature in excess of 400°F would be needed for the well to be commercial for a double flashed steam power plant.

(3) The well is presently closed in while Dr Keller conducts temperature measurements. On June 21, at conclusion of drilling the bottom hole temperature was at 105°F. The temperature reached 272°F when the well was closed in. The temperature has remained constant for five weeks and is expected to remain so for one to two more weeks before heat from the zone reaches the well bore by conduction.

E. Future Program & Alternatives

Adequate temperature information must now be collected. Equilibrium temperatures in excess of 300°F are assured and with the promising flow rate, the area might support a binary power plant. If the temperatures do reach 400°F, then a double flash power plant design might be feasible. Various proposals for temperature measurements are now being studied.

Alternative sites for study would include the lease in the Escalante Desert of Iron County and the Roosevelt Hot Springs area east of Milford, Utah. Geophysical studies have just been completed in Iron County where the resistivity survey showed a large anomaly. A well drilled by Pan American Oil Company in 1970 just outside the eastern border of the anomaly produced 10,000 barrels/hour of low saline water (5,000 ppm) at 195°F.

The Roosevelt Hot Springs area is a much smaller anomaly according to our surveys, but does have a shallow steam well drilled to 266 feet by Thermal Power Company of Utah. The temperature of the steam exceeded 270°F.

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Aeromagnetics and the Transition Between the Colorado Plateau and Basin Range Provinces

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ABSTRACT

An aeromagnetic survey of central Utah has given improved resolution of a regional anomaly previously recognized from satellite magnetometer data. The anomaly consists of a gradient from a high over the Colorado Plateau to a low over the Basin Range province. Magnetic profiles are fit by a model in which the Curie isotherm deepens eastward in a belt up to 80 km wide, whose western side is about 50 km east of the Basin Range physiographic margin. The magnetic profiles could also be fit be a change of average crustal susceptibility instead of Curie depth. In either case we conclude that the major lateral change between Basin Range and Colorado Plateau crustal geophysical parameters occurs not at the Fenneman physiographic boundary but more than 50 km eastward of it. This suggestion is found to be consistent with data from seismic refraction, geomagnetic variation, geochemistry, and geologic structures.

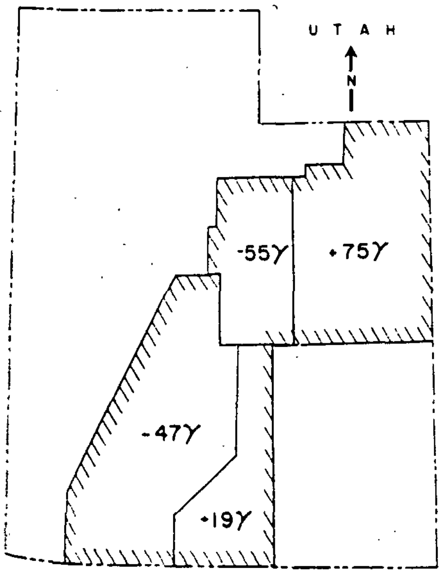

Figure 1. Outline map of Utah. Hachures indicate area of University of Utah aeromagnetic survey. Also shown are mean residual field values in gamma for four survey subdivisions.

INTRODUCTION

The Colorado Plateau and Basin Range (we will use "Basin Range" instead of the more popular "Basin and Range" because it is less awkward and seems to be the original term [Mackin, 1960, p. 114]) physiographic provinces of the western United States differ markedly not only in surface geology but also in crustal geophysics. Heat flow is low to normal in the Colorado Plateau, and high in the Basin Range (Roy and others, 1968; Sass and others, 1971). The Moho is deep under the Colorado Plateau, shallow under the Basin Range (Prodehl, 1970). The purpose of this paper is to present new aeromagnetic data on the nature of this fundamental crustal transition and to review other relevant published data.

SURVEY

In June 1971 the University of Utah flew an aeromagnetic survey of nearly half the state of Utah (Fig. 1). Its outlines were chosen to complement the aeromagnetic coverage of the U.S. Geological Survey and thus enable preparation of a complete state map. Data collection and compilation were performed so as to retain the broadest of anomalies: almost the entire survey was at the same barometric altitude of 12,000 ft. North-south flight lines were spaced at ~2 mi, and east-west tie lines at about 17 mi; lines were up to ~200 mi long. A temporary base station magnetometer was maintained within ~100 mi of the airplane. Daily variation was removed, reducing data to the mean nighttime value for June 1971. In low-gradient areas, flight lines and tie lines agreed to about ~5γ. Residual values were computed by removing the 13th order spherical harmonic expansion POGO 6/71, supplied by J. C. Cain and R. Sweeney of the National Aeronautics and Space Administration. In the area of the survey this field was quite similar to the 8th order 1965.0 IGRF. The difference was nearly constant, ranging from 384 to 393 γ.

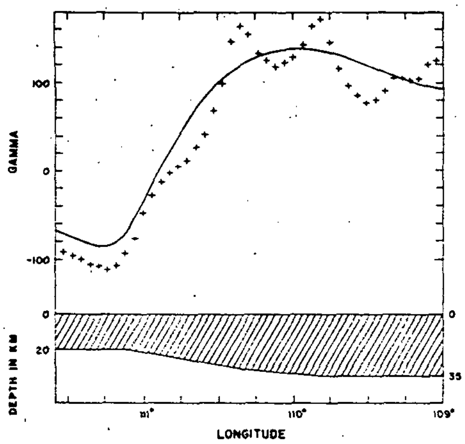

Figure 2. East-west profile across northeastern Utah. Crosses = residual magnetic field averaged over latitude from 39°26′ to 40°28′. Solid line = anomaly computed for indicated crustal thickening, assuming average susceptibility of 0.006 CGS units.

REGIONAL ANOMALY

This paper discusses only the broadest features of the magnetic data; a detailed contour map is to be released soon through the U.S. and Utah Geological Surveys. Most notable is a change in mean residual from positive in the eastern part of the survey to negative in the western part (Fig. 1). As illustrated in Figure 2, the change occurs over ~50 km. This regional magnetic pattern can also be identified on the satellite magnetometer map of Zietz and others (1970), where the contours over Utah strike north-south and define a gradient from a high over the Colorado Plateau to a low over the Basin Range province. The satellite map shows the high rising toward the south, leading to a sharp peak over west Texas. This trend is also confirmed by our data: in both of the eastern subdivisions (Fig. 1) there is a mean southward increase in magnetic residual of 0.2 γ per km. By contrast, the north-south trend in the western blocks is smaller and not always in the sense of a southward increase.

CURIE DEPTH

As Zietz and others (1970) have correlated the satellite magnetic anomalies with regional heat flow, we will consider the relation between magnetism and temperature.

Residual magnetic anomalies are due to the magnetism of crustal rocks at a temperature below the Curie point of magnetite. This temperature is 580°C in Fe_3O_4 but is significantly reduced by substitutional titanium. Curie points as low as 100°C have been measured for some volcanic rocks (Nagata, 1961, p. 96). In plutonic rocks, however, the titanium is largely exsolved as ilmenite. Buddington and Lindsley (1964, p. 313) gave the titanium content of magnetite in equilibrium with ilmenite for various oxygen buffers. These data suggest that for rocks in the deep crust and upper mantle the titanium content of the magnetite spinel phase will be 5 to 10 mole percent ülvospinel, corresponding to a Curie point of 560° to 520°C. Thus we consider that the magnetism of rocks disappears over a rather narrow depth interval corresponding to this temperature range. We will refer to this as the Curie depth, and the overlying rock as the magnetic crust. The estimates of Blackwell (1971) would place the Curie depth at about 22 km in the Basin Range province, and at 37 km in the eastern United States which the Colorado Plateau may resemble in thermal structure.

It is well known that an anomaly is not much affected by upward or downward continuation through a vertical distance less than its horizontal wave length. Therefore, an anomaly broader than the magnetic crustal thickness, such as the anomaly described in the preceding section, is insensitive to the depth of its source within the magnetic crust. Such regional anomalies reflect lateral variations in the vertical integral of magnetization. An analogy might be made with smoothed free-air gravity anomalies which reflect lateral variations in the vertical integral of density. In analogy to the Pratt-Hayford and Airey-Heiskanen theories of isostasy, it may be hypothesized that regional magnetic anomalies are due to variations either in average magnetization or in Curie depth. Zietz and others (1970) supposed that the residual magnetic gradient from Basin Range to Colorado Plateau is due to gradient of Curie depth. We will now consider the anomaly in more detail using this hypothesis.

PROFILE ANALYSIS

Figure 2 shows a stacked east-west profile across the northern part of the survey, together with the profile predicted for an eastward increase of Curie depth. No adjustment of zero level has been made. Note that for the western part of the profile the data is ~20 γ below the computed curve. This may be an error in the base level of our survey, arising either in daily variation correction or in main field removal. However, it is much smaller than the anomaly amplitude of >200 γ.

The model shown in Figure 2 closely fits the broad features of the data. However, some parameters of the model are more critical than others for this fit. All depths could be simultaneously increased or decreased by 10 km without great effect, so there is poor resolution on Curie depth. What is critical, as indicated before, is the lateral change of the vertical integral of crustal susceptibility. In particular, the beginning of the eastward increase cannot be moved more than 10 km from its optimum longitude at 111°7.5′ without significant deterioration of the fit. Additional uncertainty might be attributed to the location of this "corner," both because the profile represents an average over latitude and because it has limited extent westward from the corner. As a further check, we computed the field predicted by this model at an altitude of 300 km, taking into account the finite north-south extent of the Colorado Plateau. The result was a broad anomaly of 25 γ amplitude substantially like that shown on the satellite map of Zietz and others (1970).

South of 39° lat the situation is more complex. Our survey has lesser east-west extent (Fig. 1), although it is still characterized by negative mean residual

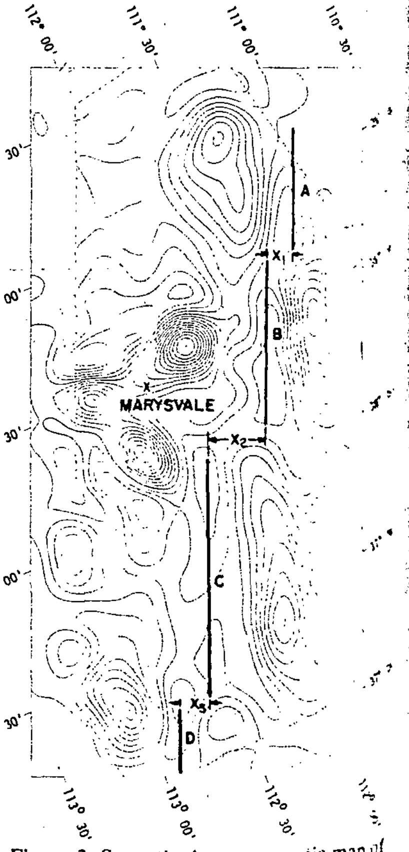

Figure 3. Smoothed aeromagnetic map of south-central Utah. Dashed line = limit of data actually used; contours outside dashed line = extrapolations. Data were reduced to pole and smoothed with low pass filter cutting off at wave lengths of 20 km. Distances X_1, X_2, and X_3 = 28, 12, and 14 km, respectively. Contour interval, 50 γ.

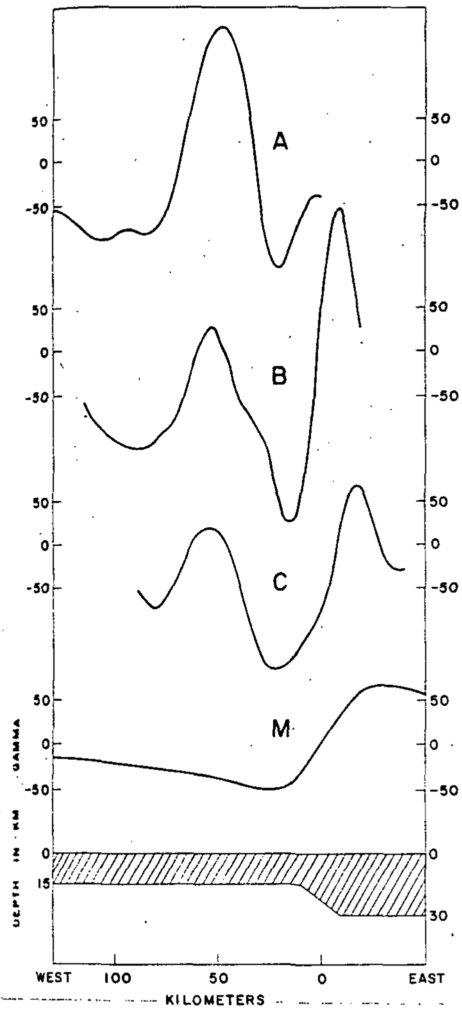

Figure 4. Stacked magnetic profiles compared to model of Curie downwarp. Profiles A, B, and C are perpendicular to corresponding segments in Figure 3, and are averaged over length of segment. Profiles were then shifted by offsets X_1 and X_2 indicated in Figure 3 to bring extrema into near coincidence. Profile M computed for model indicated at bottom of figure.

to the west, and positive mean residual to the east. The character of the map is completely different, because much of the exposed rock is igneous, whereas, in the survey area north of 39°, igneous outcrops are rare. Figure 3 shows some major features of the southern data. It omits the southeastern border of the survey, which was flown at a barometric altitude of 8,500 ft instead of the barometric altitude of 12,000 ft.

The parallelism of the contours in the eastern side of Figure 3 is striking. The feature most easily traced is the linear low or alignment of lows whose center is marked by heavy lines. Southward it may be traced at least 100 km into Arizona on the map of Sauck and Summer (1971). Northward it connects with the trough at 111°15′ long. shown in Figure 2.

One cause that may be proposed for a long linear magnetic low is hydrothermal alteration caused by solutions rising along deep crustal fractures (Gay, 1972, p. 8). In the present case we do not see how this hypothesis could be either proved or refuted. However, most of the mapped alteration in the area of Figure 3 is near Marysvale (Callaghan, 1939; Kerr and others, 1957). The magnetic map shows the Marysvale area as a saddle, and we believe the relatively low magnetic field there may well be caused by alteration. However, the field near Marysvale is *not* as low as that in the long linear low.

While the exact course of the lineament marked in Figure 3 is clearly due to lateral discontinuities of susceptibility within the crust, we propose that this low does approximately mark the *western* edge of the Curie depth downwarping under the Colorado Plateau. The extent to which this is so may be judged from Figure 4. On each of the profiles labeled A, B, and C, the minimum near the label corresponds to a segment of the linear low. To the west of these lows are highs, each probably due to deep-seated intrusives (Eppich, 1972; Schellinger, 1972). These relatively local highs are conspicuously absent from the model profile M. Note, however, that on each profile (A, B, C) the background does agree with the model. In all cases the western part has a negative mean value and a slight eastward slope. Although model M shown in Figure 4 is not exactly the same as that in Figure 2, we do not consider the difference significant, in view of the relatively large local anomalies in Figure 4.

LOCATION OF PROVINCE BOUNDARY

Figure 5 traces the course across our survey area of the low that we consider to mark the western edge of the Curie depth downwarping under the Colorado Plateau. Note that this low is at least 50 km east of Fenneman's physiographic boundary between the Basin Range and Colorado Plateau provinces. This boundary is based on topographic or geomorphic criteria. Other evidence considered in placing the major boundary includes:

1. Stratigraphy and Sedimentation. Roughly coincident with the present physiographic boundary is the Wasatch Line, which demarcates regions with very different sedimentary records (Stokes and Heylmun, 1963). If this line is defined precisely, it generally appears to be *west* of the physiographic boundary, by on the order of 10 to 30 km (Mackin, 1963).

2. Cenozoic Block Faulting. The distinguishing characteristics of the Basin Range province are arid climate and block faulting (Thornbury, 1965, p. 471). However, the block faulting continues about 50 km east of the topographic break (Fig. 5).

3. Seismicity. Epicenters are concentrated in a north-south zone called the Intermountain Seismic Belt by Sbar and others (1972). The east-west extent of this zone is roughly from the physiographic boundary eastward to the limit of block faulting. However, south of 38° N. the seismic belt appears to swing westward.

4. Seismic Refraction. A high-resolution seismic refraction profile extending from the Basin Range province into the Middle Rocky Mountains province (Braile and others, 1973) shows that the thin crust of the Basin Range province continues ~50 km east of the physiographic boundary before abruptly starting to thicken.

5. Gravity. Regional Bouguer gravity maps (American Geophysical Union, 1964; Montgomery, 1973) show a steep gradient all along the physiographic province boundary from high values in the Basin Range to low values in the

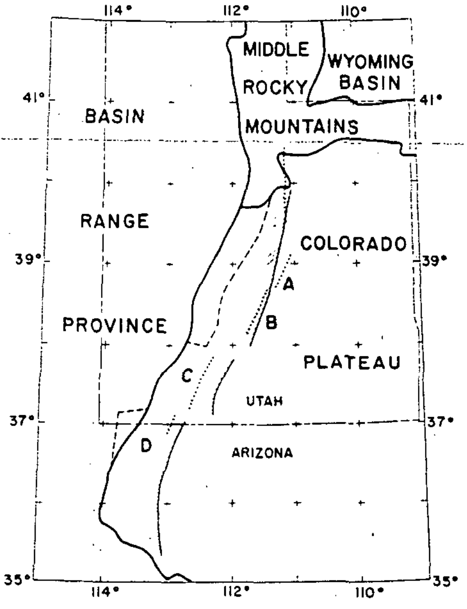

Figure 5. Relation of aeromagnetics to physiography. Solid lines = physiographic province boundaries of Fenneman and Johnson (1946); dashed line = alternative physiographic boundary chosen by Hunt (1956) and by Thornbury (1965). This latter boundary is apparently based on geologic structure as well as topography; our data might be considered to favor Hunt boundary over Fenneman boundary. Dotted lines located linear aeromagnetic lows shown in Figures 2 through 4. Hachured lines trace eastern limit of Basin Range block faulting.

Middle Rocky Mountains and the High Plateaus provinces, which lie along the western margin of the Colorado Plateau north of 37° N. In part this may be just the decrease of Bouguer gravity with increase of altitude due to isostasy.

6. Geomagnetic Variation. Variometers have been operated in east-west profiles at 37° N., 38°30′ N., and 40° N. (Reitzel and others, 1970; Porath and Gough, 1971). The 38°30′ profile unambiguously shows anomalously high upper mantle conductivity under the High Plateaus, which these authors call the Wasatch Fault Belt. Near the eastern edge of the High Plateaus is a precipitous eastward decrease in upper mantle conductivity, which is interpreted to mean a plunging of the mantle isotherms in the 1000° to 1500°C range.

7. Geochemistry. Recently, Lipman and others (1971) plotted K_2O/SiO_2 ratios for Cenozoic andesites of the western United States. In the western Pacific, this quantity is proportional to depth of a Benioff seismic zone. The depths calculated by Lipman gradually increase eastward, but with a sharp discontinuity along a line extending north-south from Canada to Mexico. This line passes east of the Marysvale volcanic area (Fig. 3) and hence definitely eastward of the boundary between Colorado Plateau and Basin Range provinces.

8. Heat Flow. As yet there are no published heat-flow values in the western Colorado Plateau, although the high heat flow in the Basin Range province is confirmed along its eastern border (Sass and others, 1971).

DISCUSSION

Our aeromagnetic survey, corroborating the satellite map of Zietz and others (1970), has shown that the vertical integral of crustal magnetization increases eastward in a belt up to 80 km wide, whose western side is about 50 km east of the eastern boundary of the Basin Range physiographic province. Supposing that this represents a thickening of the magnetic crust (that is, a deepening of the Curie isotherm), then we corroborate the isotherm shape inferred from geomagnetic variation (see no. 6, above). It is further predicted that the high heat-flow characteristic of the Basin Range province will be found to continue eastward, at least to the dotted line in Figure 5.

The magnetic profiles could also be modeled by a lateral change in susceptibility rather than in Curie depth. One argument against this is that any change of susceptibility which is really regional, that is, on a broader scale than individual flows and intrusions, would most likely occur between regions of distinctly different geologic history. Thus the most likely locus of a lateral change of average crustal susceptibility would be the Wasatch Line, which is definitely to the west of the magnetic gradient (see no. 1, above). More direct evidence of a change in Curie depth can be found by comparison of the power spectra of eastern and western blocks of magnetic data (Schellinger, 1972; Shuey, in prep.).

In conclusion, we propose that the major lateral change between Basin Range and Colorado Plateau crustal geophysical parameters occurs not at the physiographic boundary but some 50 to 100 km farther east. This conclusion can be drawn not only from aeromagnetics but also from geologic structures, seismic refraction, geomagnetic variation, and geochemistry. Of the eight types of evidence considered above, only gravity is not easily reconciled with this conclusion.

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