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publisher unknown

1974

Note Well Costs & Land Cost are as of Dec 73

ECONOMIC CONSIDERATIONS FOR GEOTHERMAL EXPLORATION IN THE WESTERN UNITED STATES

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INTRODUCTION

Geothermal exploration in the United States, to date, has been conducted by industrial companies with experience in using geology and geophysics for the location and evaluation of oil, gas, and minerals. This experience, obtained over many years, has resulted in the building of data banks of basic geologic and geophysical information concerning geothermal resource areas. Table 1, "Characteristics of favorable geothermal areas", summarizes some of this basic information.

TABLE 1

CHARACTERISTICS OF FAVORABLE GEOTHERMAL AREAS

1. PROXIMITY TO COOLING IGNEOUS INTRUSIVE.
2. RESERVOIR WITH HIGH BASE TEMPERATURE AT REASONABLE DEPTH. 200° TO 300° C OPTIMUM.
3. RESERVOIR MUST BE PERMEABLE AND EXTENSIVE WITH IMPERMEABLE CAP.
4. RESERVOIR WATER IN A RECHARGEABLE SYSTEM. CONVECTION CIRCULATION.
5. WATER SHOULD NOT CONTAIN LARGE QUANTITIES OF DISSOLVED SOLIDS.
6. DISPOSAL SYSTEM FOR FLUIDS AFTER HEAT DISSIPATION.

Geological areas offering moderate risks for geothermal exploration have been examined in detail by natural resource development companies or well-financed individual investors. Exploration to locate a geothermal prospect will be the high risk part of the geothermal industry and, as such, requires management by groups experienced in assuming risks, such as the petroleum industry. Table 2 compares the exploration requirements of the petroleum industry and geothermal exploration requirements. This management group will be experienced in reducing the expected delays of four to five years before commencement of income from the development and production of geothermal heat. The sale of the geothermal heat to the electrical producing organization and the return of the cooled fluid that transported the heat from the subsurface geothermal reservoir completes the high risk phase of the geothermal industry. This high risk part will require a high rate of return on the risk capital invested (Table 3).

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[1] Chevron Oil Company

Cost figures are rapidly becoming obsolete, the type of items are germane to exploration will be relative and the increases in worth of geothermal R B Greider

TABLE 2

COMPARISON BETWEEN PETROLEUM AND GEOTHERMAL EXPLORATION AND PRODUCTION PROCEDURES

	PETROLEUM	GEOTHERMAL
EXPLORATION		
GEOLOGY-GEOPHYSICS	PREDICT AND DETERMINE RESERVOIR EXTENT, QUALITY, AND DEPTH. TRAP CONFIGURATION, PRESSURE AND NATURE OF RESERVOIR FLUIDS.	SAME - MINOR DIFFERENCES IN DATA GATHERING TECHNIQUES
LAND LEASE	OBTAIN LEASES ON TERMS ESTABLISHED FROM ABOVE DATA	SAME
EXPLORATORY WELLS	DESIGNED TO DETERMINE RESERVOIR FLUIDS, NATURE AND PRODUCTIVITY.	SAME
PRODUCTION		
DRILLING	ROTARY MUD OR AIR	SAME
COMPLETION	INCLUDES CASING AND TUBING, BOTTOM HOLE COMPLETION AND SURFACE SEPARATOR INSTALLATIONS FOR WIDE RANGE PRESSURES AND VOLUMES.	SAME - SAME PROBLEMS AS IN LOW PRESSURE, VOLUME WET GAS COMPLETIONS
FIELD DEVELOPMENT	DESIGNS DEPEND UPON MARKET AND EFFICIENT RECOVERY.	SIMILAR BUT FIELD AREA WILL BE MORE COMPACT.

TABLE 3

GEOTHERMAL INDUSTRY

I. EXPLORATION - DEVELOPMENT - PRODUCTION
  - A. HIGHER RISKS REQUIRE HIGHER RETURN.
  - B. EXPERIENCE IN OIL & GAS TRANSFERABLE.
    - 1. MANAGEMENTS NORMALLY RISK ORIENTED.
    - 2. EXPLORATION DATA ACQUISITION & INTERPRETATION.
    - 3. DRILLING IN DIVERSE GEOLOGIC SECTIONS, WIDE CLIMATIC CONDITIONS & EXTENSIVE GOVERNMENTAL GUIDELINES.
    - 4. PRODUCTION AND DISPOSAL OF FLUIDS AT HIGH VOLUMES.

II. POWER PRODUCTION
  - A. LOWER RISK - FIXED RATE OF RETURN.
  - B. RECEIVING OF STEAM OR WATER IN 350° TO 400°F TEMPERATURE RANGE.
  - C. GENERATING AND DISTRIBUTING ELECTRICITY.

III. RECOVERY OF CONSTITUENTS OTHER THAN ENERGY
  - A. UNUSUAL CIRCUMSTANCES.
  - B. BY EITHER I OR II.

The organization receiving the heat carrying fluid will probably design, build and operate the electrical generating equipment. Management of the power plants at The Geysers, California; Cerro Prieto, Mexico; Larderello, Italy; and Wairaki, New Zealand, has provided a background of power plant problems and design solutions to these factors, so that now the electrical generation phase is "low risk" (Table 3). A fixed rate of return, with consideration for research and development expenditures in fitting present technology into the peculiar characteristics of each producing area, probably will be established by the public utility commissions in each geothermal resource producing state.

Exploration programs to find geothermal resources must offer a potential return (for the risk taken) that is competitive with the return expected if the same funds could be used to explore for oil, gas, coal, or uranium (Table 4). To acquire geothermal exploration funds, the rate of return should be more attractive for the geothermal projects than for more familiar fuels. Figure 1 shows the magnitude of production being obtained at The Geysers Field in California. Competitive fuels are being sought by sophisticated exploration groups with knowledge and experience that provide the investor with a reasonable chance of success at calculable risk factors, technology and prescribed budget framework. The majority of exploration programs for geothermal resources will be required to use a similar economic evaluation format to obtain the extremely large funds required to develop a successful find.

TABLE 4

COMPETITION FOR CAPITAL

I. FUNDS FOR GEOTHERMAL EXPLORATION AND PRODUCTION PROVIDED FROM SOURCES THAT HAVE A WIDE INVESTMENT CHOICE.

II. OIL, GAS, COAL & URANIUM EXPLORATION MATURE.
   A. TECHNIQUE EFFECTIVENESS KNOWN.
   B. PREDICTABLE COSTS & TIME FRAMES.
   C. RISK FACTORS CONFIRMED BY STATISTICAL SUCCESS.
   D. SHORT FALL BETWEEN SUPPLY & PREDICTED DEMAND ASSURES RAPID DEVELOPMENT AND SALE.

III. GEOTHERMAL MUST MEET ECONOMIC CRITERIA OF
   A. EXPLORER & PRODUCER HIGH RETURN EARLY PAYOFF.
   B. POWER PRODUCING UTILITY LOWER RISK & RETURN REGULATORY RATES.

IV. PREDICTION OF PROFITABILITY FOR GEOTHERMAL INVESTMENT.
   A. AFFECTED BY EVOLVING REGULATIONS.
      1. LEASE SALES
      2. EXPLORATION PROCEDURE
      3. LOCATION OF AND THE MANNER OF DRILLING
      4. SPACING OF WELLS
      5. PLANT & LAND SITES
   B. TYPE OF OWNERSHIP.
   C. TREATMENT OF EXPLORATION & DEVELOPMENT EXPENDITURES FOR TAX ANALYSIS.
   D. TREATMENT OF PRODUCTION TAXES.

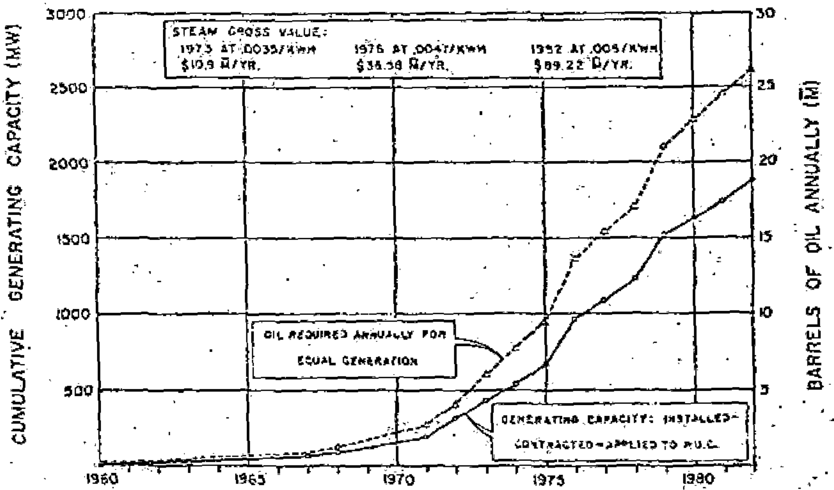

Figure 1. GEYSERS GEOTHERMAL FIELD

MAGMA ANNUAL REPORT, 1972

The profitability of any geothermal exploration program in the western United States will be affected by:

1. Inclusion of total geological, geophysical and land costs of all exploration work leading to the completion of each successful field.
2. The length of time between program initiation and payout of all expenditures or until a positive cash flow is reached.
3. Location, terrain and geology of the development site as drilling and production costs are influenced by these factors. The value of an electrical generating plant at the anomaly's location determines the price the utility can afford to pay for the heat.
4. Price for competitive fuels in the market area.
5. Tax structure and treatment of all costs applicable to this depletable resource of heat.
6. Ecological expectations existing before and after development.

Federal, state and county regulations are being developed now to provide control of lease sales, exploration procedures, location, manner of drilling, spacing of development wells, siting of steam transmission pipelines, generating plants and the electrical transmission lines. These controls can significantly affect the desirability of finding and developing geothermal resources. If the costs imposed by these regulations are such as to increase the price of geothermal heat to an amount that would not offer attractive savings over conventional fuels, the funds to explore for geothermal resources will be restricted and also associated activities. The recognition must be made that geothermal heat is a new commodity not envisioned during the time waters were considered simply surface or near surface water, potable, fit for agriculture, or deeper subsurface briny water not suitable for regulation or use, except in oil production. Thus, a sane approach should be made to determine the governmental agency responsible for regulation of geothermal activities. The mining of sand and gravels from a gold placer claim is regulated considerably differently, for example, than sand and gravel mining for concrete aggregate recovered under a lease. In the same way, brines producing steam or carrying heat under pressure are different from potable water.

ECONOMICS

The majority of published geothermal energy profitability reports have ignored treatment of exploration and development expenditures. The treatment of these items must be consistent with state and federal tax laws. For example, expensed items are those deducted from income in the year of expenditure. Capitalized items are those that have a tangible or salvageable value and are depreciated during the life of the project in a manner prescribed by Internal Revenue Service regulations.

Expenditures that are of a regional or of a reconnaissance nature, such as costs incurred in establishing the stratigraphy of a geologic province, are expensed. Expenditures that lead directly to the acquisition or retention of land in an area of interest are usually capitalized. Regional geophysical surveys, such as aerial magnetometer mapping, would be expensed. Geophysical surveys to detail the configuration of an anomaly to establish where to acquire leases would be capital in nature. Detailed temperature surveys on a leased prospect would be capitalized.

A payment to acquire a lease from the owner of the geothermal resources is treated as a lease bonus and is capitalized. Subsequent payments to maintain the lease in effect, if paid over certain definite uniform periods of time, are rentals and are expense in nature. Royalty payments prescribed in the lease or in the assignment of a lease to a third party are expensed.

Costs of unsuccessful exploratory wells may be expensed in the year incurred. Successful wells may be treated in a simple manner with all costs incurred considered to be capital in nature. If you elect to expense intangible costs incurred in drilling and completion of a successful well, this may be done. All wells must be treated consistently following such an election. The intangible expensed costs may normally account for 70% to 75% of the well's costs and do not have salvageable value at the completion of the project. These costs include: the location preparation, move in and move out of the rig, transportation of supplies and crew, drilling costs on a footage drilled basis or on a set day rate for the rig and crew, drilling fluids, cement, logging, testing and preparing the well for completion. All supplies used on the location are included in the expense category.

The tangible costs, comprising 25% to 30% of the well's costs, are usually for items having salvageable value. These include capital items such as all casing, tubing and well head equipment. Separators, gauges, valves and transmission lines are also capital in nature.

Revenue will usually be calculated on the basis of Btu's supplied, or for each kilowatt hour of electricity produced by the geothermal heat. Royalty is paid to the owner of the geothermal resource on the basis of heat supplied the electrical generating plant. At The Geysers Field, 0.5 mils per kilowatt hour of electricity produced is paid for reinjection of condensed fluid from the generating plant. This is not considered a payment subject to royalty computation. The expense for reinjection of fluids in a liquid-dominated system will be considerably larger than for a vapor-dominated system, such as The Geysers, due to the greater volumes of liquid to manage and the greater increase in corrosive material left after the steam has flashed from the liquid.

The precise amount of money generated by sales of the geothermal resource from fluid-flash systems and heat extraction systems cannot presently be determined as the tax treatment has not been tested in court. The extensive collection of data on geothermal systems from around the world now support the thesis that these systems are depletable in pressure, volume and temperature and will eventually be allowed depletion allowance for income tax computation. The flow of money generated by sales, less the expense items and the capitalized items' depreciation, will determine the amount of income subject to income tax.

Items subtracted from revenues include: exploration salaries, benefits, travel expenses, research management and administrative allocations, ad valorem taxes (county and state) and production or severance taxes. Indirect charges, such as depreciation on capitalized items and depletion allowances based on cost of a property or on a percentage of gross income, are deducted from revenue. Funds remaining after deducting income taxes are those remaining to pay out the investment which includes investments in previous failures. This deduction of income tax payments is frequently overlooked in geothermal economic discussions.

Now let us examine the framework of an exploration budget. The component costs of the various segments of the exploration program must fit within the magnitude of expenditures that can be allocated to the total budget. At this time, the exploration budget will probably include:

GEOLOGY	-Salary, office and field expenses average $3,000 to $4,000 per geologist per month - Expense all reconnaissance expenditures. (Table 5)
GEOCHEMISTRY	-Geologist and assistant with vehicle and analysis by commercial laboratory will cost $10,000 to $14,000 per month - Expense. (Table 5)
GEOPHYSICS	-Gravity $10,000 per month - Expense. Airborne magnetometer $5.00 to $10.00 per square mile - Expense. Electrical Resistivity or Micronoise $10,000 to $15,000 per project - Expense. Detailed surveys on or resulting in acquisition of leased prospects $10,000 to $14,000 - Capitalize.

Temperature surveys drilling costs $1.50 per foot for holes up to 500 feet deep. This results in the average prospects temperature surveys costing $10,000 to $15,000 per month, exclusive of geological interpretation. (Table 5)

Reconnaissance surveying costs are expensed. Detail temperature surveys on a close grid will be capitalized if leases are taken or retained.

LAND ACQUISITION -Lease bonus paid will be dependent on location of the nearest geothermal production, interest shown by academic or governmental research projects and degree of economic development. Wildcat areas will require $1.00 per acre bonus (capitalized) and $1.00 per acre per year rental (expensed). Competitive areas may require $5.00 to $10.00 per acre bonus after production has been established in the area. Broker or landmen will cost $65.00 to $130.00 per day during leasing activity. This sum is capitalized. It is anticipated that an average sized prospect should require $45,000 to $60,000 - Capitalize. Table 5 summarizes these costs.

DRILLING -Exploratory well costs in the United States will average $20.00 to $30.00 per foot down to 5,000 feet in most geothermal provinces located in sedimentary basins. In remote areas or those with igneous interbeds, costs will be $30-$60 per foot. To run casing and prepare for production will cost approximately $10.00 to $15.00 per foot down to 5,000 feet. Wells capable of production will be capitalized. Non-commercial wells that are abandoned will be expensed. When the lease or the failure is abandoned, all capital items charged to the site will be expensed. See Table 5 for a breakdown of these costs.

The above costs indicate that an average area of interest can cost approximately $75,000 to $95,000 before knowing that drilling is justified. If one out of four areas of interest is judged to be worthy of drilling for temperature and water quality data, the cost will be $300,000 to $380,000 per drillable prospect. Though most exploration programs will locate steaming water, we must assume one out of four of the prospects drilled for temperature and salinity data will have sufficient economic or technical encouragement to run pipe and complete for extensive testing. The three unsuccessful wells will cost $100,000 to $200,000 each, and the completed well $150,000 to $250,000, for a possible average total of $650,000 of exploratory drilling costs for each well worth extensive testing. If one out of four of these locate an anomaly large enough to be commercial, the program will be attractive. The cumulative exploration expenditures for all the prospects leading up to and including the sixteen prospects evaluated by drilling for each successful prospect comprise the "risk" money attributable to the success and must be paid out by that success. The cumulative expenditure average for the example given is $8,000,000. It is believed that an experienced geological-geophysical team can improve on these statistics in the next few years. There will probably be a more favorable success ratio in the early stages of geothermal energy exploration as the large, easily detected anomalies will be the first drilled. As the industry matures, higher risk projects will be explored and this 16:1 ratio will be approached.

Federal regulations prohibit the discharge of degrading effluent into a river system. Therefore, as liquid-dominated systems are the most likely system to be found, the development stage of prospect analysis should require plans for injection wells costing nearly $125,000 for a 5,000 foot deep well. As a result of the large volumes of liquid produced in a hot water geothermal field, the ratio of injection wells to producers will be nearly 1:2. Environmental concerns will dictate returning the cooled fluids to or near the original reservoir. Field operation costs will be approximately $30,000 per well, per year.

A review of case histories of geothermal energy developments indicates that a prospect located 75 to 100 miles from a market, to warrent development, should have the potential to support the generation and marketing of 250 to 275 megawatts in a base load situation. Any operation with a smaller goal than this cannot support the exploration risk, the field development investment and the charges for time value of capitol invested while waiting for revenue to be generated.

In a valid analysis of investment opportunity, one must assign a time value of money to all monies invested for "n" number of years prior to any revenue being received. A common value of money today is 12 1/2% if the venture phase is low risk, and 15% if moderate risk is expected. The value of money (VOM) for any period of time after the money is invested is calculated by the following formula:

$$(\text{Value of money today})(1 + \text{interest rate})^n = \text{Value of money after "n" years.}$$

In a similar manner, revenue expected in "n" years reduced to present value is calculated in the following formula:

$$\text{Value of money today} = \frac{(\text{Revenue expected})}{(1 + \text{Interest rate})^n}$$

Figure 2 shows the value of money invested for any period of time up to twenty years at varying interest rates. For example, one million dollars of income eight years from now discounted at 15% is valued at $325,000. Thus it can be seen that the effect of several years' wait from exploration to initiation of sales of heat is disastrous in the rate of return; thereby, endangering the economic viability of a project (Figure 2).

The amount and time that money is invested with no revenue being received may be reduced, thus improving the economic viability of the project, by the acceptance of basic reservoir engineering data obtained from the carefully designed initial drilling and text programs. Studies by Dr. H. J. Ramey, of Stanford University, on reservoir performance and reserves forecast for the liquid-dominated geothermal system in

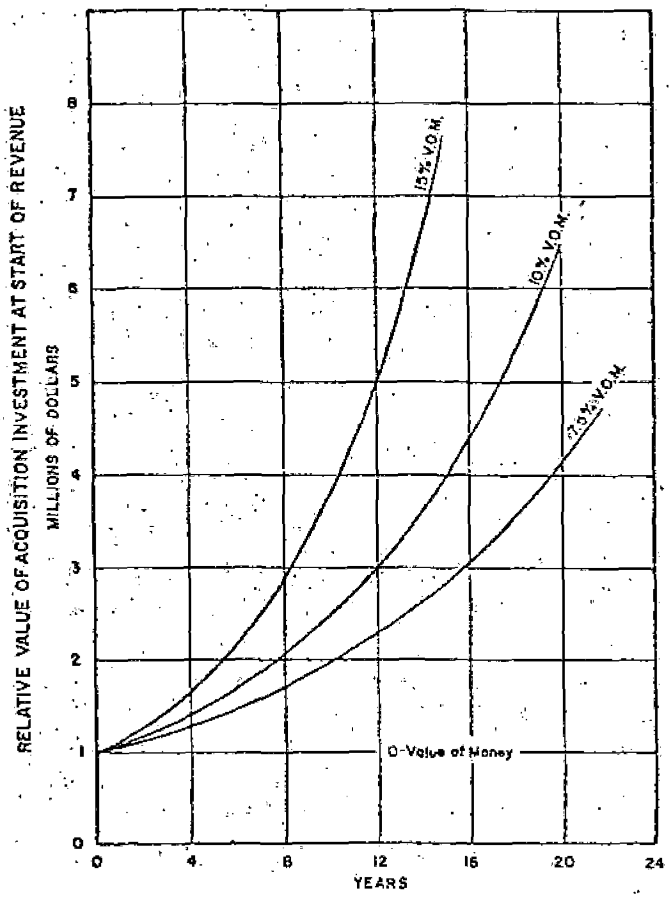

Figure 2. ELAPSED TIME BETWEEN INITAL INVESTMENT AND BEGINNING OF REVENUE

New Zealand and the vapor-dominated system at the Geysers, demonstrates that it is not necessary to completely develop a geothermal field before designing the electrical generating plant. Reliable predictions on field size can be made using material balance analysis of broadly spaced wells completed in a common reservoir.

The price for steam produced from the only producing steam field in the United States, the Geysers, is approximately 3 mils per kwh generated (Figure 1). This price is very cheap today compared to conventional electrical generating plants using the low sulfur fuels required by the Environmental Protection Agency. The sharply lower operating costs for geothermal plants compared to conventional plants using the low sulfur fuels results from elimination of boiler plant and auxiliary equipment investment and operating charges plus eliminating the $ .40 to $ .90 per million Btu low sulfur fuel used to fire the boiler plant.

A study done by Westinghouse in the Spring of 1973, equated operating and fuel costs for coal, oil, and nuclear generating systems.

In this study, the geothermal field development costs were substituted for the steam supply system of conventional plants. It was shown that approximately 6.3 mils per kwh or $250 per kw capital costs would be a reasonably competitive price for geothermal resources when nuclear fuel is priced at 21 cents a million Btu's and nuclear capital costs are held to $400 per kw.

Reviewing the various cost factors associated with exploring for a 250,000 kw (minimum) geothermal hot water field, it is estimated that the field can be found for $8,000,000. With careful planning, the drilling and completing of the 50 producing wells of the field will cost at a minimum of $7,500,000, and the 25 injection disposal wells will cost $3,500,000 to $5,000,000. Using the experience and knowledge gained in New Zealand and Cerro Prieto, Mexico, the total subsurface and surface capital investment steam facility over a 35-year field life will require between $20,000,000 and $24,000,000. Operating expenses, including remedial well work, redrills, overhead, mineral and property taxes, abandonment costs, injections costs and royalty paymets, will total approximately $2,300,000 per year or $75,000,000 to $80,000,000 for the project life. Table 6, located at the end of the paper, summarizes these costs.

The following Table is a summary of the technical conditions and economic parameters used in developing the economic model of a 275 MW hot water geothermal field.

TABLE 7

ECONOMIC MODEL

EXPLORATION PROGRAM THROUGH PRODUCTION
275 MW FUEL SUPPLY

INCLUDES ALL GEOLOGICAL, GEOPHYSICAL AND LAND EXPENDITURES REQUIRED FOR DRILLING SIXTEEN PROSPECTS TO DISCOVER ONE FIELD THAT CAN MEET THE REQUIREMENTS FOR THIS SIZE OF PRODUCTION.

1. PRODUCTION RATE WILL BE THE AVERAGE OF COMPLETED WELLS AT CERRO PRIETO, MEXICO.
2. PRODUCING WELLS SPACED 10 ACRES APART. INJECTION WELLS ON FIELD PERIPHERY.
3. 10 PRODUCING WELLS AND FIVE INJECTION WELLS REQUIRED FOR EACH 55 MW TURBINE.
4. 80% PLANT FACTOR, 90% PRODUCING WELL FACTOR AND 20% STANDBY CAPACITY.
5. 10% MAXIMUM ROYALTY EXPENSE.
6. MINERAL AND PRODUCTION TAXES ARE 6% OF GROSS WORKING INTEREST INCOME.
7. 22% DEPLETION CREDIT.

DEVELOPMENT TO 275 MW	4.8 MIL PER KWH
INVESTMENT ($000)	$20,000 TO $24,000
OPERATING EXPENSE, TAXES & ROYALTY ($000)	$75,000 TO $80,000
YEARS TO COMPLETE PAYOUT	7.3 YEARS
RATE OF RETURN	13.7%
NET PROFIT PER YEAR AFTER PAYOUT ($000)	$3,820

THE PAYOUT TIME MAY BE DECREASED TO 6.4 YEARS, AND RATE OF RETURN INCREASED TO 17%, IF (1) THE PRICE OF FUEL IS INCREASED TO 5.6 MILS PER KWH GENERATED; (2) THE DRILLING SCHEDULE OF THE FIELD IS ADJUSTED TO ACTUAL MODULE GENERATING PLANT COMPLETION, AND (3) MINERAL AND PRODUCTION TAXES ARE HELD TO 5% OF INCOME.

SUMMARY

To accelerate the utilization of geothermal resources, more knowledge is needed in:

A. The geological, engineering and economical factors that characterize favorable geothermal areas for exploration.
B. The designing and testing of methods for generating electricity using hot waters in the 300° F to 400° F (150°C to 210°C) temperature range.
C. Well completion methods that can reduce corrosion, scale build-up and control of very friable sands that cause in-sand plugging and erosion at temperatures above 450°F (230°C).
D. Understanding reservoir behavior under drilled and production regimes.
E. Determining factors that create the large occurrence of 150°C to 210°C reservoirs of hot water, and how the very limited number of those above 230°C remain hot and will respond to reinjection of fluids of a cooler temperature.
F. Early recognition of the ultimate potential of a geothermal anomaly so that an economic rate of development may be planned.
G. The exploration success for conventional fuels and their being available in sufficient amounts during the next 15 years.

In summary, it should be noted that the future for geothermal energy presents attractive economic objectives and opportunities. These are not only restricted to the attractive California energy market. In the future, we should see the scope of geothermal exploration expanded, for up to now around the world regional geothermal prospecting has been limited to those hot spring areas offering exploration potential. This is the same as limiting oil exploration to areas of oil seeps. By analogy with the petroleum industry, it is therefore expected that there is a significantly greater amount of geothermal energy to be found in the future than that recognized by hot springs alone.

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TABLE 5

GENERAL GEOTHERMAL PROJECT BUDGET COSTS

EXPLORATION

GEOLOGY	SALARY, OFFICE AND FIELD-EXPENSE	$3,000 TO $4,000 PER MONTH PER GEOLOGIST
	REGIONAL EVALUATION - EXPENSE	
	SPECIFIC PROSPECT CONFIGURATION - CAPITALIZE	
GEOCHEMISTRY	GEOLOGIST, FIELD ASSISTANT VEHICLE AND COMMERCIAL LAB. ANALYSIS	$10,000 TO $14,000 PER MONTH
	RECONNAISSANCE - EXPENSE	
	EVALUATION OF AREAS OF INTEREST - CAPITALIZE	
	BORE HOLE TEMPERATURE (WATERS) - EXPENSE	
GEOPHYSICS	GRAVITY	$10,000 PER MONTH
	BROAD COVERAGE - EXPENSE	
	CLOSE SPACED EVALUATION OF PROSPECT - CAPITALIZE	
	MAGNETICS - EXPENSE	$5,000 TO $10,000 PER MONTH
	MICRONOISE	$10,000 TO $15,000 PER MONTH
	RECONNAISSANCE - EXPENSE	
	DETAIL PROSPECT - CAPITALIZE	
	ELECTRICAL RESISTIVITY	$10,000 TO $15,000 PER MONTH
	RECONNAISSANCE - EXPENSE	
	DETAIL PROSPECT - CAPITALIZE	
	TEMPERATURE SURVEYS	$30,000 PER MONTH*
	200' DEPTH RECONNAISSANCE - EXPENSE	
	500' DEPTH PROSPECT EVALUATION - CAPITALIZE	

* ADD $10,000 PER MONTH FOR CALIFORNIA

TABLE 5
(cont.)
LAND ACQUISITION COSTS

THE FORM OF LEASE AND THE TERMS ARE DEPENDENT UPON THE STATE LAWS AND THE TYPE OF PREDOMINATE OWNERSHIP - FEE, STATE, FEDERAL, INDIAN, OR RAILROAD GRANT.

FEE - SIMPLE OWNERSHIP:

10,000 TO 20,000 ACRES MUST BE OBTAINABLE IN A REASONABLY COMPACT BLOCK. ALLOWS EXPLORATIONS TO DEFINE THE CENTER OF HEAT AND CONTROL DEVELOPMENT.

STATE - NORMAL AS FILL IN TO OTHER ACREAGE.

FEDERAL - AT THIS TIME, ACQUISITION IS NOT ASSURED.

INDIAN LANDS - WESTERN TRIBES PREFER TO NEGOTIATE INDIVIDUAL VENTURES.

RAILROAD GRANTS - ALTERNATE SECTIONS USUALLY FEDERAL - THIS IS NOT AVAILABLE. ADDITIONAL COMPLICATIONS WHERE SURFACE AND SUBSURFACE RIGHTS HAVE BEEN SEPARATED.

ACQUISITION COSTS

BONUS	- WILDCAT AREAS, LITTLE DATA ON SUBSURFACE	$1.00 PER ACRE
	- SEMI-DEVELOPED AREAS WITH STRONG DATA AT DEPTH	$5.00 TO $10.00 PER ACRE
	- DEVELOPED AREAS WITH POWER PRODUCTION	$1,000 PER ACRE
PERSONNEL	- LANDMEN KNOWLEDGE OF GEOTHERMAL PRACTICES - $65.00 TO $130.00 PER DAY.	
	TOTAL LEASING COST	$2.00 TO $3.50 PER ACRE

TABLE 5
(cont.)
EXPLORATORY DRILLING COSTS

SEDIMENTARY SECTION	
AREA REASONABLY NEAR DRILLING SERVICES: DOWN TO 5,000 FT., $20 TO $30/FT. FOR DRILLING & LOGGING, $1,200 TO $2,000 PER DAY	$125,000
COMPLETION WITH CASING & PERFORATIONS PLUS SURFACE VALUES - AVERAGE TO 5,000 FT., $10 TO $15/FT.	65,000
TOTAL	$190,000
IGNEOUS INTERBEDS & REMOTE AREAS	
DRILLING COSTS TO DEPTHS OF 6,000 FT. FROM $30 TO $60 PER FOOT OR $3,000 TO $6,000 PER DAY	$250,000
COMPLETION WITH OPEN HOLE IN FRACTURED RESERVOIR, $8.00 TO $15.00 PER FOOT	60,000
TOTAL	$310,000

CAPITALIZE SUCCESSFUL TESTS (MAY EXPENSE INTANGIBLE)

INTANGIBLES:	ACCOUNT FOR 70% TO 75% OF ALL COSTS, INCLUDING LOCATION PREPARATION, RIG MOVE IN & OUT, DRILLING AND DAY RATES DRILLING FLUIDS, CEMENT, LOGGING, TESTING, & PREPARING WELL FOR COMPLETION.
TANGIBLES:	INCLUDE CASING, TUBING, WELLHEAD EQUIPMENT

TABLE 6

Estimated Costs for Exploring for and Developing a 250,000 kw Geothermal Hot Water Field

EXPLORATION	
GEOLOGY:	
SALARY, OFFICE AND FIELD EXPENSE	$3,000 TO $4,000 PER MONTH
GEOCHEMISTRY:	
GEOLOGIST, ASS'T., VEHICLE AND ANALYSIS	$10,000 TO $14,000 PER MONTH
GEOPHYSICS:	
GRAVITY	$10,000 PER MONTH
MAGNETICS	$5.00 TO $10.00 PER SQUARE MILE
MICRONOISE	$10,000 TO $15,000 PER MONTH
RESISTIVITY	$10,000 TO $20,000 PER MONTH
TEMPERATURE SURVEYS	$1.50 PER FOOT TO 500 FEET
LAND ACQUISITION:	$45,000 TO $60,000 PER PROSPECT
WILDCAT	$1.00 PER ACRE BONUS
SEMI-DEVELOPED AREA	$5.00 TO $10.00 PER ACRE
PERSONNEL	$65.00 TO $130.00 PER DAY
DRILLING:	
EXPLORATORY WELL TO 5,000 FEET	$20.00 TO $30.00 PER FOOT
COMPLETE WITH CASING	$10.00 TO $15.00 PER FOOT
SUMMARY OF COSTS:	
AREA OF INTEREST	$75,000 TO $95,000
FOR ONE DRILLABLE AREA FOUR AREAS WILL BE WORKED	$300,000 TO $380,000
ONE AREA OUT OF SIXTEEN DRILLED FINDS 250,000 KW FIELD	
TOTAL EXPLORATION COSTS	$8,000,000
DEVELOPMENT	
50 PRODUCING WELLS	$7,500,000 TO $10,000,000
25 INJECTION WELLS	$3,500,000 TO $ 5,000,000
TOTAL SURFACE AND SUBSURFACE CAPITOL INVESTMENT COSTS	$21,000,000 TO $24,000,000 (includes exploration Costs)
OPERATING	
ESTIMATED OPERATING EXPENSES, TAXES AND ROYALTY FOR 35 YEAR FIELD LIFE	
$2,300,000 per year	$75,000,000 TO $80,000,000

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

TO ACCOMPANY MAP MR-30

MERCURY IN THE UNITED STATES

(Exclusive of Alaska and Hawaii)

By Edgar H. Bailey

INTRODUCTION

This map shows the location of mercury districts and deposits in the United States (exclusive of Alaska and Hawaii). The map was compiled from published reports and from data in the files of the Geological Survey. All map locations are numbered consecutively in each state and names, geographic coordinates, and selected references are given in the Index.

The estimated total quantity of mercury present before depletion by mining was used to assign districts to size categories; both production and reserves are included without distinction. Three sizes of mercury deposits are shown on the map: deposits of more than 100,000 flasks (76 pounds per flask); large deposits, but containing less than 100,000 flasks; and small deposits. Most mercury districts contain only one large deposit and many smaller deposits and occurrences, but a few districts contain several large deposits.

Geology

The mercury deposits of the World are confined, with a few minor exceptions, to a broad belt of late Tertiary orogeny and volcanism, a part of which extends through the Western United States. For many major deposits such as the New Idria mine in California, however, no close relation to a volcanic source can be demonstrated, and most deposits are at least a few miles from surface exposures of late Tertiary or Quaternary volcanic rocks. Most of the domestic mercury deposits are found in California and a few in Oregon and Nevada. Within this tectonic belt mercury deposits occur in rocks of all ages and of all common varieties. Structures responsible for ore localization are equally as varied. In some mines there are well-formed structural traps with "caps" of relatively impervious material, generally shale or gouge, but in some major deposits no structural control is obvious. In general, however, deposits in similar kinds of rocks exhibit similar structural environments, and an understanding of the geologic relations in one deposit can be of value in appraising or developing another deposit in the same kind of rock.

Mercury ores are formed relatively near the surface and appear to extend downward from the surface to a maximum depth of about 2,500 feet, reached at the New Almaden mine in California. The bulk of the ore that has been mined has come from depths of 1,000 feet or less. Because the deposits were formed near the surface in orogenic belts, it is likely that any geologically ancient deposits have been eroded away, and all deposits that can be accurately dated are Pliocene or younger in age.

The principal ore mineral in mercury deposits is cinnabar, HgS, but metacinnabar, native mercury, and several rare mercury minerals are found in some deposits. Because of their near-surface environment, mercury deposits exhibit great geologic variety, and even the major deposits have little in common other than their content of cinnabar and a gangue of silica or carbonate minerals. Pyrite, or more rarely marcasite, is a constituent of ores in rocks containing considerable iron, but in iron-poor rocks the iron sulfides are rare or absent. Stibnite accompanies the ore in some geologic provinces, and minor amounts of arsenic are not uncommon. Other metals, such as gold, silver, or base metals, are rarely present in more than trace amounts. In a few places a base-metal assemblage contains mercurial tetrahedrite, but these ores have not been a major source of mercury.

Production

The conterminous United States has produced a little more than 3,190,000 flasks of mercury, or nearly one-sixth of the World's supply. This has come principally from deposits in the Far Western States, but the deposits in Texas are notable exceptions and smaller deposits have been mined in Arkansas. The most productive mines, as well as the largest number, are in California. The Terlingua district in Texas makes that state second in order of production, closely followed by Nevada and Oregon. The total and relative production by state through 1960 is as follows:

State	Production (Thousands of flasks)	Percent of total
California	2,753.5	86.3
Texas	147.2	4.6
Nevada	127.1	4.0
Oregon	103.3	3.2
Idaho	30.5	1.0
Arkansas	11.4	.4
Arizona	7.0	.2
Washington	6.6	.2
Utah	3.4	.1

Within these states at least 350 mines have produced mercury, but about 90 percent of the total production has come from only 20 mines.

The following sections describe briefly the salient features of the regional and local geology of the more productive mines and districts of the conterminous United States. Similar brief accounts of these deposits, as well as other mercury deposits of the World, are given by Pennington (1959). For more detailed descriptions one may refer to the references cited.

Distribution of deposits

California

In California the principal deposits occur in the Coast Ranges in a belt about 350 miles long, extending from near Santa Barbara on the south to Clear Lake on the north. Along this belt, which has yielded more than 80 percent of the production of the United States, 18 districts are remarkably evenly spaced at intervals of about 25 miles.

The geology of the Coast Ranges is exceedingly complex. The oldest and most widely exposed rocks belong to the Franciscan formation of Jurassic and Cretaceous age, which consists of highly deformed, though not metamorphosed, graywacke, siltstone, and greenstone, with minor limestone and chert. This formation is intruded by tabular and plug-like masses of serpentine; locally their margins are hydrothermally altered to a rock consisting of silica minerals and magnesian carbonates, known as silica-carbonate rock, and many of the mercury ore bodies occur in this rock. Overlying this basement complex are thick sequences of sediments ranging in age from Cretaceous to Pliocene. Especially in the area between San Francisco and Clear Lake there are extensive flows of younger lavas ranging in composition from basalt to rhyolite.

Although 60 percent of the mercury produced in California has come from ore bodies in silica-carbonate rock, some large deposits are in younger sediments and volcanic rocks. Where mineralization can be dated it ranges from late Pliocene to Recent. Structurally the deposits show a variety of environments—some are along faults, though there are none along the great San Andreas rift; some are along margins of serpentine intrusives; some are in fractured sediments; and some are in relatively unbroken Recent volcanics. No close relationship to either granitic intrusives or younger volcanic rocks can be demonstrated for the majority of the deposits. Cinnabar is the common ore mineral, but in a few deposits metacinnabar is more abundant, and in at least two smaller deposits, native mercury is the predominant ore mineral.

Altoona district.—This district, in the northeastern part of Trinity County, contains the Altoona mine, which has produced about 35,000 flasks, and a few other mines with very small production. The mine is on the East Fork of the Trinity River in the southern part of the Klamath Mountains. The mine workings are in an area of porphyritic diorite and minor serpentine of Mesozoic age. Presumably the diorite intrudes the serpentine, although the relations are not clear in the mine. The rocks are cut by several faults; the ore minerals, cinnabar and some native mercury, occur in and near the fault gouge and are accompanied by considerable pyrite and a little ankerite, barite, and quartz.

Wilbur Springs district.—This district, in Lake and Colusa Counties, is about 15 miles east of Clear Lake. It contains a dozen mercury deposits, of which the largest, and only one producing in 1960, was the Abbott mine, with a production record of perhaps as much as 43,000 flasks

The Abbott mine is near the northwest end of a tabular mass of serpentine which is interlayered with shale and graywacke of Early Cretaceous age. The serpentine is believed to have been a flow that was deposited with the sediments. Parts of the serpentine are hydrothermally altered to form the opaline silica-carbonate rock that is the host for the ore. Cinnabar and minor metacinnabar are the ore minerals; gangue minerals are marcasite, calcite, and hydrocarbons with minor quartz. The cinnabar replaces the silica-carbonate rock along fractures and fills cracks to form relatively small, but often quite rich, ore bodies.

Clear Lake district.—This district, which is about 75 miles north of San Francisco, contains the Sulphur Bank mine, which has produced nearly 130,000 flasks, and a few other mines with very small production. Graywacke, siltstone, and greenstone of the Franciscan formation are overlain by late Tertiary and Quaternary continental sediments and volcanic rocks that range in composition from basalt to rhyolite. The ore deposits are Recent, and thermal waters are currently depositing some mercury and antimony.

Knoxville district.—This district, at the intersection of Napa, Yolo, and Lake Counties, contains the Knoxville mine, with a production of nearly 121,000 flasks, the Reed mine, with a production of over 26,000 flasks, and several less productive mines. The dominant geologic feature of the district is a large mass of serpentine, the eastern margin of which is separated from the sedimentary rocks of the Knoxville formation of Jurassic age by a fault. All the large ore bodies found in the district have been in sicila-carbonate rock formed from the sheared serpentine adjacent to this fault. Late Tertiary tuff and basalt blanket a small part of the area, and the ore of one of the smaller mines occurs in silicified tuff.

Mayacmas district.—This district, in parts of Sonoma, Lake, and Napa Counties, is the third most productive district in California. Unlike most districts, it contains several mines with large production as well as dozens of smaller ones. The more productive mines and approximate production are Oat Hill (162,000 flasks), Great Western (105,000 flasks), Aetna (66,000 flasks), and Mirabel (42,000 flasks).

The rocks of the district are mostly graywacke, shale, and greenstone of the Franciscan formation, which are mildly to intensely folded and cut by many faults and wide shear zones. The axes of the folds, and the faults and shear zones, trend west-northwest; large sill-like masses of serpentine intruded along the shear zones have a similar trend. Parts of the area are overlain by flat or gently inclined silicic flows and tuffs of Pliocene and Pleistocene age, and younger basalt flows locally cap some of the lower hills in the eastern part of the district.

The mineralized area is about 25 miles long and 7 miles wide, but the more productive deposits lie within half a mile of a straight line drawn through the length of the district. Most of the ore bodies occur in silica-carbonate rock formed by hydrothermal alteration of marginal parts of the serpentine; but ore bodies of the highly productive Oat Hill mine are along faults in graywacke of the Franciscan formation, and at the less productive Cloverdale mine the ore is in chert of the Franciscan formation. Cinnabar is the usual ore mineral, but native mercury is abundant.

Guerneville district.—This district, two miles north of the ssian River in central Sonoma County, contains the Sonoma (Great Eastern-Mt. Jackson) mine, which has produced about 85,000 flasks.

The rocks of the area are chiefly graywacke and shale of the Franciscan formation, serpentine, and silica-carbonate rock.

The mine is at the intersection of a major fault traceable northwestward for at least 20 miles and a secondary fault that trends eastward. A tabular mass of serpentine that extends northwest and east from the fault intersection is extensively altered along its southwesterly margin to silica-carbonate rock, and other silica-carbonate rock has formed within the serpentine along secondary shear zones. Thick breccia composed of shale and graywacke borders the serpentine and also occurs along shears that separate faulted portions of the serpentine; much of it is altered to a dense hard rock that cannot be distinguished easily from the silica-carbonate rock.

Cinnabar, the only important ore mineral, occurs with small amounts of pyrite and hydrocarbons disseminated in favorable parts of the silica-carbonate rock. Ore bodies are both tabular and pipelike in form.

New Almaden district.—This district, about 50 miles southeast of San Francisco, has yielded about 40 percent of the domestic mercury. The New Almaden mine, with a record of more than 1,000,000 flasks, the Guadalupe mine, with more than 100,000 flasks, and several other mines with relatively small production lie within a belt about 5 miles long and a mile wide. The deposits in this area were the first discovered in the United States, and between 1850 and 1900 they yielded enormous quantities of mercury. During the World War II years these mines produced about 10,000 flasks, but in subsequent years they have been worked chiefly by small groups of lessees.

The deposits of the New Almaden mine were first recognized to contain mercury ores in 1845, and, except for very brief periods of inactivity in recent years, have been mined ever since.

The ore bodies formed in silica-carbonate rocks near contacts with rocks of the Franciscan formation. Where these contacts are relatively flat, the ore lies in structural highs such as apices of domes or anticlines; where contacts are steep the ore appears to be localized by the presence of fractures. Cinnabar, the only important ore mineral, replaces the silica-carbonate rock that was formed by hydrothermal alteration of serpentine. Although replacement extended only a few inches away from the fractures, it was so complete that commonly over 50 percent of the rock was cinnabar. In the major ore bodies, steep fractures occur as swarms so closely spaced that much of the intervening rock is rich ore.

Small amounts of sulfides such as pyrite, stibnite, chalcopyrite, bornite, galena, and sphalerite, plus native mercury accompany the cinnabar. Introduced gangue minerals include quartz, dolomite, and hydrocarbons.

The Guadaulpe mine, about 4 miles west of the New Almaden mine has the same geologic setting.

New Idria district.—This district is in northeastern San Benito County, about 140 miles southeast of San Francisco. In 1960 the New Idria mine was one of the leading producers in the United States, having produced about 500,000 flasks.

The mine is on the northern margin of the large pluglike mass of serpentine and Franciscan rock which intrudes the shales of the Panoche formation of Late Cretaceous age. Near the plug the shales are warped upward, and in the mine area they are overturned so that they dip steeply southward toward the plug. In most of the mine area the rocks above the inward-dipping margin of the plug are sedimentary rocks of the Franciscan formation, which form a thin selvage around the serpentine. Most of the ore occurs beneath a thrust fault near the margin of the plug. In addition to the marginal fault, there are other faults, some of which offset the main thrust and are important because they create structures favorable for ore deposition.

Cinnabar is the chief mineral, but in some ore bodies metacinnabar is an important constituent. Pyrite and marcasite are abundant in places, but generally are minor constituents of the ore. Carbonate minerals and quartz are also locally common, but much of the ore contains no obvious nonmetallic gangue.

San Luis Obispo district.—In northwestern San Luis Obispo County an elongate area of about 75 square miles contains several dozen relatively small mines with an aggregate production of over 80,000 flasks of mercury. About 80 percent of the production came from the Oceanic mine (41,000 flasks) and the Klau mine (26,000 flasks).

Much of the area is underlain by sedimentary rocks of the Franciscan formation and serpentine intrusive into them. These rocks are unconformably overlain by Cretaceous sedimentary rocks in the eastern part of the area and Miocene sediments and diabase sills in the western part. Folds axes trend northwest, and the area is broken into slivers by a series of faults trending roughly parallel to the folds. Rhyolite stocks and dikes were intruded in late Tertiary or Quaternary time.

Oregon

Mercury mines in Oregon have yielded about 100,000 flasks, of which about 90 percent has come from five mines—Bonanza (35,000 flasks), Black Butte (17,000 flasks), Horse Heaven (17,000 flasks), Opalite (15,000 flasks) and Bretz (10,000 flasks). Although occurrences of mercury ores are widely distributed throughout the state, the productive deposits are in restricted areas in the central, southwest, and southeastern parts. Most of the deposits are in Tertiary rocks of pre-Miocene age, but in the Opalite district in southeastern Oregon large ore bodies occurred in tuffs and lake beds of late Miocene age. The widespread Columbia River basalt of Miocene and Pliocene(?) age, andesite of Pliocene age in the high Cascades, and younger intrusives are remarkably unmineralized.

Southwestern Oregon.—A mineralized belt, extending from Medford to Cottage Grove, includes the two most productive mines in the State, the Bonanza and Black Butte, as well as a dozen other small mines and prospects. Most of the deposits are in sedimentary rocks and lavas of Eocene age, but some small ore bodies have been found in the underlying schists of Devonian(?) age. Most of the ore bodies formed along normal faults and are accompanied by widespread veinlets of quartz and carbonates. As cinnabar is generally disseminated in the country rock beyond the limits of ore shoots, the ore bodies are bordered by unmined mineralized rock that provides a sizable reserve of low-grade ore.

The Bonanza mine workings are in a sequence of arkosic and tuffaceous sandstones, shales, and tuffs assigned to the Umpqua formation of Eocene age. The ore occurs along a zone of fractures which parallels the bedding and is developed in tuffaceous sandstone near its contact with overlying shale. In the ore zone the tuffaceous sandstone is extensively altered to clay and contains small disseminated crystals of cinnabar along with rare metacinnabar and native mercury. Other introduced minerals are quartz, chalcedony, various carbonates, and minor, through widespread, realgar and orpiment.

The Black Butte mine is in flows and beds of Eocene andesitic lavas, tuffs, and breccias that dip to the northeast and are intruded by irregular masses of basalt and andesite. The volcanic rocks are hydrothermally altered over a wide area and silicified more locally. Calcite veins and veinlets are abundant, and opal, chlorite, sericite, pyrite, and marcasite occur in minor amounts. Small crystals of cinnabar are scattered through much of the rock within and below the fault, but only in the richer parts of the shoots does it occur in distinct veinlets.

Southeastern Oregon.—In southeastern Oregon two districts contain ore bodies distinctly different from those of the rest of the state. The highly productive Opalite district, which lies in southern Malheur County and extends into Nevada, contains the Opalite and Bretz mines. Deposits in the Steens Pueblo Mountains area in southern Harney County have yielded very little mercury but are notable because of the abundance of mercurial tetrahedrite (schwatzite) that occurs in quartz veins with cinnabar, pyrite, chalcopyrite, galena, magnetite, and barite. Some of the cinnabar in the oxidized zone is clearly secondary, but some of the more crystalline cinnabar is believed to be primary.

The Opalite mine is in an area of nearly flat lying lake beds and tuffs of Miocene age. The ore occurs in a lenticular blanket of chalcedony, commonly referred to as opalite, formed by silicification of the beds. Cinnabar is scattered through much of the upper half of the opalite blanket, but the best ore is in and adjacent to steep fractures and breccia zones. Minor amounts of native mercury and mercury oxychloride (terlinguaite) accompany the ore; pyrite is present in very minor amounts. The rocks beneath the opalite blanket have been extensively altered to clay, and locally a little cinnabar occurs in the argillized lake beds.

The Bretz mine, which has yielded more than 10,000 flasks of mercury, is in Miocene tuffs and lake beds adjacent to a fault bounded on the north by andesitic and rhyolitic pyroclastic rocks. In contrast to the ore bodies formed in a similar geologic setting in the Opalite mine area, the ore bodies of the Bretz mine are largely in unaltered lake beds or argillized tuffs layered along fault zones. The cinnabar occurs disseminated in the lake beds and as thin films along the bedding planes, but locally the beds contain high-grade bunches and nodules.

Central Oregon.—An area in eastern Jefferson County and Crook County contains the Horse Heaven mine, with a production of about 17,000 flasks, and nearly a score of small mines and prospects. Ore bodies are in andesite and basalt flows and tuffs of Eocene age or in younger intrusive plugs of andesite or rhyolite, but nearly all the more productive ore bodies are in brecciated marginal parts of a rhyolite plug.

The most abundant ore mineral is cinnabar, which generally fills openings but locally replaces the host rock. Native mercury is locally abundant, and metacinnabar, though scarce, is widely distributed. The principal gangue minerals are marcasite, carbonates, and silica minerals. The wall rocks are extensively altered to clays.

Washington

Although mercury minerals have been found at several places in Washington, the only production has been from the Morton district in Lewis County. The district is unusual because some of the best ore occurs in seams of coal.

The mineralized area extends northeasterly about two miles and has a width of about half a mile. The rocks are shale, tuffaceous sandstone, and coal assigned to the Puget group of Eocene age, and basic sills and dikes that have intruded them. Several faults, formed at different times and having different kinds of displacement, appear to have localized the ore. Most of the cinnabar produced comes from brecciated sediments along a steep fault, but two of the richest ore bodies are in relatively unbroken sandstone beneath a clay gouge developed along a gently dipping thrust fault.

Idaho

Idaho contains two mercury mines with significant production—the Cinnabar (Hermes) mine near Yellow Pine, with a production of about 15,000 flasks, and the Idaho-Almaden mine near Weiser with a production of nearly the same amount.

The Cinnabar mine is in limestone and shale strata of Paleozoic(?) age that are a part of a series of metamorphosed sedimentary rocks forming a roof pendant in the granite of the Idaho batholith. Dikes of aplite and granite that cut the sedimentary rocks and are exposed in the underground workings do not appear to be genetically related to the ore. The host rocks were argillized, sericitized, and silicified along a broad fault zone prior to mineralization. Cinnabar, the only ore mineral, ocurs as fracture fillings and disseminations chiefly in the altered limestone; associated with it are pyrite, stibnite, realgar, and orpiment.

The main ore body of the Idaho-Almaden mine is of the opalite type and occurs as a blanket above beds of feldspathic sandstone which are part of the Payette formation of Miocene and Pliocene age. In the mineralized area an anticline is crossed by a pronounced northwest-trending sag, the margins of which are in part flexures and in part faults of small displacements. Fractures with little or no offset are developed both parallel to the anticline and to the transverse downwarp, forming a series of blocks; much of the best ore is in places where these fractures are closely spaced. The dominant silica mineral is opal, but chalcedony also is common; clay minerals are abundant in places but are inconspicuous in much of the opalite. Cinnabar, the only ore mineral, is disseminated as minute crystals in the opalite and also occurs in steep opal veins that fill fracture zones. A very small amount of pyrite accompanies the ore.

Nevada

Nevada contains more than 100 mines that have produced some mercury, distributed among about 30 districts, most of which are confined to a northerly trending belt in the central third of the State. Ore bodies are unusually diverse; they include small deposits containing some of the richest ores ever mined in the United States as well as large bodies of low-grade ore. Host rocks are equally varied as they include sandstone, limestone, sinter, opalite, rhyolite, andesite, and granitic rocks. The mines in andesitic flows and breccias, however, have yielded two-thirds of the total production. By the end of 1959 the State had produced about 120,000 flasks of mercury of which more than half came from the Cordero mine. The mine is in an extension of the opalite district of southeastern Oregon.

The rocks in the mine area are andesitic flows, breccias, and tuffs of Tertiary age. Near the surface, parts of these rocks were silicified to form opalite, but the rocks below the shallow opalite are largely argillized rather than silicified. The chief ore mineral is cinnabar, although native mercury and mercury oxychlorides were found in small amounts in the near-surface workings. Cinnabar occurs disseminated in the porous altered volcanic rocks, accompanied in many places by microcrystalline hematite, and in veins with silica minerals and abundant pyrite and some marcasite. The opalite, consisting of both chalcedony and opal, contains cinnabar disseminated through the rock in an irregular fashion; however, the major ore bodies are stratigraphically below the opalite in a mineralized zone about 500 feet long and 100 feet wide.

Utah

Nearly all the 4,000 flasks of mercury recovered in Utah has come from three mines, and all but 110 flasks was produced prior to 1910. Most of the production came from the Sacramento gold mine, in the Mercur district in Tooele County. Here earthy cinnabar occurs in bands in altered limestone of Late Mississippian age adjacent to a dike and fracture zone. The Lucky Boy mine near Marysvale in Piute County yielded in the 1880's about 250 flasks from tiemannite (mercury selenide) ore occurring in limestone.

Arizona

Southern Arizona contains more than twenty small mercury mines and prospects with an aggregate production of 5,000 flasks. The larger mines are the Ord in the Mazatzal Mountains in western Gila County and the Sunflower and Pine Mountain mines lying a few miles west of the Ord mine in eastern Maricopa County.

Most of the deposits in Arizona occur along fault zones in Precambrian schists. The mineralogy of some of the ores is unusual; in the Dome Rock Mountains cinnabar occurs with gold, wulfenite, and copper minerals, and in the Mazatzal Mountains the lodes contain tourmaline, mercurial tetrahedrite, and other copper minerals. Although the ore bodies occur along well-defined structures and contain some rich ores, the overall grade has been too low to permit sustained mining.

Texas

Texas is in second rank among mercury-producing states because of the large output from the Terlingua district. The district has yielded more than 140,000 flasks of mercury since production began in 1895, and over 90 percent came from the Chisos-Rainbow mine (100,000 flasks), the Maricopa mine (20,000 flasks), and the Study Butte mine (10,000 flasks).

The Terlingua district, which is mainly in Brewster County in the southern part of the Big Bend region, is a narrow east-trending area about 20 miles long. The layered rocks of the district consist of about 5,000 feet of Cretaceous limestone and shale overlain by early Tertiary volcanic rocks. These are intruded by dikes, sills, and laccoliths that have compositions ranging from basaltic to rhyolitic, with a widespread phase characterized by analcite. The district is dominated by an east-trending monocline, which is broken in places by northwest-trending graben. Small faults of northeasterly trend are abundant, and many of these are mineralized. Other structural features that have localized important ore bodies are collapse breccias in pipelike and tabular bodies.

The Chisos-Rainbow mine lies immediately north of a prominent graben in gently folded and strongly faulted Cretaceous shale and limestone. Here three types of ore bodies have been mined: (1) deposits in calcite veins, (2) deposits near the contact of the Devils River limestone with the overlying Grayson formation of Late Cretaceous age, and (3) deposits in brecciated rocks. The vein deposits are in calcite-filled fissures along steep normal faults. Only parts of the veins are mineralized with cinnabar, and few ore shoots are over 100 feet long or as much as 100 feet deep. The deposits along the contact in limestone beneath the Grayson formation are in flat troughlike zones of altered rock localized by faults of small displacement in the underlying limestone. In these zones cinnabar generally occurs only within 50 feet of the contact. The breccia deposits, richest and most productive in the mine, occur in fault breccia zones in limestone and in a pipelike body of breccia in the Grayson formation. The pipe ore body is a vertical cylinder of breccia composed of jumbled blocks and fragments of limestone with cinnabar enclosed in a matrix of clay in the Grayson formation.

At the Mariposa mine erosion has stripped the Grayson formation from all but the central part of the deposit; most ore bodies are therefore exposed at the surface. Along northeast-trending faults of small displacement the limestone just below the clay was dissolved by hydrothermal solutions, producing elongate zones of altered clay that sagged and collapsed into the limestone. These altered zones, which are locally 100 feet wide, are termed "cave fill zones" and are locally mineralized with cinnabar. Near the surface, parts of the zones also contained notable amounts of calomel, mercury oxychlorides, native mercury, montroydite, and rarer mercury minerals.

The Study Butte mine workings are mainly in a wedge-shaped sill of fine-grained quartz syenite intruded into calcareous shales of Late Cretaceous age. Cinnabar occurs principally in the intrusive rock but also forms ore in the shale. Seams of cinnabar and pyrite ranging from a film to an inch in thickness were deposited along steep northeast-trending fractures in the intrusive rock. The ore in the shale occurs as irregular impregnations and veinlets of pyrite, cinnabar, and calcite.

Arkansas

About 10,000 flasks of mercury have been recovered from a single district in the southwestern part of Arkansas. More than two dozen mines and prospects occur in the district along an east northeast-trending belt over 30 miles long and less than a mile wide. Small ore bodies occur in sandstone of late Paleozoic age; some are pipe-like and formed at fault intersections, and others are tabular parallel to the bedding. The ore consists of cinnabar disseminated in sandstone. Minor amounts of several rarer mercury minerals have been found, and a little pyrite and stibnite accompany the ore. Gangue minerals are quartz and dickite.

Mercury Index

District or region	Lat. N.	Long. W.
Arizona		
1. Mazatal Mountains Faick, 1958	33°58′	111°28′
2. Dome Rock Mountains Lausen and Gardner, 1927	33°32′	114°19′
Arkansas		
1. Pike County Gallagher, 1942	34°10′	93°35′
California		
1. Patrick Creek	41°58′	123°54′
2. Beaver Creek	41°57′	122°50′
3. Altoona Swinney, 1950	41°08′	122°33′
4. Wilbur Springs	39°04′	122°26′
5. Clear Lake Everhart, 1946	39°00′	122°41′
6. Knoxville Averitt, 1945	38°51	122°22′
7. Mayacmas Yates and Hilpert, 1948	38°45′	122°42′
8. Guerneville Myers and Everhart, 1948	38°34′	122°59′
9. Oakville Fix and Swinney, 1949	38°27′	122°26′
10. Vallejo	38°07′	122°11′
11. Mt. Diablo Ross, 1940	37°54′	121°53′
12. New Almaden Bailey, 1951	37°14′	121°51′
13. Phoenix Hawkes and others, 1942	37°24′	121°23′
14. Stayton Bailey and Myers, 1942	36°57′	121°13′
15. Central San Benito Yates and Hilpert, 1945	36°37′	121°00′
16. New Idria Eckel and Myers, 1946	36°21′	120°38′
17. Parkfield Bailey, 1942	35°55′	120°19′
18. San Luis Obispo Eckel and others, 1941	35°41′	121°03′
19. Rinconada Eckel and others, 1941	35°11′	120°22′
20. Cachuma Everhart, 1950	34°43′	119°53′
21. Los Prietos	34°33′	119°40′
22. Tehachapi Bailey and Swinney, 1947	35°13′	118°32′
23. Coso Ross and Yates, 1943	36°01′	117°47′
Idaho		
1. Yellow Pine Schrader and Ross, 1926	44°55′	115°18′
2. Weiser Ross, 1956	44°15′	116°41′
Nevada		
1. Opalite Yates, 1942	42°00′	117°55
2. National Roberts, 1940a	41°45′	117°35′
3. Bottle Creek Roberts, 1940b	41°23′	118°17′
4. Poverty Peak Bailey and Phoenix, 1944	41°22′	117°25′
5. Tuscarora Bailey and Phoenix, 1944	41°20′	116°13′
6. Ivanhoe Bailey and Phoenix, 1944	41°07′	116°35′
7. Dutch Flat Bailey and Phoenix, 1944	41°08′	117°28′
8. Imlay Bailey and Phoenix, 1944	40°31′	118°10′
9. Goldbanks Dreyer, 1940	40°30′	117°41′
10. Mt. Tobin Bailey and Phoenix, 1944	40°21′	117°32′
11. Spring Valley Bailey and Phoenix, 1944	40°17′	118°06′
12. Antelope Springs Bailey and Phoenix, 1944	40°08′	118°05′
13. Wild Horse Dane and Ross, 1942	39°51′	117°28′
14. Castle Peak Bailey and Phoenix, 1944	39°28′	119°37′
15. Union Bailey and Phoenix, 1944	38°54′	117°31′
16. Belmont Bailey and Phoenix, 1944	38°38′	116°58′
17. Pilot Mountains Phoenix and Cathcart, 1952	38°22′	117°55′
18. Fish Lake Valley Bailey and Phoenix, 1944	37°53′	118°18′
19. Fluorine Bailey and Phoenix, 1944	36°53′	116°38′
Oregon		
1. Oak Grove	45°04′	121°58′

Schuette, 1938		
2. Horse Heaven Waters and others, 1951	44°40′	120°35′
3. Ochoco Schuette, 1938	44°24′	120°30′
4. Maury Mountain Schuette, 1938	44°05′	120°25′
5. Bear Creek Schuette, 1938	44°01′	120°43′
6. Black Butte Wells and Waters, 1934	43°33′	123°08′
7. Bonanza-Nonpareil Brown and Waters, 1951	43°23′	123°10′
8. Tiller Schuette, 1938	43°02′	122°56′
9. Trail Schuette, 1938	42°38′	122°58′
10. Steens-Pueblo Mountains Williams and Compton, 1953	42°35′	118°32′
11. Opalite Yates, 1942	42°00′	117°55′

Texas

1. Terlingua Yates and Thompson, 1959	29°19′	103°40′
2. Mariscal	29°07′	103°12′

Utah

1. Mercur Gilluly, 1932	40°19′	112°12′
2. Mt. Baldy (Lucky Boy mine)	38°24′	112°16′

Washington

1. Morton Mackin, 1944	46°35′	122°18′

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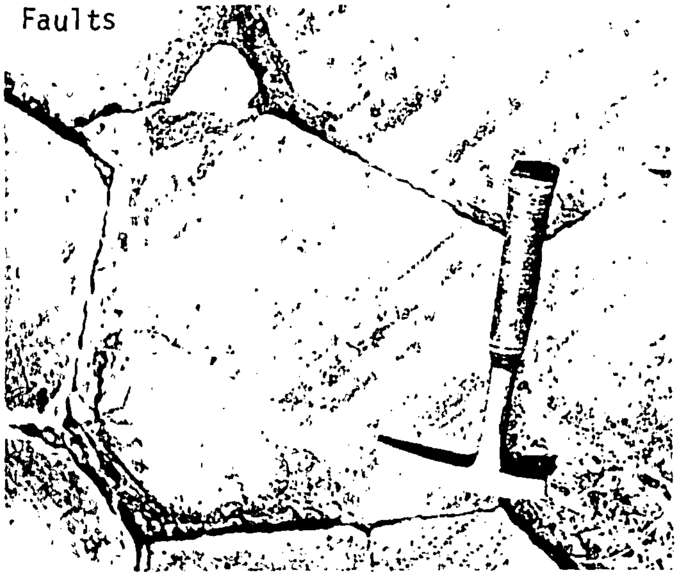

FIGURE 187.5.—Nonorthogonal contraction-crack polygons in basalt, Devils Post Pile National Monument, Calif. (Photo by Gordon W. Greene.)

etc.) may produce an oriented orthogonal system. This is consistent with the observed fact that ceramic polygons evolve gradually. The classic occurrences of columnar basalt joints described in the literature seem to be of the nonorthogonal type; consistent with the requirements of thermal and mechanical homogeneity and low plasticity (fig. 187.5).

Dessication polygons in mud and shrinkage polygons in concrete seem generally to be of the orthogonal type, although certain complications beyond the scope of this paper are introduced by their plastic behavior. Inasmuch as cracks in these media are often irregular, they have many "convexities" at which orthogonal intersections (fig. 187.4a) could be confused with nonorthogonal ones (fig. 187.4b) as the cracks widened. Laboratory experiments by the writer confirm that in general mudcracks propagate slowly, do not branch, and form orthogonal intersections. This is consistent with the present point of view which calls for high propagation velocities and branching to produce nonorthogonal intersections.

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188. CURVATURE OF NORMAL FAULTS IN THE BASIN AND RANGE PROVINCE OF THE WESTERN UNITED STATES

USGS PP. 400B

By JAMES G. MOORE, Menlo Park, Calif.

Work done in cooperation with the Nevada Bureau of Mines

Recently many new data have become available on details of the topography of the Basin and Range province. The new series of Army Map Service topographic maps provides almost complete coverage of the province at a scale of 1 : 250,000 with a 200-foot contour interval. One of the most striking features that the maps show is the nonlinearity of the ranges. Many of the ranges are arcuate, the longer ranges being linked segments of arcs. The arcuate pattern of a range as a whole is believed to reflect the arcuate pattern of the main bounding fault.

Many of the individual ranges of the Basin and Range province are tilted Cenozoic fault blocks (Davis, 1925; Mackin, 1960; Osmond, 1960). The geology of many ranges is still little understood, but geologic mapping in recent years has yielded information on the direction of tilt of some of the ranges. The criteria by which the direction of Cenozoic tilt of ranges is determined are listed in order of decreasing reliability: (a) general direction of dip of Cenozoic sedimentary and volcanic rocks, (b) distribution of rocks of different ages within a range, (c) topographic asymmetry of a range, (d) dip of major Cenozoic normal faults, and (e) general dip and structure of pre-Tertiary strata. In addition, criteria which point to the asymmetry (and hence direction of tilt) of the intermontane basins also provide data on the Cenozoic tilt of adjacent ranges. These criteria include topographic shape of basin surface as well as the topography of the buried bedrock surface determined by geophysical measurements, chiefly gravity surveys.

An interesting relation appears to exist between the tilt of each range and its map plan. Many of the ranges exhibit an arcuate map pattern. Fairly simple tilted block mountains are made up of a single arc which is generally from 10 to 30 miles long with a radius of curvature of 20 to 40 miles, and the ranges are generally tilted toward the convex side of the arc.

TABLE 188.1.—*Fault block ranges in the Basin and Range province showing direction of curvature and probable Cenozoic tilt. Fifty-five of better known ranges have been selected*

Range	Army Map Service sheet	East tilt			West tilt		
		Convex east	Convex west	Straight, irregular	Convex east	Convex west	Straight, irregular
Abert Rim	Klamath Falls		[1] ×				
Amargosa Range	Death Valley			×			
Argus Range	Death Valley			×			
Bare Mountain	Death Valley	×					
Belted Range	Goldfield	×					
Black Rock Range, south end	Vya	×					
Bristol Range	Lund	×					
Buckskin Range	Reno						×
Cedar Mountains	Tooele			×			
Cortez Mountains	Winnemucca	×					
Coso Range	Death Valley						×
Deep Creek Range	Delta				×		
Dove Creek Mountains	Brigham City					×	
East Humboldt Range	Winnemucca	[1] ×					
Egan Range, northern part	Ely					×	
Egan Range, southern part	Lund	×					
Eugene Mountains	Lovelock			×			
Fish Springs Range	Delta					×	
Fortification Range	Lund	×					
Grant Range	Lund			×			
House Range	Delta	×					
Inyo Range, south end	Death Valley					×	
Kawich Range	Goldfield	×					
Kingsley Range	Elko	×					
Kings River Range, southern part	Vya	×					
Klamath Lake, rim east of	Klamath Falls	[1] ×					
Last Chance Range	Goldfield	×					
Mineral Mountains	Richfield	×					
Monitor Range	Millett					[1] ×	
Newfoundland Mountains	Brigham City					×	
North Promontory Mountains	Brigham City	×					
Oquirrh Mountains	Tooele			×			
Osgood Mountains, southern part	McDermitt					×	
Pahrock Range (southern)	Caliente					×	
Panamint Range	Death Valley			×			
Poker Jim Ridge	Adel	×					
Reveille Range	Goldfield	×					
Ruby Mountains	Elko					×	
Seven Troughs Range	Lovelock					×	
Sheep Range	Caliente	×					
Shoshone Range, south part	Winnemucca	×					
Simpson Park Mountains	Millett	×					
Singatse Range	Reno						×
Spruce Mountain Ridge	Elko	×					
Stansbury Mountains	Tooele			×			
Steens Mountain	Adel					×	
Sulphur Springs Range	Millett					×	
Terrill Mountains	Reno					×	
Toiyabe Range	Millett					[1] ×	
Virginia Range							×
Wah Wah Mountains	Richfield	×					
Warner Mountains	Alturas					×	
West Humboldt Range	Lovelock	×					
West Tintic Mountains	Delta	×					
Winter Rim	Klamath Falls					×	
Total		25	1	8	1	16	4

[1] Refers to ranges composed of more than one linked arcuate segment.

For example, the north-trending House Range in western Utah is convex to the east in plan and is tilted to the east. The central Ruby Mountains of northeastern Nevada is convex to the west in plan and is tilted to the west. More complex ranges are made of several of these arcuate segments, as, for example, the Egan Range and the Toiyabe Range of central Nevada. Each segment must be considered rather than the range as a whole, and clearly defined arcs of the scale indicated above generally are convex toward the direction the range is tilted. Ranges that are nearly straight in plan are generally those which are more horstlike, that is, flanked on both sides by major faults.

Table 188.1 lists 55 ranges about which there is some data on the direction of tilting. Of 34 ranges tilted east, 25 are convex east, 1 is convex west, and 8 are rather straight or irregular in shape. Of 21 ranges tilted west, 16 are convex west, 1 is convex east, and 4 are straight or irregular in shape. This relation between the arcuate plan and sense of tilt of mountain blocks is not entirely consistent, but the pattern is repeated so frequently that it is considered to be an important feature of basin-range structure. The curvature of the fault block ranges reflects the curvature of the main bounding fault in plan; hence, the fault itself is believed to be convex toward the direction of tilt of the range, or concave toward the downthrown side of the fault (fig. 188.1).

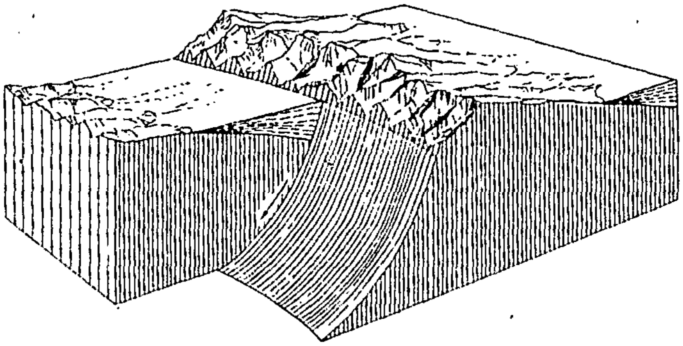

FIGURE 188.1.—Block diagram showing typical curvature and tilt of ranges in the Basin and Range province. The fault surface is believed to be doubly concave (spoon-shaped) toward the downthrown side.

There is evidence that the master normal faults which bound the ranges are also curved in section so that they dip less steeply with depth. Tilting and rotation of blocks is facilitated by a downward flattening of the fault surface (De Sitter, 1956, p. 155), and perhaps for this reason the main normal faults are shown in recent papers (Mackin, 1960, p. 112; and Osmond, 1960) to flatten with depth. Davis (1925) calls on a mathematical analysis and experiments to show that normal faults should flatten with depth. Longwell (1945) finds that many normal faults in southern Nevada flatten downwards.

The fact that many normal faults in the Basin and Range province are concave in plan toward the downthrown side, together with the evidence that many are concave in section upwards, indicates that many of the fault surfaces are probably doubly concave toward the downthrown side. This double concavity suggests that the fault surfaces are spoon-shaped in much the same way that the faults that bound many landslides are spoon-shaped surfaces (Eckel, 1958, p. 24).

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189. VOLCANISM IN EASTERN CALIFORNIA—A PROPOSED ERUPTION MECHANISM

By L. C. PAKISER, Denver, Colo.

Geologic and geophysical evidence suggests that the volcanic rocks along the eastern front of the Sierra Nevada were erupted from regions of relative tension or stress relief in offsets of a major left-lateral en-echelon shear zone (fig. 189.1). This hypothesis was recently put forward for the volcanic activity in Owens

AREA
USwest
Cascades

in Menlo Park

goals are set for research in Cascades

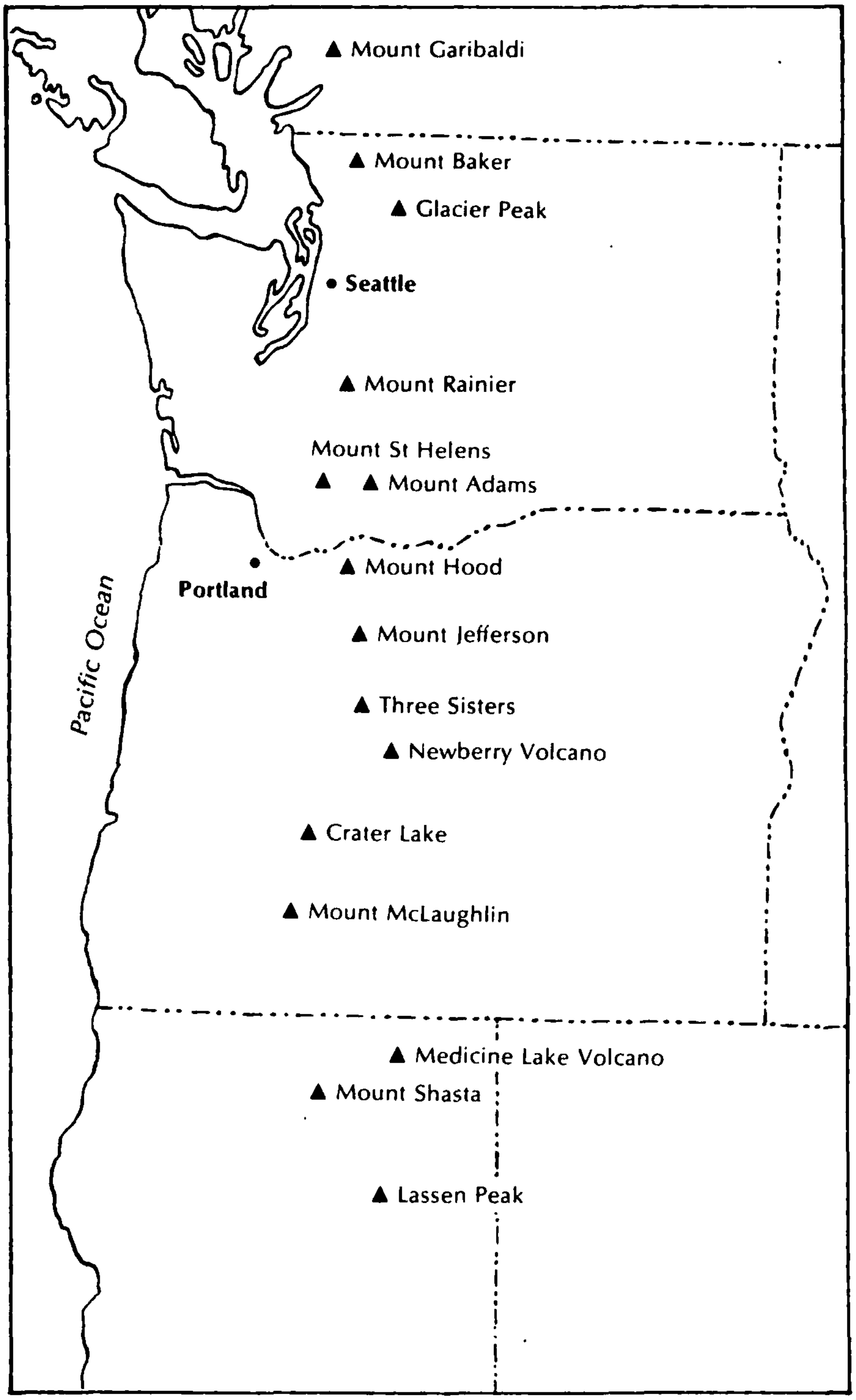
Even as Mount St Helens began to awaken last February, a 3-day conference on the tectonics, volcanology, and geothermal potential of the Cascade Range was held at the U.S. Geological Survey in Menlo Park, Calif. The conference, sponsored by the Survey's Geothermal Research Program, drew about 150 participants from government agencies, universities, industry, consulting firms, the Geological Survey of Canada, and the Pacific Geoscience Centre; they presented results of a wide range of research projects ranging from the Garibaldi belt of southern British Columbia to the Lassen region of northern California.

Topics included regional geologic, tectonic, geophysical, and geochemical studies, crustal structure, volcanic petrology, volcanic hazards, hydrothermal systems and attendant alteration, hydrologic setting of Cascade volcanoes, geophysical exploration methods for geothermal systems, and specific examples of drilling for geothermal resources in the Cascades. The multidisciplinary scope of the conference and the representation of research groups from government, academia, and the private sector created an extremely productive atmosphere of coöperation and enthusiasm for continued multidisciplinary coördinated studies in the Cascades.

The final afternoon of the conference was devoted to 5 workshops on the status, coördination, and future direction of different aspects of Cascade geoscience with stress on improving the understanding of geologic processes and the geothermal resource potential of the range. The results of the workshops reflected the major points of the earlier presentations, as well as considerable exchange of ideas and data that took place during breaks and in workshops themselves.

Knowledge of the regional stress field and of tectonic processes operating in the Cascade region through time is critical to an understanding of Cascade volcanic and hydrothermal systems. Installation of additional seismic stations, especially in Oregon, will lead to improved location of earthquake hypocenters and regional compilation of epicenters and focal mechanisms. Delineation of faults, mapping of dikes and volcanic vent locations, and paleomagnetic studies are improving models of the relations of volcanism to plate interactions, rotations and translations of crustal blocks, and the locations of preëxisting structures. The tectonic environments of neighboring regions (e.g., the Juan de Fuca Plate, the Columbia Plateau) can be used to shed light on the tectonics of the Cascade Range—information that is directly applicable to prediction of fracture patterns that may control the movement of geothermal fluids.

Much is being learned of the nature of the crust beneath the Cascades from seismic-refraction, teleseismic, aeromagnetic, gravity, magnetotelluric, and geomagnetic-induction surveys. Deep seismic-reflection lines, such as those being undertaken by COCORP, and additional seismic-refraction profiling using blasts at quarries and construction sites could further improve the picture of deep crustal structure beneath the range. The nature of the High Cascade—Western Cascade boundary in Oregon and of the transition in composition of the exposed crust along the axis of the range in southern Washington are among pressing problems that might be attacked with those techniques.



Mount St Helens is merely the most active volcano of the Cascade Range.

The convective transfer of heat to the upper crust through volcanism probably provides an increment of thermal energy above the regional conductive component and sustains Cascade geothermal systems. Further detailed volcanologic and petrologic studies are needed, both on the scale of long-term geologic evolution and on the scale of individual eruption sequences. Such research should be complemented by isotopic and petrochemical studies of mid-Tertiary plutons and their wall rocks. The techniques of tephrochronology, paleomagnetic stratigraphy and geochronology need to be more extensively applied to mapping and stratigraphic studies, with emphasis on coördinating them with petrochemical and isotopic research. Further development of new geochronologic techniques, such as thermoluminescence and U-Th disequilibrium dating, would be extremely useful. It is clear that the Cascade volcanic chain must be treated in segments, rather than as a whole, and that we need to learn much more about volcanism away from the major andesitic stratocones. The goal should be to determine time/volume/composition relations of the different regions of volcanism in the Cascade province.

The current eruption of Mount St Helens underscores the urgency of establishing a coördinated program to assess volcanic hazards, monitor Cascade volcanoes that may be dangerous, acquire baseline data, and learn to predict eruptions. Is is also recommended that the research community coöperate to improve its preparedness to maximize the scientific benefit from studies of any future volcanic eruption.

Geologic mapping is fundamental to evaluating the geothermal potential of the Cascade region. Compilation of existing maps has been undertaken; new mapping, both regional and detailed, is urgently needed. The U.S. Geological Survey is compiling a geological map of the range at a scale of 1:500,000 that can be used to target areas for further study and to serve as a base for data from regional gravity, aeromagnetic, and other geophysical surveys. We also need compilation of existing geochemical data and periodic release of new data. It was suggested that a digitized data bank be set up to include sites of dated and chemically analyzed samples and measurements of geophysical properties such as heat flow, gravity, and magnetotellurics.

The hydrologic setting of hydrothermal systems in the Cascades is just beginning to be evaluated. There may be 2 broad classes of hydrothermal systems: those directly associated with volcanic edifices, and those associated with fracture systems and faults, particularly in the Western Cascades. The configuration, circulation patterns, and sources of heat for Cascade hydrothermal systems are virtually unknown, partly due to the near-surface hydrologic regime characterized by flow of cool meteoric water in fractures or zones of high permeability enclosed in relatively impermeable rocks. Analyses of spring and surface waters for chloride content and stable-isotope ratios may detect an imprint of a hidden hydrothermal system within a given drainage basin. A knowledge of the structural geologic setting is necessary to understand the hydrothermal 'plumbing systems'. Examining fossil hydrothermal systems exposed in the Western Cascades and in some eroded High Cascade stratovolcanoes will help model modern hydrodynamics. Refining and testing models will require confirmatory drilling of a few deep (greater than 2 km) holes into and perhaps through Cascade hydrothermal systems.

Before any drilling is undertaken in a particular area, detailed geological and geophysical studies should be made in order to site holes appropriately. Geophysical-exploration tools that have been effective include resistivity, magnetotelluric, and aeromagnetic surveys. Shallow drilling for thermal-gradient studies is hampered by near-surface hydrology, as mentioned earlier. Many holes result in 'stair-step' or even reversed thermal gradients. Shallow heat-flow holes are best sited in impermeable rocks in valley floors. Considerably more carefully sited drilling will be needed in order to document regional variations in heat flow and to define anomalous areas. Preliminary data suggest a steep positive gradient in regional heat flow from west to east in the vicinity of the Western Cascade—High Cascade transition in Oregon and a region of high heat flow over a probable graben structure within the High Cascades. Regions of low near-surface heat flow, which may be areally extensive (e.g., the Medicine Lake highland), generally seem to correspond to topographically high recharge areas.

The consensus was that a few deep drill holes are needed soon, at an early stage of research and exploration, so that the relative merits of the various geochemical- and geophysical-exploration tools can be evaluated and calibrated at specific sites in the Cascade environment where thermal anomalies are well documented. Such drilling could possibly be done under the auspices of the Continental Scientific Drilling Program, now being formulated by the National Research Council, or by coöperative industry/government projects such as those presently conducted by the Department of Energy. Existing data from exploration geophysical surveys, geochemistry of waters, and logging of shallow drill holes suggest that viable geothermal resources exist within the Cascade Range. It appears that these resources can be defined and, where appropriate, developed with minimal impact on the environment.

The response from the research and exploration communities to the conference and the results of the workshops underscore the benefits of such meetings in providing a continuing forum for discussion and coördination of efforts during the active phases of multidisciplinary research.

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U.S. Geological Survey geothermal research program in the Cascade Range

INTRODUCTION

This list summarizes U.S. Geological Survey (USGS) activities that are already in progress or are about to begin in the Cascade Range of Oregon, Washington, and California. The list is divided into two parts: (1) projects associated with the geothermal research program, and (2) activities outside the geothermal research program. Work in progress by non-USGS groups under contracts, extramural grants, or Department of Energy funding is not included.

The Cascade Range comprises one of the major belts of active volcanoes of the world. Being located near several population centers, the Cascade volcanic chain would seem to be an attractive prospect for the development of geothermal energy. However, the geothermal potential of the Cascades cannot be accurately assessed until the geological history of the region, its structure, hydrology, and volcanic and hydrothermal processes are more thoroughly understood.

In combination with other research groups, the U.S. Geological Survey Geothermal Research Program has undertaken a number of long-term geologic, geophysical, geochemical, and hydrologic studies of the Cascade Range on both regional and local bases. A geologic map of the Cascade Range will be compiled and supplemented with detailed mapping in specific areas. Aeromagnetic, gravity, and heat flow maps are being prepared to complement the geologic maps. Additional geophysical investigations include both active and passive seismic, electrical, and remote sensing techniques. Petrologic and geochronological data are being acquired in conjunction with geologic mapping. Studies of the geochemistry of hydrothermal alteration and geothermal fluids have also been initiated. Reports and maps will be published by the USGS and in scientific journals as individual projects are completed.

A significant portion of the work included in the USGS program is being done by universities, state agencies, and private institutions under contracts and extramural grants. Throughout these investigations, a conscientious effort is being made to coordinate activities with others working in the Cascade Range under funding from different sources (for example, the Department of Energy). The Geothermal Research Program Coordinator has designated Charles R. Bacon, Menlo Park, California, as geologist responsible for coordination of USGS geothermal investigations in the Cascades.

Letters after researchers' names indicate USGS offices in the following cities: D = Denver, Colorado; MP = Menlo Park, California; R = Reston, Virginia; S = Seattle (LIA), Washington; and SLC = Salt Lake City, Utah.

USGS PROJECTS IN THE CASCADE RANGE ASSOCIATED WITH THE GEOTHERMAL RESEARCH PROGRAM

Geophysical studies

Geothermal geophysics—D. R. Mabey (SLC): Evaluation of KGRA's in Cascades using geophysical data including aeromagnetic, gravity, SP, MT, AMT, EM, and active seismic techniques.

Teleseismic and microearthquake geothermal studies—H. M. Iyer (MP): Delineation of magma systems and the deep structure under the Cascades, particularly in Oregon, through microearthquake surveys and teleseismic P-wave studies.

Geothermal/Tectonic seismic studies—C. S. Weaver (MP): Detailed seismicity studies to understand the tectonic environment of the Cascades in relation to possible geothermal systems, particularly in central and southern Washington.

Active seismic exploration of geothermal sources—D. P. Hill (MP): Detailed determination of the velocity structure of the crust and upper mantle beneath the Cascades. Use of this information in interpreting the pressure-temperature conditions in the crust in conjunction with laboratory measures of physical properties.

Geothermal processes, heat flow—A. H. Lachenbruch (MP): Measurement and theoretical studies of heat flow in the Cascades of northern California and southern Oregon.

Geoelectric studies—W. D. Stanley (D): Use of deep electrical sounding techniques to investigate crustal structure beneath the Cascades.

Geophysical characterization of young silicic volcanic fields—D. W. Williams (D): Characterization of volcanic geothermal areas using gravity, aeromagnetic, and other geophysical data.

Engineering geophysics—H. D. Ackermann (D): Determination of the relationships between the rock properties in areas of geothermal interest and their seismic-wave transmission properties from seismic measurements in the field.

Geothermal regional studies—R. Simpson (D): The use of deep-sounding magnetotelluric measurements to provide information on broad crustal-mantle structure and on areas of geothermal interest.

Electrical techniques applied to shallow- to medium-depth exploration for geothermal resources—D. B. Hoover (D): Development and application of AMT, SP, and telluric techniques for exploration and characterization of geothermal systems to a depth of about 1 km.

Transient geomagnetic and telluric investigations—J. N. Towle (D): Use of a geomagnetic-telluric array to study the conductivity of the crust and upper mantle under the Cascades.

Heat flow, Crater Lake—D. L. Williams (D): Measurement of heat flow in bottom sediments and photographic coverage of selected sites on the bottom of Crater Lake, Oregon.

Seismic stratigraphy and geologic history of the floor of Crater Lake—C. H. Nelson (MP): Detailed seismic reflection profiling of the floor of Crater Lake to study sedimentation processes and relations between submerged volcanic features.

Lineament analysis—D. Knepper (D): Preparation of maps of lineaments in the Cascade Range from LANDSAT imagery.

Geologic studies

Geology of Newberry and Three Sisters Volcanoes—N. S. MacLeod (MP): Geologic mapping and related studies of Newberry and Three Sisters volcanoes. Geologic map of the west half of the Crescent 2° Quadrangle, Oregon.

Hydrothermal alteration in the Cascades—M. H. Beeson (MP): Detailed field mapping and laboratory petrological and mineralogical studies of selected areas of hydrothermal alteration associated with active and fossil geothermal systems of Western and High Cascades.

Geology of young volcanic rocks and thermal areas in and around Lassen Volcanic National Park—L. J. P. Muffler (MP): A geologic study of the volcanic rocks and hydrothermally altered areas in the region of Lassen Peak to provide the geologic framework for understanding the geothermal resources of the southernmost Cascades.

Regional volcanology—R. L. Smith (R): Classification, characterization, and geothermal evaluation of volcanic systems in the Cascades.

Volcanology and petrology of Mt. Shasta—R. L. Christiansen (MP): A study of the volcanic evolution of Mt. Shasta and the Cascade Range in its vicinity.

Medicine Lake Volcano—J. M. Donnelly (MP): Geology of Medicine Lake Highland with emphasis on its volcanic evolution in time, space, and composition.

Volcanic evolution of the Crater Lake region—C. R. Bacon (MP): Geology and petrology of Mt. Mazama and vicinity, with emphasis on processes leading to the development of shallow silicic magma reservoirs.

Mt. St. Helens—W. Hildreth (MP): Geochemistry and petrology of Mt. St. Helens, in collaboration with the USGS volcano hazards studies and other non-Survey researchers.

Regional petrologic reconnaissance of the Cascades—W. Hildreth (MP): Geochemical and isotopic reconnaissance of the many lesser vents between the major stratocones to develop a better understanding of the characteristic scales and longevities of the Cascade volcanic foci.

Geologic map of the Cascades—R. G. Luedke (R): Compilation of a geologic map of the Cascade Range in California, Oregon, and Washington to be used in conjunction with regional geophysical maps for evaluation of the geothermal resource potential and tectonic regime of the modern Cascade Range.

Fluid geochemistry and hydrology

Rock-water interactions—R. O. Fournier (MP): Development of geochemical techniques for estimating conditions deep in hydrothermal systems from chemistry of geothermal fluids.

Geochemical indicators—A. H. Truesdell (MP): Application of chemical and isotopic methods to the study of geothermal systems to determine subsurface temperatures, flow directions, origins, and ages of geothermal waters.

Chemistry of thermal waters—R. H. Mariner (MP): Collection and analysis of liquid and gas samples from thermal springs and wells of the Western and High Cascades for chemical and isotopic data used to estimate reservoir temperatures, outline areas for further geothermal exploration, identify potential pollution problems, and estimate recharge-discharge relations.

Geothermal hydrologic reconnaissance of the southern Cascades—E. A. Sammel (MP): Description and evaluation of the hydrology of several geothermal areas in the southern Cascades, including the Klamath Falls, Newberry, Medicine Lake, Shasta, and Lassen areas.

Hydrologic studies at Mt. Hood—J. H. Robison (MP): Hydrologic reconnaissance of Mt. Hood with emphasis on the warm springs and drill holes on the

North and Middle Sister, part of the Three Sisters Wilderness Area now being studied by the USGS as part of its geothermal research program. (Oregon State Highway Division photo)

south flank.

Geochronology

Potassium-argon dating—M. A. Lanphere (MP): Determination of age and evolution rate of volcanic centers in the Cascades using K-Ar radiometric dating.

Thermoluminescence dating—R. J. May (MP): Development of the thermoluminescence (TL) dating technique for volcanic rocks in the age range of 10^3 to 10^5 years.

Carbon-14 dating—S. W. Robinson (MP): Use of radiocarbon dating to provide chronology of episodes of late Pleistocene volcanism and lacustrine episodes in areas of geothermal potential.

Paleomagnetic studies—C. S. Grommé (MP): Dating young volcanic rocks using the paleomagnetic record of Holocene secular variation and the application of other paleomagnetic and rock-magnetic techniques to the study of volcanic geothermal systems.

USGS ACTIVITIES OUTSIDE THE GEOTHERMAL RESEARCH PROGRAM

Geophysical studies

Pacific states geophysical studies—A. Griscom (MP): Synthesis and interpretation of gravity and aeromagnetic data over northern California to gain a better understanding of the regional tectonism and structure.

California gravity—H. W. Oliver (MP): Preparation of interpretive text to go with preliminary Bouguer gravity map of California (1:750,000).

Geomagnetic polarity time-scale and paleosecular variation—E. A. Mankinen (MP): Paleomagnetic data from volcanic areas in California, Nevada, Arizona, and New Mexico will be used to determine paleosecular variation in the western United States during the last five to six million years.

Geophysical studies in Medford 2° Quadrangle (CUSMAP)—R. J. Blakely (MP): Gravity and aeromagnetic studies in the Medford 2° Quadrangle.

Thermal infrared studies of Cascade volcanoes—J. D. Friedman (D): Repetitive thermal infrared surveys of Cascade volcanoes for the purpose of delineating and monitoring areas of anomalously high surface temperature.

Remote sensing geothermal—K. Watson (D): Preparations of master image set for Mt. Hood and Newberry Crater areas from repetitive thermal infrared and multispectral data and ground meteorological measurements.

Geologic studies

Volcanic hazards overview—D. R. Mullineaux (D): Preparation of overview maps of volcanic hazards for Oregon (1:1,000,000) and western U.S. (1:2,500,000).

Volcanic hazards—D. R. Crandell (D): Rocks and unconsolidated deposits of volcanic origin and of late Quaternary age are being studied at volcanoes in

Newberry Volcano, near Bend, Oregon. Note Big Obsidian Flow in center of photo. The USGS is studying Newberry Volcano and surrounding volcanic features with its geothermal research program. (Oregon State Highway Division photo)

Washington, Oregon, and California for the purpose of evaluating potential hazards from future eruptions. Includes recent eruptive histories of Glacier Peak (J. E. Beget, Univ. Washington), Mt. St. Helens (R. P. Hoblitt [D]), Mt. Hood (Crandell), Mt. Shasta (C. D. Miller [D]), and studies of Holocene pyroclastic flows (Crandell).

Tephra hazards, Cascade Range volcanoes—D. R. Mullineaux (D): Study of large single shower beds of tephra, mainly from Mt. St. Helens and Mt. Mazama, to evaluate potential tephra hazards downwind from Cascade Range volcanoes.

Tephrochronology of the western region—A. M. Sarna-Wojcicki (MP): Isotopic age determination, and correlation of late Cenozoic ashes and tuffs by means of instrumental neutron activation, X-ray fluorescence, and electron probe analyses of volcanic glass, and by petrography and paleomagnetism. Includes studies of tephra units and source areas in the south, central, and north Cascade Ranges.

Sacramento Valley—Northern Sierran Foothills—E. J. Helley (MP): Preparation of geologic maps of Quaternary alluvial deposits and late Cenozoic volcanic rocks of the Sacramento Valley and Northern Sierran Foothills, with special emphasis on the age of associated faulting.

Medford-Coos Bay Quadrangles (CUSMAP)—J. G. Smith (MP): Preparation of a multidisciplinary land-resource analysis folio of Medford 2° Quadrangle, with primary emphasis on the evaluation of potential mineral resources and their relation to regional structure, tectonostratigraphic units, and plate tectonic models.

Geochemical exploration of Medford 2° Quadrangle (CUSMAP)—D. J. Grimes (D): Collection and analysis of stream sediment samples for 32 elements; preparation of preliminary maps and identification of target areas for detailed studies.

Mineral resources of Spirit Lake Quadrangle—R. P. Ashley (MP): Preparation of a geologic map and reports on geology and mineral resources of Spirit Lake 15' Quadrangle, Washington.

Wenatchee 2° Quadrangle—R. W. Tabor (MP): Preparation of geologic maps of four 1:100,000 quads making up Wenatchee 2° Quadrangle, Washington, with emphasis on tectonics.

Port Townsend 1:100,000 Quadrangle, Washington—J. T. Whetten (S) and H. D. Gower (MP): Preparation of geologic map with emphasis on tectonics.

Geologic map of Columbia Plateau; Columbia River Basalt—D. A. Swanson (MP); **Genesis of basalt**—T. L. Wright (R): Continuing studies of Columbia River Basalt in southeastern Washington and northeastern Oregon.

Seismo-tectonic analysis of Puget Sound province—H. D. Gower (MP): Investigation of suspected Quaternary and bedrock faults by marine seismic profiling; aeromagnetic, gravity, and geologic investigation; geologic reconnaissance of arcuate topographic feature east of Seattle in Western Cascade Range.

Tectonic analysis—K. F. Fox, Jr. (MP): Compilation of tectonic map of Washington (1:500,000).

Mt. Baker monitoring—D. Frank (S): Photographic surveys of fumarolic emission and associated snowmelt patterns, and chemical analysis of stream draining Sherman Crater for the purpose of monitoring activity of Mt. Baker.

Wilderness studies

Caribou-Thousand Lakes—A. Till (University of Washington)

Baker Cypress-Lava Rock—J. A. Peterson (MP)

Sky Lakes—J. G. Smith (MP)

Salmo Priest—F. K. Miller (MP)

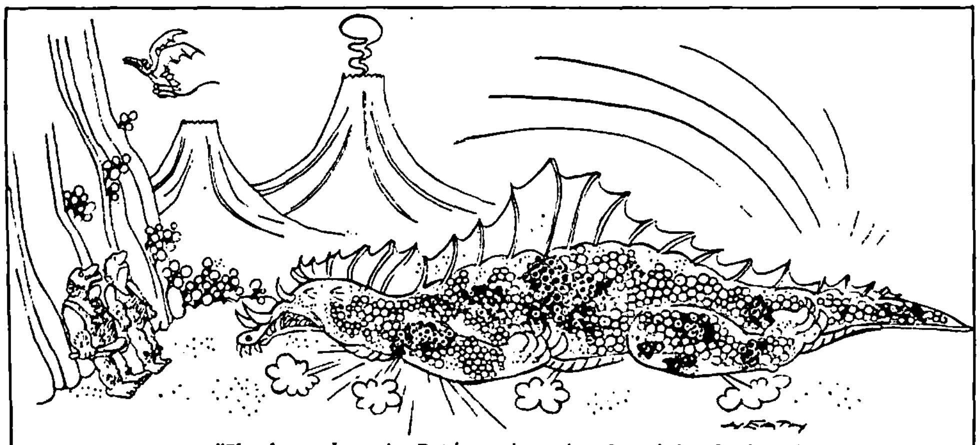
Three Sisters—N. S. MacLeod and G. W. Walker (MP)

Mt. Washington—N. S. MacLeod (MP)

Mt. Hood-Zigzag—T. E. C. Keith (MP)

Goat Rocks—D. A. Swanson (MP)

Glacier Peak—J. G. Evans and R. W. Tabor (MP) ☐



"Thank goodness! Extinct just in the nick of time!" (C) Punch-ROTHCO

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Character and Chronology of Basin Development, Western Margin of the Basin and Range Province

ABSTRACT

Near the western margin of the Basin and Range Province in an area encompassing some 1,500 km^2 between Mono Lake, California, and Yerington, Nevada, six structural basins contain thick accumulations of Miocene-Pliocene sedimentary and volcanic rocks. From approximately 22 to 18 m.y. ago, the area was a highland from which ignimbrite flows of Oligocene age were generally eroded. Subsequent eruptions of andesitic rocks blanketed the area with flows and breccia. Between about 12.5 and 9 to 8 m.y. ago, the area became an integrated basin of sedimentation in which some 2,500 m of strata accumulated. During this period, faulting, along west and northwest trends, and volcanism occurred. Within the basin, surface environments varied from fluvial to lacustrine, and basin margins fluctuated, the maximum extent of the basin having been reached about 10.5 m.y. ago, but a single integrated basin persisted. By approximately 7.5 m.y. ago, the region had been disintegrated by normal faulting into existing structural blocks. Faults of this episode generally trend northeast, east, and northwest. Relative tectonic quiescence ensued for about 4 m.y. During this time a well-graded erosional surface evolved and was locally covered by basic volcanic flows and silicic protrusions, commonly emplaced along faults of the earlier episode. Broad upwarping and block faulting during the Quaternary Period produced the present topography. In contrast to trends of faulting prior to 7.5 m.y. ago, Quaternary normal faults have a north orientation. These faults terminate en echelon in structural warps or by abrupt decrease in displacement to define a northeast-trending lineament across the area, parallel to the Mono Basin–Excelsior zone to the south and the Carson lineament to the north.

INTRODUCTION

The region studied for this report includes a thick sequence of stratified rocks, both sedimentary and volcanic, that is exposed over an area large enough to encompass six existing structural basins in the western part of the Basin and Range Province. The sedimentary rocks in the sequence vary sufficiently in lithology and facies characteristics to provide a stratigraphic basis for interbasin correlation and for interpretation of depositional environments. Furthermore, many of the rocks are datable by radiometric means, and the sequence is nearly continuous from about 12.5 to 6 m.y. ago. Coupled with the younger sequence involved in studies made in the adjacent Mono Basin area (Gilbert and others, 1968; Christensen and others, 1969), a nearly continuous record of the last 13 m.y. is provided for this general region. The report that follows describes first the character, age, and relations of the various rock units, and then considers the chronology and character of the late Cenozoic deformation.

The area that has been mapped extends more or less continuously from Fletcher and Lucky Boy Pass on the south to Smith and Mason Valleys on the north, and from the western flank of the Wassuk Range to the western part of the Pine Grove Hills (Fig. 1). Mapping on a scale of 1:62,500 or larger was completed in most areas where late Tertiary sedimentary and volcanic rocks are exposed; less attention was given to older volcanic rocks, and basement rocks were not differentiated.

An extensive gravity survey was made to supplement surface mapping, the results of which will be reported in a later publication. It is expected that the gravity data will provide

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Geological Society of America Bulletin, v. 84, p. 2489–2510, 7 figs., August 1973

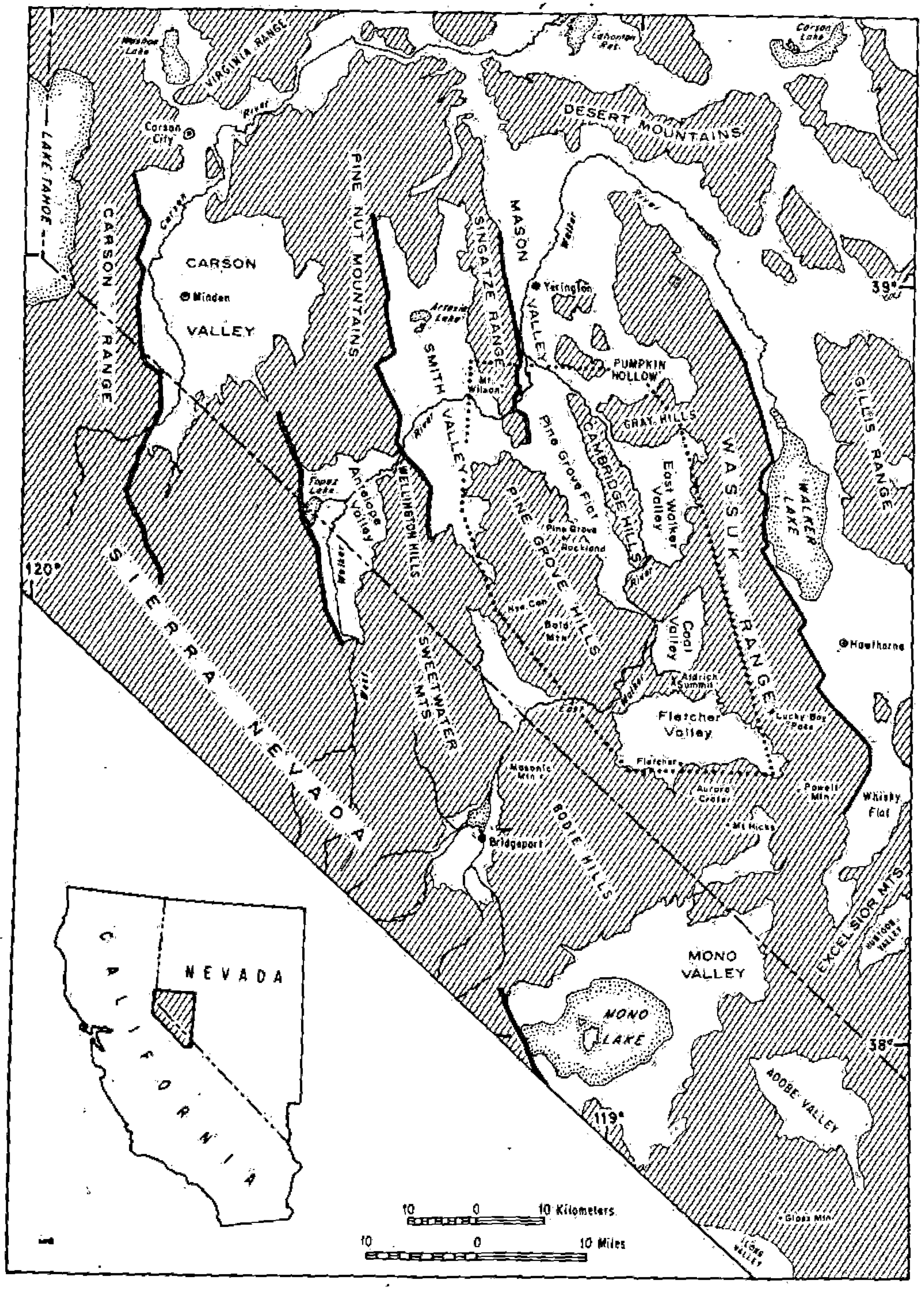

Figure 1. Index map showing part of the western margin of the Basin and Range Province. Dots outline the approximate area mapped during this study, and heavy lines are Quaternary normal faults referred to in the text.

additional information on the depth and configuration of existing structural basins in which the younger sedimentary rocks are preserved.

GENERAL CHARACTER AND AGE OF ROCK UNITS

Regional Basement

Granitic, metavolcanic, and metasedimentary rocks of Mesozoic age are the basement rocks of the region. Over large areas they are buried unconformably by thick accumulations of Cenozoic sedimentary and volcanic rocks. Most of the exposed basement within the region studied for this report consists of quartz monzonite or granodiorite together with a variety of more mafic intrusive rocks. Metamorphic rocks occur as small remnants or pendants in the granitic intrusive rocks. They are undoubtedly of Triassic and Jurassic age (Moore, 1960, 1969), but they were not differentiated.

Quartz monzonite masses in the western Pine Grove Hills have been dated radiometrically as 87 and 90 m.y. old (Krueger and Schilling, 1971, p. 11). These dates correlate the Pine Grove Hills pluton with the Cathedral Range intrusive epoch of Late Cretaceous age in the Sierra Nevada (Evernden and Kistler, 1970). A Late Cretaceous age has also been reported for plutons in the Wassuk Range at Lucky Boy Pass and near Powell Mountain, but a pluton at the northern end of the Wassuk Range has a Late Jurassic age of 140 m.y. (Evernden and Kistler, 1970). Clearly, more than one intrusive epoch is represented by the granitic rocks of the area.

Older Volcanic Rocks

The oldest Cenozoic rocks are rhyolitic ignimbrite flows that are probably correlative with the Hartford Hill rhyolite tuff in the Virginia Range (Moore, 1969). Within the area mapped, these ignimbrites occur in thin sequences in the western Pine Grove Hills, near Morgan Ranch, and at two localities along the eastern margin of Coal Valley (Fig. 2). They are more widespread and thicker to the north along the northeast margin of East Walker Valley and on the northern flank of the Gray Hills, southeast of Yerington. West of Yerington, in the northern Singatze Range, a thick sequence of rhyolitic ignimbrites was mapped in detail by Proffett (1972), who reported K-Ar ages for them ranging from 25 to 28 m.y. The ages of two

Grove Hills were determined by Eastwood (1969) as 22.8 and 28.8 m.y. Farther south, similar rocks having similar ages were mapped east of Mono Lake (Gilbert and others, 1968). During early Miocene time, rhyolitic ignimbrites probably covered most of this part of western Nevada and adjacent parts of California. Within approximately 5 to 7 m.y., however, they had been deformed and extensively eroded, for Miocene andesite overlaps them and rests directly on eroded basement over most of the area mapped for this study.

Andesitic flows and clastic rocks of Miocene age are widespread and locally thick in western Nevada and in the Sierra Nevada northward from Mono Lake (Ross, 1961; Slemmons, 1966; Gilbert and others, 1968; Bonham, 1969; Moore, 1969). Flows and coarse breccia predominate, but tuff and andesitic sandstone and conglomerate are interbedded in many places. Locally, at the base of the sequence in the southern Singatze Range and in the western part of the Wassuk Range, bouldery sedimentary lenses containing a variety of basement rocks represent drainage channels across the underlying surface. These channels appear to trend roughly east.

The K-Ar age of a hornblende andesite flow about 15 m above granitic basement in the central Cambridge Hills is approximately 15 m.y. (KA2493, Table 1). Proffett (1972) reported K-Ar ages of andesite flows in the northern Singatze Range from 17.0 to 18.9 m.y. In the Mono Basin area, the oldest andesite flows are interbedded with rhyolitic ignimbrite about 22 m.y. old (Gilbert and others, 1968; samples KA1974, KA2000, KA2074).

Andesitic rocks of equivalent age in the southern part of the area mapped have been silicified, argillized, and propylitized almost beyond recognition. Extensive exposures of these altered rocks occur in the canyon of the East Walker River southeast of the Pine Grove Hills, and along the western flank of the Wassuk Range for several kilometers north and south of Lucky Boy Pass. Near the East Walker River (N. 38°26.45′, W. 118°58.5′), hydrothermally altered andesite is overlain unconformably by unaltered remnants of a hornblende-biotite andesite flow having an average K-Ar age of 12.2 m.y. (KA2362, KA2364, KA2368, Table 1). A dikelike mass of similar andesite in the same area, also unaltered, was intruded along a fault between altered andesite and

TABLE 1. ANALYTICAL DATA FOR POTASSIUM-ARGON AGE DETERMINATIONS

SAMPLE[1]	ROCK TYPE LOCATION (latitude - longitude)	MINERALS ANALYZED	K WEIGHT PERCENT	SAMPLE WEIGHT IN GRAMS	$^{40}Ar_{rad}$ moles/g x 10^{-11}	$\frac{^{40}Ar_{rad} \times 100}{^{40}Ar_{total}}$	CALCULATED AGE 10^6 YEARS
Older andesite							
KA2493	Andesite N38°43.1' - W119°01.8'	Hornblende	0.6550	2.76115	1.7956	41.0	14.88 ± 0.47
Hornblende-biotite andesite dike and flow							
[2] KA2362	Andesite (flow) N38°26.45' - W118°58.35'	Plagioclase	0.5377	5.19389	1.1611	40.95	12.11 ± 0.39
KA2364		Hornblende	0.6159	4.63701	1.3254	28.53	12.07 ± 0.50
KA2368		Biotite	6.123	1.05060	13.4685	31.36	12.33 ± 0.31
KA2372	Andesite (dike) N38°27.3' - W118°58.55'	Biotite	5.489	0.99832	12.1607	41.66	12.42 ± 0.17
KA2373		Hornblende	0.631	5.14858	1.4556	36.03	12.93 ± 0.45
Aldrich Station Formation							
KA2379R	Tuff N38°24.8' - W118°56.5'	Biotite	6.111	0.19171	12.4257	17.6	11.40 ± 0.54
KA2375	Tuff N38°28.8' - W118°58.7'	Plagioclase	0.5239	5.00115	1.2121	46.03	12.97 ± 0.39
KA2380		Hornblende	0.66895	4.01535	1.1467	28.33	12.00 ± 0.50
KA2381	Tuff N38°37.2' - W118°54.9'	Plagioclase	0.5795	5.06752	1.2102	48.94	11.71 ± 0.34
KA2440		Hornblende	0.5837	2.92661	1.3381	21.50	12.46 ± 0.67
KA2438	Tuff N38°36.97' - W118°56.3'	Plagioclase	0.4154	3.09160	0.7931	7.8	10.55 ± 1.45
KA2503		Hornblende	0.6593	3.42699	1.5483	36.10	12.76 ± 0.45
KA2501	Tuff N38°43.85' -W119°10.63'	Hornblende	0.7205	4.31707	1.4797	63.7	11.15 ± 0.24
KA2434		Biotite	6.627	0.91006	11.3416	60.9	9.30 ± 0.09
KA2581	Andesite N38°47.9' - W119°12.1'	Plagioclase	0.6165	3.62521	1.2649	25.7	11.15 ± 0.52
Coal Valley Formation							
KA2431	Tuff N38°41.15' - W119°05.3'	Plagioclase	0.6051	3.38040	1.0250	28.7	10.23 ± 0.44
KA2432		Hornblende	0.6479	1.01648	1.2248	25.0	10.42 ± 0.49
KA2439	Tuff N38°41.85' - W119°04.5'	Hornblende	0.5538	3.22236	0.9318	24.0	9.14 ± 0.44
Basalt flows							
KA2341	N38°40' - W119°12.5'	Whole rock	2.014	5.86923	2.4435	19.4	6.80 ± 0.30
KA2365	N38°36.05' - W119°03.4'	Whole rock	1.824	5.53146	2.1949	63.73	6.76 ± 0.06
KA2366	N38°34.5' - W118°58.3'	Whole rock	2.127	5.20183	2.4895	20.22	6.57 ± 0.27
KA2367	N38°33.67' - W119°10.8'	Whole rock	1.906	5.43180	2.2352	41.23	6.59 ± 0.12
KA2369	N38°35.4' - W118°55.15'	Whole rock	1.740	5.11579	2.2303	65.60	7.20 ± 0.07
KA2496	N38°42.5' - W119°06.4'	Whole rock	1.6185	2.98161	2.2062	42.0	7.41 ± 0.15
KA2497	N38°42.75' - W119°09.7'	Whole rock	1.384	2.85923	1.8124	24.5	7.12 ± 0.24
KA2582	N38°52.65' - W119°12.55'	Whole rock	1.053	8.94159	1.4035	26.13	7.25 ± 0.30
Rhyolitic protrusions and intrusions							
KA2370	Perlite N38°34.9' - W119°07.4'	Biotite	6.272	1.04844	8.2547	25.0	7.39 ± 0.24
KA2502		Sanidine & Plagioclase	2.584	2.48456	2.6246	60.3	5.57 ± 0.06
KA2435	Perlite N38°36.5' - W119°02.7'	Biotite	6.6045	0.91486	8.2698	41.7	6.74 ± 0.12
KA2437		Sanidine & Plagioclase	3.788	4.00287	4.4882	17.2	6.44 ± 0.34
KA2428R	Perlite N38°37.0' - W119°02.3'	Biotite	6.400	0.98639	8.1397	32.8	6.92 ± 0.16
KA2427		Sanidine & Plagioclase	4.183	5.47083	4.4248	74.2	5.82 ± 0.05
KA2494	Dacite N38°40.5' - W119°02.8'	Plagioclase	0.6686	0.87441	0.6859	8.5	5.58 ± 0.70
KA2436	Rhyolite N38°39.6' - W119°05.25'	Biotite	7.165	1.12696	8.6362	60.2	6.56 ± 0.05
Unnamed sedimentary rocks, Smith Valley							
KA2491	Tuff N38°45.63' - W119°13.8'	Hornblende	0.7365	1.13548	0.4204	21.3	5.02 ± 0.26
KA2513		Biotite	5.803	0.90156	5.1695	13.1	4.97 ± 0.35

[1] K-Ar Laboratory, Department of Geology and Geophysics, University of California, Berkeley, sample number

[2] Dates on sample from same hand specimen

KA2373, Table 1). Unconformities between altered and unaltered andesite were also mapped some 15 km farther south, by Johnson (1951) and Al-Rawi (1969) north of Bodie and again south of Aurora, where one of the younger unaltered andesites has a K-Ar age of 12.5 m.y. This unconformity represents a distinct period of faulting, hydrothermal alteration, and erosion during late Miocene time. In this paper the term "older andesite" refers to andesitic rocks that antedate this discontinuity and are older than about 15 m.y.

Upper Miocene and Pliocene Sedimentary Formations

Axelrod (1956) named and described three sedimentary formations in Coal Valley which together measure approximately 2,500 m in thickness and constitute the Wassuk Group. The two oldest of these, the Aldrich Station and Coal Valley Formations, are fluviolacustrine deposits consisting largely of andesitic detritus and containing numerous tuff beds. The younger Morgan Ranch Formation consists largely of basement detritus; it contains numerous coarse sedimentary breccias and a few tuff beds. Fossil floras and mammalian faunas collected from these formations have led to age assignments of upper Barstovian–lower Clarendonian for the Aldrich Station Formation, Clarendonian–lower Hemphillian for the Coal Valley Formation, and Hemphillian for the Morgan Ranch Formation (Axelrod, 1956, p. 61; Evernden and others, 1964, p. 162–164).

Four K-Ar ages determined from biotite from tuff beds in the uppermost part of the Aldrich Station Formation, as defined by Axelrod (1956), average 11.0 m.y., and a date for biotite from a tuff bed near the base of the Coal Valley Formation is 10.8 m.y. (Evernden and others, 1964). The boundary between Aldrich Station and Coal Valley Formations is hereby redefined, and all of the foregoing tuff beds are considered to be lower Coal Valley. Biotite from tuff near Wilson Canyon in the southern Singatze Range in what is now recognized as the upper part of the Coal Valley Formation has a K-Ar age of 9.3 m.y. (Evernden and others, 1964). During the present study, K-Ar ages were determined for tuff beds at different localities in the Aldrich Station and Coal Valley Formations (Table 1). These dates taken in conjunction with those reported by Evernden and others (1964) indicate for the Aldrich Station Formation, as presently defined, an age of about 12.5 to 11 m.y., and for the Coal Valley Formation an age of about 11 to 9 m.y. The overlying Morgan Ranch Formation is itself overlain unconformably by olivine basalt flows as old as 7.4 m.y.; it has also been intruded by rhyolitic rocks approximately 7 m.y. old.

Formations of the Wassuk Group extend the length and breadth of the area mapped, but they now are preserved in separate structural basins. From south to north, these basins are Fletcher Valley and Baldwin Canyon, Coal Valley, Wichman Valley, East Walker Valley, Pine Grove Flat, and Smith Valley (Fig. 1). Stratigraphic relations show, however, that the formations accumulated in a single large basin having a northwest trend and extending at times beyond the limits of our mapping.

Younger Volcanic Rocks

Tuff and andesite breccia and flows in the Aldrich Station and Coal Valley Formations testify to continuing volcanism during late Miocene and early Pliocene time. The large volume of volcanic debris in these formations was partly derived from erosion of older andesites, but much of it was supplied by contemporary volcanism. One center of contemporary eruption has already been mentioned, a dike and flow of hornblende-biotite andesite near the East Walker River south of Coal Valley, which has an age of about 12.5 m.y. A few other eruptive centers are inferred near localities where flows or coarse eruptive breccia are interbedded in the sedimentary formations, for example, at the northeastern end of Coal Valley and south of Wilson Canyon. Other areas of active volcanism during this period, between about 8 and 12.5 m.y. ago, have been reported to the south in the Bodie Hills and eastern Mono Basin (Gilbert and others, 1968; Silberman and Chesterman, 1972), to the west in the Sierra Nevada (Slemmons, 1966), and to the north in the Virginia Range (Bonham, 1969).

Volcanic rocks younger than the Morgan Ranch Formation include flows of olivine basalt and andesite and irregular intrusive bodies and protrusions of flow-banded rhyolite and dacite. Small flows of olivine basalt ranging in age from 6.6 to 7.4 m.y. (Table 1) occur north and east of Morgan Ranch, at a number of localities around the Pine Grove Hills, and in the Singatze Range. Intrusions and protrusions of flow-banded rhyolite and dacite, many of them glassy and perlitic, are abundant in the central and eastern parts of the Pine Grove Hills and along the eastern margin of the range. The average of four K-Ar ages for feldspar in these rocks is 5.8 m.y.; the average age for biotite is 6.9 m.y. (Table 1). The southern portion of the Pine Grove Hills structural block, known as Bald Mountain, was the center of late andesitic eruptions, and most of the range south of Nye Canyon is covered by andesite flows. Along the south side of Nye Canyon and at the southwest margin of Wichman Valley, andesite flows of the Bald

Mountain complex overlie olivine basalt flows having ages of 6.6 and 6.8 m.y. (KA2365, KA2367). The andesite flows represent a distinctly younger volcanic episode than both the basalt and rhyolite, for in Nye Canyon they are unconformable against rhyolite and are separated from the dated basalt by gravel and lenticular shale. Reliable radiometric dating of the Bald Mountain andesite complex has not been possible, presumably because of abundant inclusions of glass throughout feldspar phenocrysts and widespread oxidation of mafic minerals; however, we consider an age of at least 5 m.y. likely. Our judgment is based on the fact that the Bald Mountain rocks were erupted prior to the upwarp which has produced rejuvenation and extensive dissection in the area. A small, completely separate andesitic complex intrudes the upper part of the Coal Valley Formation north of the mouth of Pine Grove Canyon and may have been erupted during this same interval.

Volcanic rocks younger than the Bald Mountain complex have not been recognized within the area mapped during the present study. Pleistocene basalt flows occur along the southern margin of the area, near Fletcher, and volcanic rocks younger than 3.5 to 4 m.y. are widespread farther south (Gilbert and others, 1968). Pleistocene volcanic rocks, mostly basaltic flows, also occur farther north in the area between Truckee and the Virginia Range; reports of these were summarized by Bonham (1969, p. 39).

Younger Sedimentary Deposits and Erosional Surfaces

Tuff interbedded with arkosic sandstone and conglomerate at the southeast margin of Smith Valley (Fig. 3; N. 38°46′, W. 119°14′) has a K-Ar age of about 5 m.y. (KA2491, KA2513, Table 1). These strata are, therefore, late Hemphillian (Evernden and others, 1964, Table 6). They overlie upper Coal Valley strata unconformably and have themselves been tilted to the northwest by as much as 20°. The exposed thickness is approximately 60 m.

Pediment gravel and alluvium cover most of the surface in the large structural depressions where the Miocene-Pliocene sedimentary formations are preserved. In Coal Valley, three pediment levels can be distinguished, the highest and oldest of which has been named the Lewis Terrace by Axelrod (1956, Fig. 2). This surface now stands 250 m above the East Walker River; near Aldrich Station it has been dissected by tributary streams to a depth on the order of 150 m (Fig. 4). Two lower and younger pediments are evident above the level of present drainage channels in many parts of Coal Valley. Also, along the eastern margin of the Pine Grove Hills, three pediment levels can be distinguished, and at least two can be distinguished in East Walker Valley, Fletcher Valley, and along the southeast margin of Smith Valley. Wherever the pediment surfaces have not been dissected and remain intact, the underlying rocks are concealed by pediment gravel, but the gravel is everywhere only a veneer. In most parts of the area, extensive bedrock exposures are to be found in the numerous gulches that have been cut into the pediments.

Remnants of the Lewis Terrace are preserved on hilltops and ridges south and west of Aldrich Station, where they truncate tilted flows of older andesite and strata of the Aldrich Station, Coal Valley, and Morgan Ranch Formations (Fig. 2). The surface is remarkably even and is mantled by coarse, subangular gravel from 1 to 25 m thick which was derived from local basement rocks and Miocene andesite. The broad extent and general accordance of the Lewis Terrace with erosion surfaces cut across basement both north and west of Coal Valley are evident and impressive when viewed from the terrace level just north of Aldrich Summit (Fig. 4). The surface slopes generally westward toward the East Walker River, approximately 50 m per km near the base of the Wassuk Range and less steeply farther west. Near the river at the southwest corner of Coal Valley, accordant surfaces on granitic rock have little apparent slope, and west of the river, they slope eastward. Taken together, these remnants of the Lewis surface suggest a very broad, well-graded valley, presumably the valley of the East Walker River at an earlier stage in its history.

A detailed structural chronology requires that the age of the Lewis surface be estimated as closely as possible. It is older than the regional uplift which has caused the youthful dissection of the area, and that uplift was presumably coincident with the late period of deformation in Mono Basin, which began between 3 and 4 m.y. ago (Gilbert and others, 1968). The Lewis surface was the landscape at that time, but it undoubtedly had evolved during a considerable period of tectonic stability and erosion. A surface of low relief, in places cut across tilted Morgan Ranch strata and buried locally by basalt flows 6.6 to 7.4 m.y. old, probably represents the early part of that period of erosion, for that surface west of Coal Valley and west of Morgan Ranch is accordant with the Lewis Terrace. North of Coal Valley, however, remnants of basalt flows stand 60 to 90 m above adjacent parts of the Lewis surface cut across granitic basement, indicating some further evolution of the surface after outpouring of the flows in that area (Fig. 4). Furthermore, the occurrence of sedimentary deposits about 5 m.y. old and as thick as 60 m in Smith Valley indicates at least local downwarping and basin filling while the Lewis surface evolved. Thus, we regard the Lewis surface to be the product of slow erosion during a period of relative tectonic quiescence that lasted about 4 m.y. Probably the surface evolved more rapidly and was largely developed during the early part of this period and thereafter was but little modified until regional rejuvenation began 3 to 4 m.y. ago.

A fossil mammalian fauna from pockets of sandstone in the northern part of Wichman Valley (Fig. 2) is reported to be of Blancan age, approximately 1.5 to 3.5 m.y. (Macdonald, 1956; Evernden and others, 1964, Table 6). The deposits containing these fossils are, therefore, younger than the Lewis surface, and they presumably accumulated during the period of regional rejuvenation while a younger pediment graded to the rejuvenated river was developing across Wichman Valley. In the vicinity of the fossil locality (N. 38°37.8′, W. 119°0.8′), strata as thick as 200 m and tilted westward are exposed beneath younger, coarse pediment gravels. The tilted strata include mudstone, arkosic sandstone and siltstone, pebble conglomerate, diatomite, and tuff. Exposures are fragmentary so that the structure and relations of the deposits are uncertain. Coal Valley beds crop out farther east, and the tilted beds at the fossil locality appear to be in an overlying position. Farther west, a small, isolated remnant of olivine basalt (undated) overlies pebble conglomerate similar to that near the fossil locality, and near the western margin of Wichman Valley, small exposures of tilted tuffaceous mudstone and arkosic sandstone and conglomerate are intruded and overlain by rhyolitic perlite having an average age of 6.5 m.y. (KA2435, KA2437, KA2428R, KA2427). We regard the deposits containing the Blancan fossils as being a local accumulation lying unconformably on older tilted strata, which are probably Morgan Ranch.

STRATIGRAPHY OF THE WASSUK GROUP

The three formations assigned to the Wassuk Group by Axelrod (1956) are of special importance to this report because their distribution and internal facies changes provide

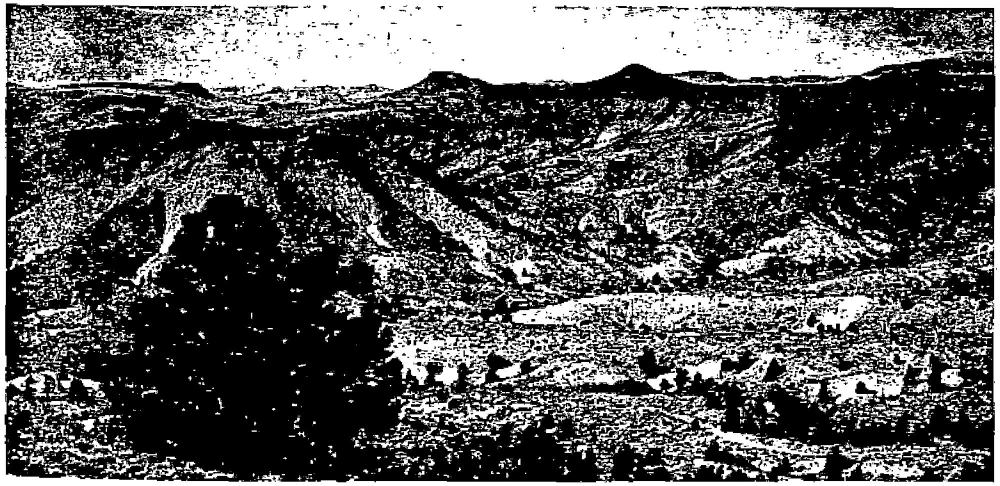

Figure 4. Lewis Terrace, viewed north from equivalent surface on the north side of Aldrich Summit. Pediment gravel mantling the surface rests on tilted beds of the Coal Valley Formation. Peaks rising above the surface in the background are capped by a basalt flow 7.2 m.y. old.

evidence concerning the times and extent of basin development and, locally, of faulting. These formations, the Aldrich Station, Coal Valley, and Morgan Ranch, crop out more widely than Axelrod described in his treatise on the flora of the type locality. Characteristics of the formations at their type localities were summarized by Axelrod (1956, p. 23–35, Fig. 3). This portion of our report describes the areal extent, important characteristics, and intrabasinal correlation of the formations. We conclude that they were deposited successively in a basin that differed in size and configuration during late Miocene and Pliocene time. The maximum extent of the basin was reached about 10.5 m.y. ago during deposition of the Coal Valley Formation. During deposition of each formation the basin was significantly larger than present basins in this portion of the Basin and Range Province.

Aldrich Station Formation

This formation crops out in separate fault blocks from near Aldrich Station northward to Wilson Canyon (Figs. 2, 3, 5). It is composed of an easily recognizable sequence of carbonaceous mudstone and siltstone, diatomaceous shale, lithic arenite, and pebbly lithic arenite beds; the finer grained rocks are dominant. Thin vitric tuff beds are present in all sections, and units of vitric crystal tuff, locally reaching thicknesses of 55 m, are present at Aldrich Station, Lapon, Mickey, and Wilson Canyons (Fig. 5). Correlation of specific tuff units, however, is not always possible among sections, but generally similar sequences can be identified. Stratified and massive andesite tuff breccia units are interbedded in the upper part of the formation in the southern part of the Singatze Range south of Wilson Canyon, and thin lenses of tuff breccia are present southwest of Aldrich Station. An undated sequence of andesite tuff breccia, tuff, thin carbonaceous shale, and lithic arenite, underlying a thin sequence of typical Aldrich Station rocks in the northeast corner of Coal Valley, may be correlative with a part of the formation at other sections.

We concur with the interpretation of Axelrod (1956, p. 26–28) that the rocks were deposited in alternating lacustrine and fluviatile environments, with lacustrine conditions prevailing across the basin for longer durations than fluviatile conditions. Eruptions of andesite tuff breccia occurred near the basin margins late in Aldrich Station time.

The terrigenous rocks are generally pale brown and upon weathering or drying assume a characteristic white or very pale-orange color. Beds split shaly to produce smooth slopes locally interrupted by ledges of resistant sandstone or tuff beds. Red beds, at places containing cobbles and boulders of older andesite, mark the base of the formation southwest of Aldrich Station, in the East Walker Valley, and south of Wilson Canyon.

The formation rests unconformably on the sequence of older andesite flows and tuff breccia. Generally, the contact is sharp and relief along it seems to be low. Elsewhere the formation is faulted along high-angle faults against various units including the Morgan Ranch Formation (Mickey Canyon; Fig. 3) and Mesozoic granitic or metamorphic rocks (south of Lapon Canyon; Fig. 2).

At Aldrich Station the formation is about 755 m thick.[1] Northward along the west flank of the Wassuk Range to the East Walker Valley the formation thins, and in the last exposures it is about 300 m thick (N. 38°37.2′, W. 118°-54.67′). Within a distance of 2.4 km westward from that locality, the formation thins to about 185 m. Such abrupt thinning, largely at the expense of diatomaceous claystone and mudstone near the center third of the formation, may reflect incipient uplift near the Cambridge and Gray Hills. At Mickey Canyon the Aldrich Station is 370 m thick, but it thickens northward to about 730 m at Wilson Canyon as tuff breccia beds appear in the formation. The most marked thickness change occurs at the southern exposures of the formation where the formation thins from 610 to about 70 m across a fault that was active during deposition.

Uniformly fine-grained rocks comprising the formation across the area attest to a nearly continuous depositional basin surrounded by land areas of low relief. The approximate positions of the southern and northern margins of the basin can be defined by facies and thinning relations (Fig. 5). From Aldrich Station southwest to the limits of the exposure west of Aldrich Summit, the formation thins abruptly across a west-northwest-trending fault (N. 38°28.67′, W. 118°55′ to N. 38°29.05′, W. 118°56.3′; Fig. 2). Most of the thinning occurs in the lower half of the formation, seemingly by the loss through convergence or

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[1] Axelrod (1956, p. 24) measured 1,235 m, but this thickness includes some beds (his unit A_8) assigned in this report to the Coal Valley Formation.

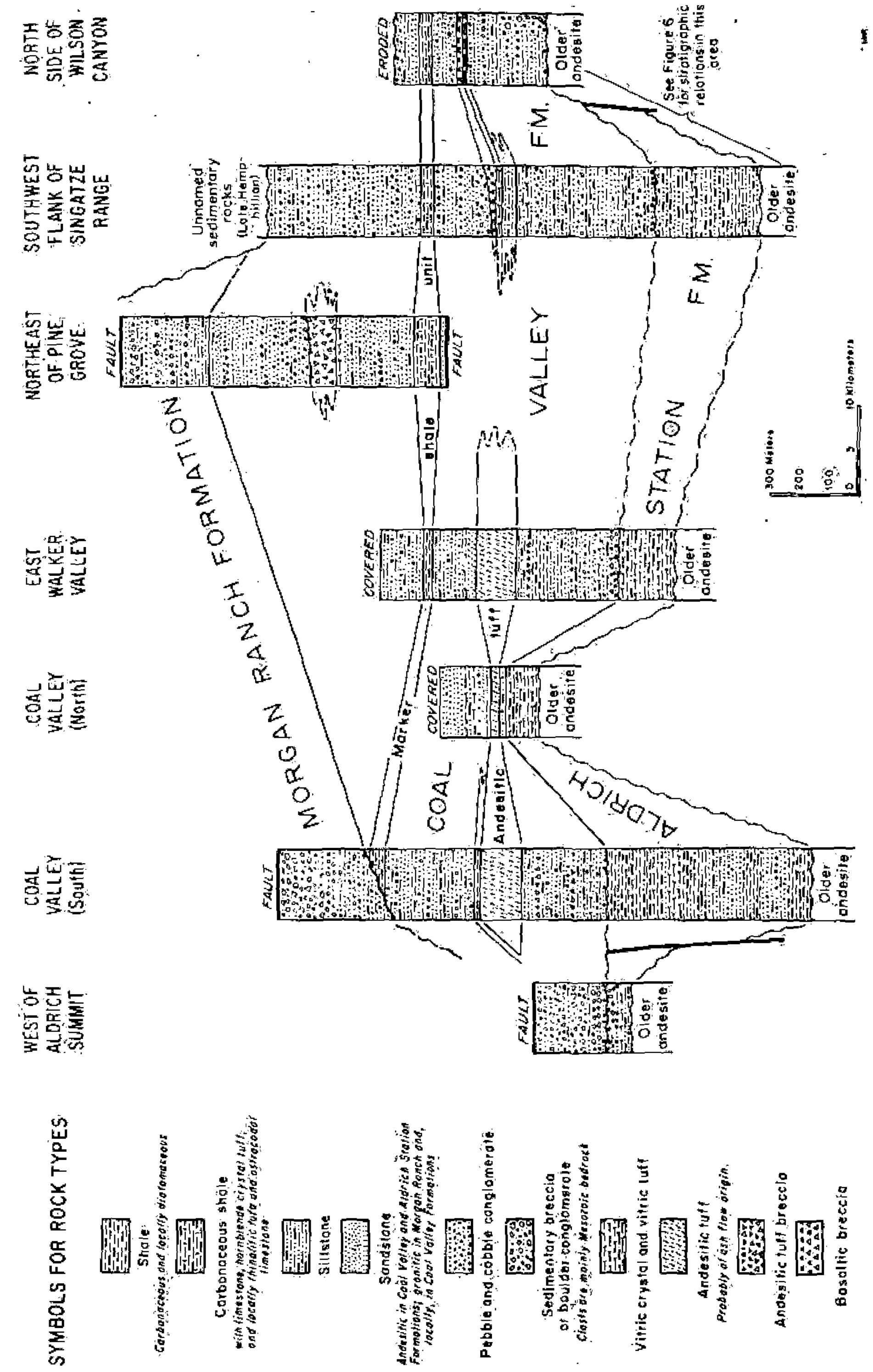

Figure 5. Correlation of Wassuk Group strata from Coal Valley to the southern part of the Singatze Range.

deposits. Coincident with the thinning is a marked coarsening of sediments and an increase in the amount of conglomerate in the formation. Lenses of andesite pebble conglomerate crop out north of the fault, but south of the fault cobble and boulder conglomerate beds are the dominant rocks in the thinned stratigraphic section. Clasts are andesite, altered andesite, and granite; the matrix is usually andesitic or arkosic sand. Clearly, the fault was active during deposition. About 4.8 km farther southwest near the East Walker River and east at Baldwin Canyon, the formation is absent. Thus the southern margin seems to be defined by an east-northeast-trending highland through Aldrich Summit. The presence of the growth fault, described above, nearby to the north suggests that the southern margin of the basin may have owed its elevation to faulting.

Another abrupt facies change south of Wilson Canyon in the Singatze Range implies a basin margin nearby on the north. The lower portion of the formation contains typical mudstone, siltstone, and carbonaceous shale beds with lenses of lithic arenite and pebble conglomerate. Upward, the abundance of pebble conglomerate increases and beds of lapilli tuff are present; a conspicuous unit of water-reworked biotite crystal tuff present both in this sequence and in the finer-grained section of the Aldrich Station Formation at Mickey Canyon demonstrates equivalence of the rocks. About 85 m stratigraphically above the tuff at Wilson Canyon, units of stratified andesite tuff breccia, which pass laterally and vertically into massive units of tuff breccia, are interbedded with carbonaceous and porcellaneous shale, siltstone, and pebbly conglomerate. These units contain very common fragments of petrified wood. Tuff breccia near the top of the formation at Wilson Canyon is dated radiometrically as 11.15 m.y. (KA2581), thus confirming the temporal equivalence of these rocks with fine-grained sedimentary rocks in the formation to the southeast. The northern margin of the sedimentary basin seems to have been north of Wilson Canyon where a center of andesitic volcanism existed.

Late Tertiary and Quaternary uplift and erosion across the Wassuk Range on the east and Pine Grove Hills on the west preclude close definition of the basin margins in those directions. Fine-grained facies of the Aldrich Station Formation immediately adjacent to the present ranges indicates that the basin extended at least partway across the sites of the ranges. Only at the center of the present Wassuk Range (N. 38°36.67', W. 118°52.8') is a possible margin suggested by thinning of the formation and interfingering of volcanic breccia and tuff.

The identified approximate margins suggest a depositional basin elongate in a northwest direction and encompassing the area of four present valleys and parts of three present mountain ranges.

Coal Valley Formation

The Coal Valley Formation is the most widespread formation of the Wassuk Group as it now crops out in five separate basins. The southernmost outcrops of the formation are along Mud Spring Creek at the south edge of Fletcher Valley where only a thin portion of the formation is exposed; more extensive exposures in that present basin are in Baldwin Canyon. From its type section in Coal Valley the formation crops out discontinuously from Morgan Ranch northward to the north flank of Mount Wilson in the Singatze Range, north of which it is absent (Proffett, 1972). The northwest end of the Pine Grove Hills and the west flank of the Wassuk Range define the known west to east extent, respectively, of the formation (Figs. 2, 3).

Andesitic sandstone, pebble and cobble conglomerate, and mudstone and siltstone are dominant rocks in the formation (Fig. 5). Beds of vitric or crystal tuff are scattered through the formation, and lenses or thick accumulations of andesite breccia are interbedded, particularly in Coal Valley and east of Pine Grove. For mapping, the base of the formation is defined to include the lowest sequences of andesite pebble conglomerate and sandstone overlying the highest continuous thick sequence of mudstone beds typical of the Aldrich Station Formation. This horizon marks an unconformity identifiable across the southern end of Coal Valley. Coupled with the lithologic change, it is our basis for revising downward the formation boundary initially described by Axelrod (1956, p. 29–30). We place the boundary at the base of his uppermost (A_6) Aldrich Station unit.

In detail, the stratigraphic succession varies vertically and laterally as strata of fluviatile and locally lacustrine origin interfinger at all scales. Near the Lewis Terrace, the formation is a monotonous succession of interbedded bluish-gray or olive-gray weathering andesitic sandstone, pebble conglomerate, and tuffaceous siltstone. These same rocks characterize the major part of the formation across the region. Several distinctive units can, however, be traced from valley to valley to facilitate correlation among sections now separated by bedrock uplifts (Fig. 5).

One such unit in the lower part of the formation is a remarkable bed of andesitic tuff (unit C_2 of Axelrod, 1956, p. 30), interpreted here as being an ash-flow tuff. The base of the bed is coarse grit composed of angular fragments of andesitic tuff, granite, and feldspar. In the coarse-grained part are angular blocks and fragments as much as 35 m long, torn from underlying portions of the formation and incorporated at odd angles within the bed. The grain size decreases uniformly upward to the top, which consists of silt and clay-sized particles. The center of the bed weathers to reveal closely spaced tubules aligned normal to the contacts of the bed, which are interpreted as being formed by channels of gas-streaming during cooling of the bed. The bed thickens from a feather edge to about 150 m south of Lewis Terrace, but northward as far as East Walker Valley the thickness ranges from 5 to 125 m. In general, the thinner sections are farther east than the thicker ones.

A second unit, important for correlation in the upper part of the Coal Valley Formation along the east flank of the Pine Grove Hills and west flank of the Singatze Range, consists of a sequence of white-weathering tuffaceous siltstone and shale beds, containing a few thin layers of buff aphanitic, ostracodal limestone and hornblende pumice tuff. Calcareous sandstone and fine-pebble conglomerate beds locally interfinger with the finer grained rocks, and the upper part of the unit contains beds of distinctive thinolitic tufa. In Coal Valley the unit is 45 m thick; limestone and tufa beds are absent, but shale and hornblende pumice tuff beds persist. There the younger Morgan Ranch Formation rests unconformably on the unit but truncates it 0.5 km farther south (N. 30°30', W. 118°56'). On the east flank of the Pine Grove Hills, the unit is about 100 m thick and is overlain by as much as 550 m of typical rocks of the Coal Valley Formation. The unit then thins northward to 50 m on the north side of Wilson Canyon, where it is separated below by about 55 m of andesitic siltstone, sandstone, and pebble conglomerate beds from a conspicuous biotite crystal tuff and basalt breccia unit. Evernden and others (1964, p. 178; KA485) dated the crystal tuff as 9.3 m.y. old, although following Axelrod (1956, p. 67); they assigned the unit to the Morgan Ranch Formation. Clearly, these rocks belong to the Coal Valley Formation, and the date establishes an early Hemphillian age for the upper part of the formation. The lower part of the formation, dated at approximately 11 m.y., is of Clarendonian age.

Several facies changes can be defined in the Coal Valley Formation using the two described units for reference. Southwest from Lewis Terrace, increasing amounts of coarse sedimentary breccia interfinger with sandstone and conglomerate beds. At the southwesternmost exposures of the formation (N. 38°27.5', W. 119°0'), massive beds of sedimentary breccia form the entire preserved part of the formation. Rock fragments in the breccia units include andesite and propylitized andesite of Miocene age and metavolcanic, metasedimentary; and granitic rocks of Mesozoic age. The edge of the basin along which basement rocks were exposed lay only a short distance west and southwest. Farther southwest, slightly younger latite ignimbrite units (about 9.5 m.y.) are separated from Miocene andesite or Mesozoic basement rocks by only a veneer of andesitic sandstone and conglomerate (Gilbert and others; 1968, p. 286).

In the lower part of the Coal Valley Formation; mudstone and siltstone beds and carbonaceous siltstone beds are common between Lewis Terrace on the south and near Lapon Canyon on the north. These rocks grade southward into andesitic sandstone interbedded with andesitic tuff breccia and northward into andesitic sandstone and siltstone. These relations suggest that the deepest part of the basin, in which lacustrine and paludal environments prevailed, lay in the area of the present Coal Valley. A similar unit consisting of diatomaceous mudstone, siltstone, and very fine-grained sandstone, as much as 25 m thick, overlies the marker andesitic tuff from Lewis Terrace to Lapon Canyon. South and north of these localities the unit thins and grades into sandstone and siltstone beds of fluviatile origin. Apparently, for a second time during deposition of the Coal Valley Formation, a lacustrine environment persisted in the Coal Valley area long enough for a significant thickness of sediment to accumulate before fluviatile sediments again blanketed the area.

A pronounced facies change occurs in the lower part of the formation in the vicinity of Wilson Canyon (Figs. 5, 6).

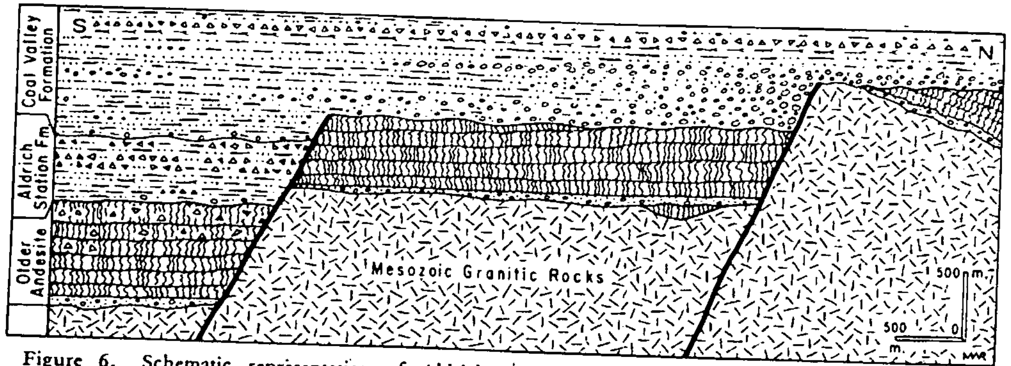

Figure 6. Schematic representation of Aldrich Station and Coal Valley strata across late Clarendonian–early Hemphillian faults in the southern Singatze Range near Wilson Canyon and Mount Wilson. Northward coarsening of Coal Valley strata reflects proximity of the basin margin.

of the Pine Grove Hills, the lower part of the formation contains dominantly fine-grained rocks including siltstone and fine-grained sandstone, locally tuffaceous, that weather to form smooth, soft slopes. The lowermost beds are juxtaposed against older andesite along a fault just south of Wilson Canyon (N. 38°48.5′, W. 119°13.0′), but the upper portion of these beds extends continuously across the fault and across Wilson Canyon. This relation dates movement along the east-trending fault (Figs. 3, 6) as latest Clarendonian. Finer grained rocks that are not offset by the fault interfinger rapidly northward across Wilson Canyon with coarse sandstone, conglomerate, and bedded sedimentary breccia. Clasts include granodiorite and granitic debris, metavolcanic rocks, and Miocene andesite.

On the south flank of Mount Wilson, clasts coarsen to as large as 4 m across adjacent to a northeast-trending fault. There the Coal Valley Formation is composed mostly of granodiorite boulder conglomerate. Along the fault nearly all of the conglomerate sequence on the south abuts granodiorite on the north (Fig. 3). However, the uppermost beds of boulder conglomerate and overlying beds, including the distinctive biotite crystal tuff and basalt tuff breccia, can be mapped unbroken across the projection of the fault. Southward the boulder bed interfingers in a succession of sandstone and siltstone beds. The fault was active during deposition of part of the formation with the upthrown block of basement rock on the north contributing granitic debris to the basin adjacent on the south (Fig. 6).

Although most rock fragments in the Coal Valley Formation are andesite and altered andesite, clasts of granitic composition or minerals derived from granitic rocks are locally important constituents and are significant in interpreting the tectonic history of the region. As noted, coarse granitic debris is abundant near the identifiable margins of the basin on the southwest and north. Within the basin the lowermost 185 m and the uppermost 275 m of the formation on the north flank of the Pine Grove Hills contain granitic clasts. Similarly, the upper quarter of the formation in Coal Valley is locally arkosic. These occurrences indicate that basement rocks were exposed, possibly by recurrent faulting west of the basin, during early and late Coal Valley time. Both the granitic debris and the thick sections of andesitic sediments in the upper part of the formation suggest the possibility that progressive uplift along the western margin of the basin led to erosion of previously deposited Coal Valley sediments there, and to their redeposition together with granitic debris farther east in the continuously subsiding deeper portion of the basin. The apparent near conformity between the Coal Valley and overlying Morgan Ranch Formation in the deeper part of the basin lend support to this interpretation of progressive, rather than abrupt, uplift to the west.

Complete sections of the Coal Valley Formation are exposed only at the north end of the Pine Grove Hills and at the southern end of Coal Valley; elsewhere in the area only partial sections are present, owing to later faulting or erosion. At the former locality the formation is about 1,350 m thick, whereas at the latter we measured 970 m.

At most localities the Coal Valley Formation rests unconformably on older units. North of Mount Wilson it rests on granitic basement

rocks; south of Mount Wilson and also west of Aldrich Summit, it rests on older andesite. Disconformity with the underlying Aldrich Station Formation is evident near Aldrich Station and at Lapon Canyon where cobble conglomerate comprises the basal Coal Valley beds. Unconformable relations are especially evident in the southern part of the Singatze Range where the Coal Valley rests on progressively older beds of the Aldrich Station from north to south (Fig. 3).

The Coal Valley Formation was deposited in a basin that extended beyond the present limits of its outcrop. The eastern basin margin is unknown, but judging from the thickness and extent of beds along the west flank of the Wassuk Range, it must have been east of the range. Similarly, the western margin is unknown; coarser facies in the vicinity of the Pine Grove Hills suggest a margin not far beyond the present hills. On the south a margin must have extended east-southeast from Fletcher toward Powell Mountain. During deposition the northern margin migrated progressively northward with time, overstepping fault blocks rising across the southern part of the Singatze Range (Fig. 6). It is likely that the final northern margin lay at the latitude of the present central part of the range. Thus, the basin seems to have been elongate in a northwest direction. Uplands composed primarily of andesitic volcanic rocks must have been rising to the southwest, west, and northwest, with faulting and erosion at least locally exposing crystalline basement rocks. Within the basin, localized volcanic eruptions produced andesite breccias interbedded in the formation.

Morgan Ranch Formation

At the type locality the Morgan Ranch Formation consists of coarse clastic sediments overlying Coal Valley strata and in fault contact with granitic basement along the western margin of Coal Valley. It measures as much as 400 m thick in this area. The primary basis for distinguishing the sequence is a change from tuff and andesitic sandstone, which characterize the Coal Valley Formation, to arkosic sandstone and breccia derived principally from granitic and metamorphic basement rocks. The general color of the two units also differs, being gray to light brown in the Coal Valley and orange-brown to yellow-brown in the overlying Morgan Ranch strata. The Morgan Ranch sequence coarsens upward, and the uppermost portion is largely coarse, poorly sorted breccia, which Axelrod (1956) interpreted as fanglomerate deposited against a rising escarpment in front of a basement high. Feldspathic sandstone, commonly coarse and pebbly, is interbedded with breccia units and predominates in the lower part of the formation. The sandstone beds are as much as 3 to 6 m thick; many are cross-bedded and show scour along upper and lower surfaces.

The name Morgan Ranch is used in this study also for arkosic strata that crop out extensively west and north of Morgan Ranch and along the northeastern margin of the Pine Grove Hills (Fig. 3); limited exposures occur at the northeast end of Coal Valley. These rocks are composed largely of debris derived from local basement rocks with a variable admixture of andesitic debris. They are generally similar in character and age to type Morgan Ranch strata, but they are thicker and tend to be finer grained. Along the northeast flank of the Pine Grove Hills, Morgan Ranch strata are approximately 1,225 m thick, and most of the exposed sequence consists of well-bedded, brown sandstone, siltstone, and shale or mudstone. Beds of coarse, poorly sorted breccia are also present and are as characteristic of the formation here as they are in the type locality, particularly in the upper part of the formation, but in most exposed sections the breccia beds are fewer and thinner than they are in Coal Valley. Breccia units are interbedded with friable, brown sandstone, and they contain principally granitic and metamorphic debris and relatively little andesitic debris. The coarse breccia beds contain blocks 1 to 2 m across, with sporadic larger blocks, and they occur in units as much as 15 to 25 m thick. Typically, such units are graded without distinct stratification, and the upper portions are made up of fragments no larger than 5 or 6 cm. Fine-grained breccia also occurs separately in units as much as 1 m thick.

The relation between Morgan Ranch and Coal Valley Formations is variable. In most places, exposed contacts are faults. Where depositional contacts can be mapped, as in Coal Valley, stratification is generally approximately parallel in the two formations, and they appear conformable. Axelrod (1956) reported that they are conformable. Careful mapping in Coal Valley shows, however, that stratal units in the underlying Coal Valley Formation are progressively overlapped southward. To the north the two do indeed appear to be conformable, but at the northwestern margin of Coal Valley a pronounced local unconformity occurs. Both formations are truncated along a fault against granitic basement east of Morgan Ranch (Fig. 2). On the upthrown block north of this fault, Coal Valley strata are absent, and the Morgan Ranch Formation rests directly on older andesite. Both formations have been displaced, but Coal Valley strata together with any Aldrich Station strata originally present had been removed from the upthrown block before Morgan Ranch strata were deposited. A similar unconformity is evident across the fault at the mouth of Scotts Canyon (Fig. 3). South of Pine Grove Canyon (N. 38°41.3′, W. 119°5.3′), Morgan Ranch strata disconformably overlie the Coal Valley Formation.

Facies changes in the Morgan Ranch Formation along the northeast flank of the Pine Grove Hills are evident but can be delineated only in a general way. Part of the section exposed northeast of Mickey Canyon Spring consists primarily of thin-bedded, gray, silty shale which is commonly carbonaceous; the section coarsens to the southwest. Breccia is a lithofacies particularly characteristic in the upper part of the formation, but it also varies laterally and is partly controlled by proximity to the fault bounding the basement block. Many individual breccia units terminate abruptly. For example, northeast of Mickey Canyon Spring, where the exposed section strikes toward the fault (Fig. 3), breccia units increase in number, coarseness, and thickness as the fault is approached. South of Pine Grove Canyon, the upper part of the exposed section contains abundant units of coarse breccia; traced northwestward toward Pine Grove Canyon, breccia units lens out and the equivalent section becomes largely sandstone with only a few interbedded breccia beds.

Units of porous limestone and calcite-cemented breccia are interbedded in the Morgan Ranch Formation at several localities along the Pine Grove Hills fault zone. They have the appearance of tufa-type deposits and were probably produced by springs emerging along the fault. They are interbedded through about 100 m of section, indicating that the fault was presumably active during deposition of the strata. Best exposures of these rocks are to be found on the southeast flank of Mount Etna (Fig. 3); others occur northwest of Mickey Canyon Spring.

These facies relations suggest to us that the fault bounding the Pine Grove Hills basement block approximately delineates the western margin of Morgan Ranch deposition. The formation probably accumulated, as Axelrod (1956) inferred, in front of a rising basement block, the breccia representing both the times and the places of most active colluvium and fanglomerate deposition, the finer facies representing the more distal depositional environments on the subsiding block to the northeast. Such origin would probably produce thicker sections to the west near the fault and thinning to the east, but this cannot be established from existing surface exposures.

PERIODS OF FAULTING AND WARPING

Quaternary movement along normal faults has produced steep escarpments and delineated a number of the most prominent ranges and valleys in this general region, notably the escarpment near Topaz Lake facing Antelope Valley, and the eastern escarpments of the Carson Range facing Carson Valley; the Pine Nut Mountains and Wellington Hills facing Smith Valley; the Singatze Range facing Mason Valley; and the Wassuk Range facing Walker Lake and Whisky Flat (Fig. 1). These escarpments are all steep and lofty and have been relatively little eroded. Their youthful age has been demonstrated in a number of places. Along the southern part of the Wassuk Range, olivine basalt flows having an age of about 3.5 m.y. have been displaced the full height of the range front (Gilbert and others, 1968). The escarpment of the Sierra Nevada facing Mono Basin is younger than basaltic flows having a K-Ar age of about 3 m.y. and also younger than the earliest glacial stage (Curry, 1966; Gilbert and others, 1968). Recent movement along the front of the Carson Range has long been recognized (Lawson, 1912; Moore, 1969, Fig. 8). A basalt flow that caps the Singatze Range and is offset by the frontal fault about 7 km north of Wilson Canyon has a K-Ar age of 7.25 m.y. (KA2582).

By contrast, geologic relations mapped during the present study demonstrate that the faults delineating the Pine Grove Hills and Coal Valley structural blocks are older than about 7.5 m.y. and have not been reactivated during the Quaternary deformation of the region. The eastern front of the Pine Grove Hills, for example, is not a Quaternary fault scarp despite the fact that the margin of the basement block is a fault of large displacement; nor has the fault zone that bounds the basement block west and northwest of Coal Valley had Quaternary movement.

Deformation during early or middle Miocene is indicated by the unconformity between rhyolitic ignimbrite 22 to 28 m.y. old and andesite 15 to 18 m.y. old. The wide regional distribution of the ignimbrite units suggests that they formed a more or less continuous terrane during the time of eruptions, but they are lacking in many parts of the area mapped during the present study. Younger andesite flows lie directly on basement rocks in the southern Singatze Range, in the Cambridge Hills, on the structural high between Coal Valley and East Walker Valley, and along the margins of Fletcher Valley (Figs. 2, 3). It appears that the area mapped was structurally high and eroded during the period between about 18 and 22 m.y.

Faults of late Miocene age have been mapped near the southern margin of Coal Valley and in the southern Singatze Range. One near the East Walker River, south of Coal Valley (N. 38°27.4′, W. 118°59.9′), is the contact between altered andesite and granitic rock and has been followed by a dikelike intrusion of younger andesite having an age of about 12.5 m.y. The younger andesite has not been sheared, as is evident from its glassy contact selvages, and fault movement must have occurred between about 12.5 and 15 m.y. This fault trends approximately east and is nearly vertical. A second fault cutting Aldrich Station and lower Coal Valley strata north of Aldrich Summit trends west-northwest to northwest, dips steeply, and was active during deposition of the displaced strata. In the Singatze Range, two east-northeast-trending faults, one just south of Wilson Canyon and the other on the south flank of Mount Wilson, displaced lower Coal Valley strata but are overlapped by upper Coal Valley beds only slightly older than 9.3 m.y. (Figs. 3, 6). Major displacement along the southern fault occurred during an interval between deposition of Aldrich Station and Coal Valley strata. On the downthrown block to the south, Coal Valley beds unconformably overlie an Aldrich Station sequence 740 m thick, whereas on the upthrown block to the north, Coal Valley beds rest directly on older andesite flows. The uppermost Aldrich Station strata have a K-Ar age of 11.15 m.y. (KA2581), and the oldest unfaulted Coal Valley strata are only slightly older than tuff dated as 9.3 m.y. old.

Movement along many of the faults began before and continued after Morgan Ranch deposition. Along some of these faults, such as near Morgan Ranch and at Scotts Canyon, earlier movement followed by erosion of Coal Valley and Aldrich Station strata from the upthrown blocks has resulted in local unconformities where younger Morgan Ranch beds overlap the faults. The evidence for both pre– and post–Morgan Ranch movement along these faults is indisputable, and a similar history is probable along many other faults in the area. Along the Pine Grove Hills fault zone, movement during Morgan Ranch deposition is indicated by facies relations of Morgan Ranch strata, but pre–Morgan Ranch movement cannot be proved, because all of the sedimentary formations are confined to the downthrown block. This very fact, however, suggests that movement along the Pine Grove Hills fault zone probably began during pre–Morgan Ranch time, resulting in removal of older strata and exposure of basement rocks west of the fault by the time Morgan Ranch strata were accumulating. Perhaps movement along the fault zone was more or less continuous. Arkosic Morgan Ranch strata would then have accumulated east of the uplifted block when and where basement detritus became predominant. If such was indeed the history, one must conclude that the boundary between Coal Valley and Morgan Ranch Formations is a lithologic boundary that is probably not the same age throughout the area.

Morgan Ranch strata, as well as older strata, have been faulted and tilted, locally to high angles. This deformation was completed before eruption of the younger volcanic rocks 6 to 7 m.y. ago. East of Mickey Canyon Spring, a flow of olivine basalt having a K-Ar age of 7.1 m.y. (KA2497) unconformably overlies the tilted and faulted formations of the Wassuk Group, and a dikelike mass of the basalt is intruded along the Pine Grove Hills fault southeast of the spring. In the southern Singatze Range north of Mount Wilson, olivine basalt having a K-Ar age of 7.25 m.y. (KA2582) unconformably overlies tilted Coal Valley beds faulted against granitic basement. Likewise, north of Morgan Ranch, tilted and faulted Morgan Ranch Strata are buried by relatively undeformed basalt having an age of 6.6 m.y. (KA2366). An andesite flow belonging to the Bald Mountain complex buried tilted Morgan Ranch Formation and older andesite in fault contact with granitic basement west of Morgan Ranch (Fig. 2). Furthermore, rhyolitic protrusions have been emplaced along and across the Pine Grove Hills fault. The largest and most numerous of these occur west of Wichman Valley, where they have obscured the fault boundary between granitic basement and Morgan Ranch Formation (Fig. 2). The northernmost is a small protrusion situated squarely on the fault at Mount Etna north of Scotts Canyon (Fig. 3).

The structural history of this area during the last 7 m.y., since the eruption of basalt and andesite flows and rhyolitic protrusions, does not include reactivation of earlier faults. Broad uplift has occurred, however. This is clear from the rejuvenation of the East Walker River along its course between Bridgeport and Mason Valley. The river is incised below the Lewis surface by as much as 250 m in the area west and southwest of Coal Valley. The amount of incision decreases northward and is negligible at the southern end of Mason Valley, so that the uplift has the appearance of a broad upwarp. The sequence of dissected younger pediments below the Lewis Terrace testifies to some periodicity in the upwarping movement.

A more pronounced and local upwarp has produced the higher elevation of the old erosion surface on the summit of the Pine Grove Hills and is responsible for the present relief of that range. Specific evidence of the upwarp can be seen along the northern flank of the range. Here, young basalt flows were erupted onto surfaces of low relief cut across relatively nonresistant sedimentary formations. The flows are now tilted northward at angles as high as 20° and have been deeply dissected. Even here, however, older faults were not reactivated despite the proximity of the Singatze fault block which was uplifted during Quaternary time. Displacement along the young fault zone at the eastern front of the Singatze Range diminishes southward from Wilson Canyon and disappears at the Pine Grove Hills upwarp, about 8 km south of Wilson Canyon.

Other local Quaternary upwarps may be present in the region but are not clearly distinguishable. The Cambridge Hills may be one, but exposures along its margins are so poor that structure and history are uncertain. Along the eastern side of the Cambridge Hills, relatively small escarpments trending north are suggestive of normal faulting, and this may be a small Quaternary fault block, tilted westward like others in the region.

GEOMETRY OF STRUCTURES

Regional Configuration

Faulting prior to 7.5 m.y. produced structurally low areas in which the Miocene-Pliocene sedimentary formations are preserved, and intervening structurally high areas where older rocks are now exposed and elevations are generally higher. Each large structural block is itself complexly faulted, but the gross configuration of structural highs and lows reflects the structural trends characteristic of the earlier period of Basin-Range deformation. These trends are typically northeast to east and northwest. Coal Valley, for example, is separated from Fletcher Valley and Baldwin Canyon to the south and from Wichman Valley and East Walker Valley to the north by structural highs that trend east-northeast and northeast, respectively. The Gray Hills trend nearly east and separate two structural lows, East Walker Valley to the south and Pumpkin Hollow to the north. The Pine Grove Hills trend northwest.

By contrast, all of the Quaternary fault block ranges in the region have general trends that are north or north-northwest (Fig. 1). These younger fault blocks stand prominently in the general topography, and they tend to obscure the earlier structures and structural trends. However, many faults within the young-range blocks are of earlier (Tertiary) age and trend northeast or northwest at marked angles to the general north trend of the range as a whole. Over most of the area mapped during the present study, Quaternary faulting was minimal or did not occur, and the major fault zones trend either northwest or northeast.

Miocene-Pliocene Faults

Most of the faults mapped during the present study are normal faults that have displaced formations of the Wassuk Group and older volcanic rocks but have not been active during the last 7.5 m.y. Most dip at angles between 50° and 70°, but dips range from 40° to vertical. Most individual faults of this age, as well as major structures, trend northeast, but some individual faults and fault segments trend nearly north. Of the latter, only a few have large displacement and seem significant. One of these on the west flank of the southern part of the Singatze Range (Fig. 3) forms the east boundary of the sedimentary section in that area. Another at the mouth of Scotts Canyon had both pre– and post–Morgan Ranch movement, and another at the southern end of East Walker Valley truncates a sequence of Aldrich Station strata 300 m thick against granitic basement. Several north-trending faults along the eastern margin of Coal Valley are relatively small and may have had Pleistocene movement. The most extensive fault zones having the largest displacements are the Pine Grove Hills fault zone forming the northeastern margin of the Pine Grove Hills basement block and the Coal Valley fault zone forming the northwest margin of the Coal Valley block and the southeast margin of the Pine Grove Hills block. These fault zones consist of fault segments that strike in different directions producing an irregular fault trace that is locally zig-zag. Because of this irregularity, we conclude that movement along the zones has been dip-slip without significant strike slip.

Along the Pine Grove Hills fault zone, the basement complex forming the higher part of the range is faulted against Morgan Ranch strata, except along the northernmost and southernmost parts where older andesite is faulted against granitic rocks (Fig. 3). The trace of the fault can be mapped in detail from a little south of Pine Grove Canyon to the northernmost part of the range; farther south, it is obscured by rhyolitic protrusions that bury or intrude it (Fig. 2), so that only the general location of the fault can be determined. Northwestward from Pine Grove Canyon, the general trend of the fault zone is N. 60° W., but the trace is irregular and consists of segments as long as 2 km which strike northwest, north, and east-northeast. Where the attitude of the fault surface can be determined, it dips away from the range at an angle of about 60°. Southeastward from Pine Grove Canyon, the general trend is S. 35°, E. 40° as far as the southern margin of Wichman Valley. There the fault bounding the basement block turns west-southwest beneath andesite breccia units and flows of the Bald Mountain complex and reappears 3.5 km to the south where it strikes east through Morgan Ranch to an intersection with the Coal Valley fault zone (Fig. 2).

The Coal Valley fault zone is the margin of the basement complex west of Coal Valley. Its general trend is northeast, but its trace is irregular. For about 3 km east of Morgan Ranch, the trace is zig-zag, consisting of short east, northeast, and northwest-trending segments (Fig. 2). In this area the fault surface dips toward Coal Valley at an angle of 40° to 45°. Farther east, poor exposures preclude detailed mapping, but the general trend continues northeast. South of Morgan Ranch, the general trend of the fault zone for about 5 km is approximately north, and again the trace is very irregular. The fault surface dips steeply eastward in this area, but at one locality the dip is steeply westward. The fault turns again toward the southwest and continues across the East Walker River toward the structurally low area south of the Pine Grove Hills. South of Morgan Ranch, the Coal Valley fault zone is the southeastern terminus of the Pine Grove Hills structural block.

Fault structures on the western flank of the Wassuk Range between Lucky Boy Pass and Aldrich Station are a series of northeast-trending horsts and grabens bounded by steeply dipping normal faults (Fig. 2). Most noteworthy is the Baldwin Canyon graben within which about 600 m of Coal Valley strata are exposed between granitic basement on the northwest side of the graben and older andesite and basement rocks on the southeast. Farther north also, the eastern margin of Coal Valley is cut by faults trending northeast into the Wassuk Range, although some north-trending faults occur here as well. Faults cutting sedimentary strata within Coal Valley most commonly have northeast trends.

The structure east of the Cambridge Hills is obscured by pediment gravel and alluvium. Rocks exposed at the southern end of East Walker Valley have been displaced along faults trending northeast, northwest, and north. To the north, our gravity traverse across the Gray Hills shows a pronounced negative anomaly in the north end of East Walker Valley relative to gravity values over basement in the Gray Hills. These data are not yet fully analyzed, but a fault along the southern margin of the Gray Hills, trending approximately east, is probably to be inferred with a buried sequence of Miocene-Pliocene sedimentary rocks south of it.

Major Miocene-Pliocene faults cross the southern Singatze Range near Wilson Canyon and along both the north and south flanks of

Mount Wilson. All are normal faults having dips between 45° and 70° and trends that are east-northeast or northwest. They are demonstrably older than 7.5 to 9.3 m.y. Moore (1969, p. 19) reported that a major fault zone trending east-northeast marks the southern end of the Pine Nut Mountains and suggested that this may be the same as the east-northeast-trending fault zone crossing the Singatze Range at Wilson Canyon. Whether the two are the same fault zone cannot be established, but they probably are of similar age and have had little or no Quaternary movement. The present study demonstrates conclusively that the fault crossing the Singatze Range at Wilson Canyon was active during late Miocene time (Clarendonian) and has not been active since. Present relief at the southern end of the Pine Nut Mountains is probably to be attributed to relatively deep erosion of nonresistant sedimentary rocks on the downthrown block to the south rather than to late fault movements.

Folds Related to Miocene-Pliocene Faulting

Low-amplitude folds, approximately 0.5 to 3 km across, are associated with faults in Coal Valley and near Pine Grove Canyon (Figs. 2, 3). The folds undoubtedly developed as normal faulting deformed the margins and floors of the present basins. Axes of the folds trend N. 30° E. to N. 90° E., although a fold at Lewis Terrace trends N. 70° W. Several are cross folded into asymmetric basins. For example, northwest of Lapon Canyon (Fig. 2), two such folds whose dominant axes trend northeast parallel to the Coal Valley fault zone are arranged en echelon between east-northeast–trending faults within Coal Valley; their minor axes trend nearly due east. Beds of the Wassuk Group at Lewis Terrace are folded in a westward-plunging syncline, the axis of which is normal to a strong basinward salient in the Coal Valley fault zone (Fig. 2). Folding there seems to have occurred as basement rocks were forced prowlike along the fault into the sedimentary section.

Small folds south of Wilson Canyon, whose axes trend north to northeast, appear to be related to movements along a swarm of small north-trending faults that cut the upper Coal Valley strata in that area (Fig. 3).

Quaternary Faults

Range-front fault zones bordering the north-trending ranges of Quaternary age characteristically have zig-zag traces, and the fault scarps show topographic salients and re-entrants. These features are clearly depicted by Moore (1969) for the Carson Range, Pine Nut Mountains, and Singatze Range. Of these young fault blocks, only the southernmost portion of the Singatze Range has been mapped during the present study. Here, the surface of the frontal fault dips toward Mason Valley at angles between 50° and 60°. The zig-zag trace of the east-facing escarpment and of the frontal fault is evident, particularly just south and north of Wilson Canyon. At least some of the jogs in the range front coincide with locations of large Miocene-Pliocene faults within the range block. For example, the earlier east-northeast fault just south of Wilson Canyon probably controlled the prominent east trend of the range front at that point. Similarly, the easterly jog of the frontal fault zone 3 km farther north coincides with an earlier east-northeast-trending fault that crosses the range on the south side of Mount Wilson, and the succeeding northwesterly jog is approximately in line with an earlier northwest-trending fault that crosses the range north of Mount Wilson and along which west-dipping Coal Valley strata have been faulted down against the granitic basement of the range summit. In similar fashion, the Pine Nut Mountains–Wellington Hills frontal escarpment shows an easterly jog at the juncture between the two blocks, where an east-northeast fault zone of presumably pre-Pleistocene age crosses the ranges.

SUMMARY AND CONCLUSIONS

Cenozoic History

The earliest Cenozoic rocks in the area studied are rhyolitic ignimbrite flows of early Miocene age; these are succeeded by widespread andesitic flows and breccia. Deformation during early and middle Miocene time is indicated by an unconformity between the Miocene andesite flows and underlying rhyolitic ignimbrite. Few details are known about this early deformation, but the absence of rhyolitic ignimbrite over much of the area mapped indicates that this area was relatively high. By approximately 12.5 m.y. ago, however, the same area was the site of sedimentation in an extensive basin. The record of events thereafter is preserved more completely in a thick sequence of upper Miocene and Pliocene sedimentary and volcanic strata that accumulated in the basin. Stratigraphy and facies characteristics of these strata, which now are preserved in separate fault blocks, indicate that all the strata were deposited in a single large basin that was much more extensive than present basins in the area. Volcanism was contemporaneous with sediment accumulation, for many strata are volcanogenic; centers of eruption were mostly close to the margins of the basin of accumulation or beyond them.

Fault movements contemporaneous with sediment deposition have been established at a number of localities. By approximately 7.5 m.y. ago, the original basin and the extensive sedimentary formations that accumulated in it had been disintegrated into the separate structural blocks that now characterize the region. We conclude that the fault movements that accomplished the breakup of the once continuous sedimentary terrane were in progress during an interval between approximately 10 and 8 m.y. ago; that is, they began during Coal Valley deposition and continued during Morgan Ranch deposition. Faulting had ceased and an erosion surface of low relief had developed by about 7.5 m.y. ago. Basic flows and rhyolitic protrusions were erupted locally onto this surface. During a period of tectonic inactivity which lasted until 3 to 4 m.y. ago, a well-graded erosion surface evolved. Broad pediments extended across the less-resistant sedimentary rocks preserved on the lower structural blocks, and accordant surfaces of low relief developed on the higher blocks where older rocks are exposed. Across this graded surface, the courses of the East and West Walker Rivers were established.

During the Quaternary period, warping and faulting resumed. Young fault-block ranges and valleys, which are the most prominent features of the present regional topography, developed at that time, and the rivers were incised across the upwarped and upfaulted areas.

Basin-Range Deformation

At least two distinct periods of late Cenozoic deformation can be recognized in this portion of the western Basin and Range Province. Data from the area mapped during the present study establish an earlier period of faulting and tilting prior to 7.5 m.y. ago. Data from the adjacent Mono Basin area establish another period later than 3 to 4 m.y. ago (Gilbert and others, 1968). Development of the extensive and remarkably even Lewis erosion surface between these two periods of deformation indicates that they were separated by an interval of little tectonic activity that lasted about 4 m.y. Significantly, this interval was also an interval of minimum volcanic activity in the Mono Basin area, where volcanism has otherwise been essentially continuous during the last 12 m.y. (Gilbert and others, 1968). The only volcanism recorded in the Mono Basin area during that interval is a small volume of rhyolite in the western Bodie Hills which has been dated at 5.3 to 5.7 m.y. (Silberman and Chesterman, 1972).

Stress relief during the later period of Basin-Range deformation did not follow the pattern established prior to 7.5 m.y. ago. The earlier period was characterized by normal faults and fault blocks having northeast and northwest trends. The more recent deformation has been characterized by tilted fault blocks that trend north to north-northwest and by broad areas of warping with little faulting. Zig-zag traces of young range-front fault zones are at least partly a reflection of earlier fault structures within the range blocks, but the north trend of zones along which major Quaternary displacements occurred is in marked contrast to the trends of earlier fault structures. A similar variation between early and late fault patterns in the western Basin and Range Province has been reported by Ekren and others (1968) at the Nevada Test Site, but there the change in pattern occurred about 10 m.y. earlier, between 14 and 17 m.y. ago.

The pattern of Quaternary deformation in the area of this report is distinctive and is separated from adjacent segments of the western Basin and Range Province by two major northeast-trending structural zones (Fig. 7). To the south is the Mono Basin–Excelsior Mountains zone (Shawe, 1965, Fig. 7; Gilbert and others, 1968) in which left lateral movement during Pleistocene and Holocene time has been recognized. The zone also has been a locus of Quaternary volcanic activity. South of the Mono Basin–Excelsior Mountains zone, Quaternary deformation has been characterized by large, continuous horsts and grabens trending approximately north: Owens Valley graben, Inyo–White Mountains horst, and Fish Lake Valley graben. The junction of the zone and the fault structures to the south is marked by a structural "knee" where trends change from north to northeast (Gilbert and others, 1968, p. 313–314). To the north is the Carson lineament,

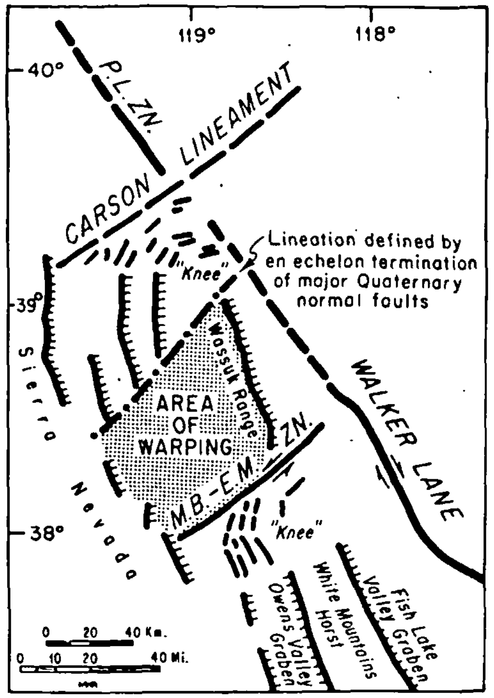

Figure 7. Sketch map showing major fault zones and lineaments near the western margin of the Basin and Range Province and the pattern of Quaternary faulting and warping. P.L. ZN. is zone of faulting in the Pyramid Lake area, and M.B.-E.M. ZN. is Mono Basin–Excelsior Mountains structural zone. Traces of the Walker Lane, Pyramid Lake zone, and Carson lineament are after Shawe (1965, Fig. 8), and traces of short faults south of the Carson lineament are after Moore (1969, Pl. 1).

extending as much as 150 km northeastward from Carson City (Shawe, 1965, p. 1373–1375) and forming the northern boundary of the regional block including the area of this report. Quaternary structural trends north of this lineament are north or northeast, except near Pyramid Lake where a northwest-trending zone of Quaternary faults (Bonham, 1969) seems to be a continuation of the Walker Lane described to the southeast (Shawe, 1965, p. 1374).

Within the block bounded by the Mono Basin–Excelsior Mountains zone, the Carson lineament, and the Wassuk Range, Quaternary deformation has included a broad southern area of warping with minimal faulting and a northern area of block faulting (Fig. 7). Most of the mapping during this study has been in the southern area where broad warping has been the characteristic style of Quaternary deformation. Quaternary fault-block ranges occur en echelon in a belt that extends southwestward from the northern end of the Wassuk Range. The alignment of the southern ends of these fault blocks establishes a northeast-trending lineament that is approximately parallel to the Mono Basin–Excelsior Mountains zone and to the Carson lineament (Fig. 7). The fault blocks are much smaller than those south of the Mono Basin–Excelsior Mountains zone, and they have all been tilted westward and are separated by east-dipping normal faults. Range-front fault zones typically terminate in areas of warping (Moore, 1969, p. 16); one example of this, the southern terminus of the Singatze fault block, has been documented in the present report.

Near the Carson lineament, at the northern ends of the Pine Nut Mountains and the Singatze and Wassuk Ranges, the structural trend changes from north to northeast and east (Fig. 7; Moore, 1969, Pl. 1). This change in trends seems to define a structural "knee" adjacent to the Carson lineament similar to the "knee" along the southern margin of the Mono Basin–Excelsior Mountains zone. If so, the lineament defined by en echelon termination of Quaternary fault zones near the center of the regional block described here may represent a break at depth in the crust between a relatively more stable block to the south deformed by warping and a block to the north deformed primarily by horizontal shear at depth resulting in normal faulting at the surface.

ACKNOWLEDGMENTS

Geologic mapping, gravity survey, and radiometric dating of rock samples were supported by Grant GA-19311 of the National Science Foundation. Radiometric ages were determined at the University of California, Berkeley, under the supervision of G. H. Curtis. We are indebted to student assistants and colleagues for advice and assistance, particularly to Lane R. Johnson for assistance with the geophysical aspects of the study..

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MANUSCRIPT RECEIVED BY THE SOCIETY NOVEMBER 7, 1972
REVISED MANUSCRIPT RECEIVED FEBRUARY 17, 1973

FALL, 1976

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DISTRIBUTION IN TIME AND SPACE OF LATE PHANEROZOIC NORMAL FAULTING IN NEVADA AND UTAH

by Anne Kramer Loring[1]

ABSTRACT

To understand the timing of extensional deformation which has occurred in the Great Basin since the close of the Sevier orogeny, a compilation of normal fault ages was made for Nevada and western Utah. Available literature indicates that normal faulting occurred there on a regional scale in the Late Mesozoic and Early and Middle Tertiary as well as in the Late Tertiary and Quaternary. There is no apparent spatial pattern in the age of initial normal faulting in Nevada and Utah; apparent areal differences in the intensity of fault development for a given time period may be real or a function of missing stratigraphic units needed to define properly the ages of faulting. Although Late Tertiary and Quaternary normal faults would probably be classified as basin-range faults by most workers, a question remains as to the nature of the Late Mesozoic and Early and Middle Tertiary normal faults. They could represent initial basin-range type extension, or they could represent a distinct episode of extension between the Sevier and "Basin-Range" orogenies.

INTRODUCTION

The Basin and Range Province has long attracted the attention of geologists, because of its unusual physiographic character with many generally north-trending ranges and alternating basins. Early theories on the origin of the ranges were summarized by Nolan (1943) and include suggested origins by erosion, regional compression, and regional extension. Regional extension is now the most widely accepted theory. Normal faults are the predominant Cenozoic structure of the province, but as will be discussed later, the actual definition of basin-range structure is by no means clear.

To understand the age relationships of extensional deformation in a part of the Basin and Range Province—the Great Basin, a summary of normal fault ages in Nevada and western Utah (figure 1) was compiled based on published information. The study was specifically aimed at extensional tectonism that has occurred in the Great Basin since the Late Mesozoic Sevier orogeny (Armstrong, 1974); at least part of that post-Sevier extension is considered classic basin-range faulting. This paper presents the results of that summary (Loring, 1972) updated as of mid-1974.

This study attempted to analyze the age of normal faulting that was associated with regional extension in the Great Basin. Consequently, limits were placed on the data used. Only those normal faults found within the physiographic Basin and Range Province or in immediately adjacent areas were considered. Normal faults obviously related to local structures such as intrusive domes were excluded. Faulting identified as basin-range faulting and block faulting was considered along with normal faulting; high-angle faults were also included if they had no obvious history of reverse or solely strike-slip movement.

AGE OF NORMAL FAULTING IN THE GREAT BASIN

This section describes selected examples of Mesozoic through Middle Tertiary normal faults as given in the literature. More emphasis is placed on Mesozoic through Middle Tertiary faulting than on later structures because I believe earlier faulting is most often overlooked. Late Tertiary and Quaternary faulting is illustrated but not fully described. Loring (1972) gives a more detailed description of Mesozoic through Quaternary normal faults. Where ages are given in millions of years, the 1964 time scale of the Geological Society of London (1964) has been used to assign them to Tertiary epochs. Paleocene and Eocene are considered Early Tertiary; Oligocene and Early Miocene, Middle Tertiary; Middle and Late Miocene and Pliocene, Late Tertiary; and Pleistocene and Recent, Quaternary.

This paper does not attempt to deal with the volcanic record of the Great Basin. Early literature references to stratigraphic age undoubtedly will be, or have been, changed on the basis of radiometric dating. Consequently ages based on the relationship between faults and undated volcanic rocks are considered tentative pending radiometric age determinations on the volcanic units.

Figures 2 through 5 show localities of Mesozoic-Early Tertiary, Middle Tertiary, Late Tertiary, and Quaternary normal faulting in Nevada and Utah. Numbers adjacent to Mesozoic, Early Tertiary, and Middle Tertiary fault descriptions in the text refer to fault localities on figures 2 or 3. The strike of faulting to the nearest 45 degrees is indicated on the figures.

Mesozoic-Early Tertiary

Normal faults dated as Mesozoic or Early Tertiary or both are found in Nevada and Utah (figure 2). In the northern Muddy Mountains of southern Nevada, Longwell (1949) mapped the generally north-striking Baseline normal fault that offsets the Late Cretaceous Willow Tank Formation but does not affect most of the Late Cretaceous or Early Cenozoic Overton Fanglomerate (1). Bowyer (1958) reported north-trending, tilted fault blocks, which he claimed to be Late Cretaceous or Early Tertiary in age, in the south Virgin Mountains of southern Nevada (2). These blocks were probably younger than Mesozoic strata and thrusts but were offset by strike-slip faults prior to deposition of Miocene(?) lake beds (Bowyer, 1958).

Southwest of Las Vegas in the Goodsprings quadrangle, some normal faults may be Late Mesozoic to Middle Tertiary in age (3). Some north- and northwest-striking normal faults displace thrusts but contain pre-Miocene mineralization; other normal faults are still younger but preceded Miocene igneous activity (Hewett, 1931). Since the thrusts are pre-Late Jurassic to Late Cretaceous

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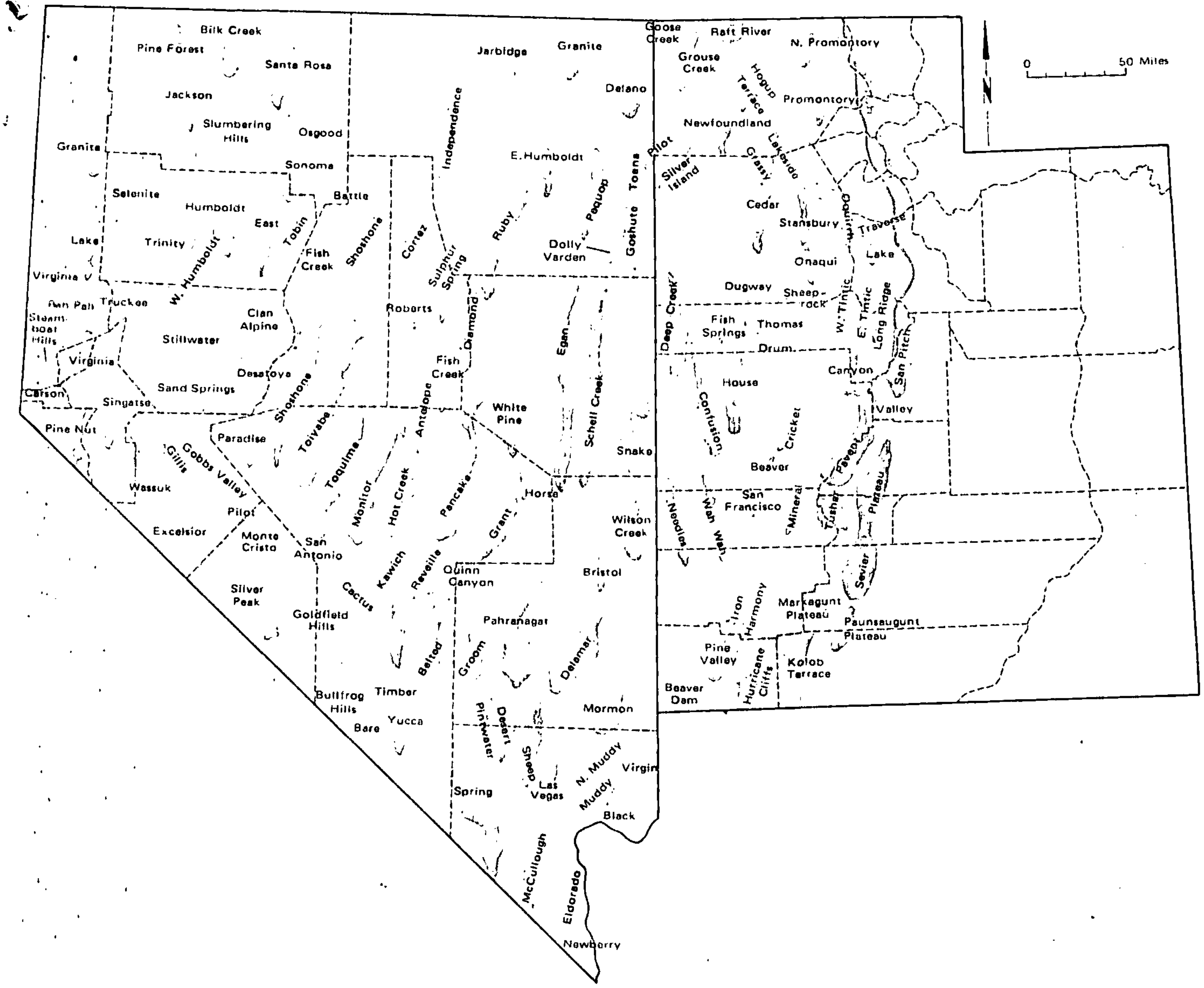

Figure 1. Index map to selected mountain ranges of Nevada and Utah.

in age (Burchfiel and Davis, 1971), the normal faults are between Late Mesozoic and Miocene in age. Late Mesozoic or Early Tertiary northwest-striking high-angle faults are reported from the Yucca Flat area in Nye County (Hinrichs, 1968) (4).

A few normal faults in Lincoln County in east-central Nevada cut the Cretaceous(?) volcanic rocks and Paleozoic rocks but not Middle Oligocene and younger volcanics (Tschanz and Pampeyan, 1970) (5). According to Threet (1960), Early to Middle Tertiary block faulting occurred throughout east-central Nevada (6). Threet noted that high-angle faults displace older folded and thrust-faulted surfaces and that many also break Early Cenozoic sediments and volcanics but that these early faults lack geomorphic expression.

Normal faulting in the Bristol Pass region between the Bristol and Fairview Ranges is mostly older than probable Late Eocene to Oligocene volcanism (Langenheim and others, 1971) (7). Some normal faulting, including a north-northwest-striking range-front fault, is younger than the volcanism (Langenheim and others, 1971). North-south faults and the range-front and related faults cut and are cut by a west-northwest, high-angle, transverse fault set, so all the faults appear to belong to the same structural event (Langenheim and others, 1971). Some of these faults truncate the Tertiary volcanic rocks, whereas others appear to be overlapped by the volcanics.

In the southern Egan and Schell Creek Ranges, normal faulting had started by the beginning of the Cenozoic (Kellogg, 1960) (8). In the southern Egan Range, several northeast-striking normal faults are Eocene in age as shown by paleogeologic reconstructions that are prior to deposition of the Eocene Sheep Pass Formation (Kellogg, 1964) (9). The east- to northeast-striking Shingle Pass normal fault had some Eocene movement, indicated by a wedge of Eocene conglomerate immediately north of the fault, and some Late Eocene or Early Oligocene uplift; movement continued into the Late Tertiary (Kellogg, 1964). Depression of the hanging wall of the largest low-angle normal fault in the southern Egan Range began in Eocene time (Kellogg, 1960). This and other low-angle normal faults in the area originally dipped 31 to 58 degrees but were later tilted to their present low angle by normal faulting and tilting in Late Tertiary time (Kellogg, 1960). Some of the north-striking normal faults in the

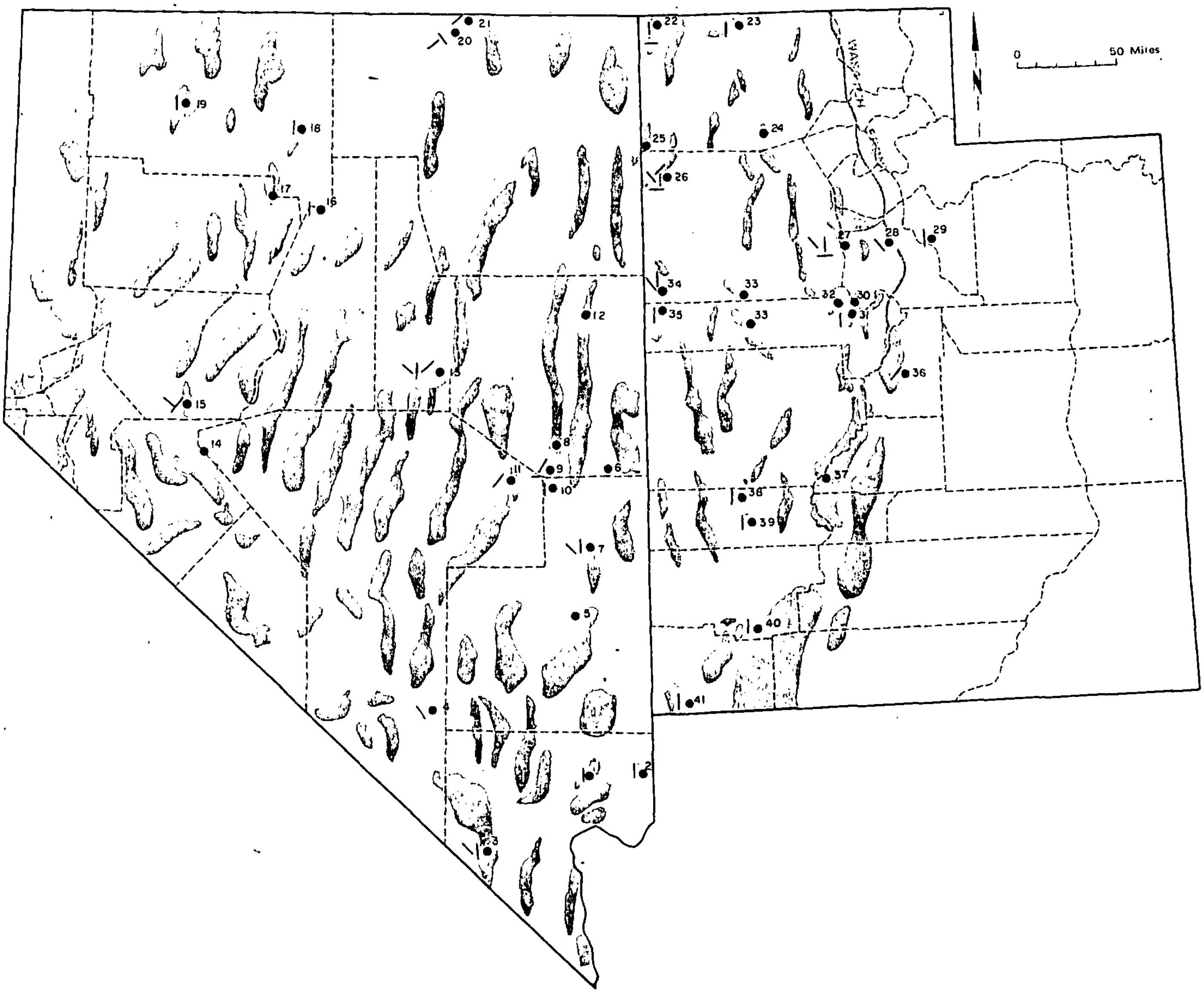

Figure 2. Localities of Late Mesozoic-Early Tertiary normal faulting in Nevada and Utah. Lines indicate the strike of faulting to the nearest 45 degrees. Numbers correspond to references in the text.

Egan Range probably began in the Early Tertiary, and some have been inactive since the deposition of the Oligocene(?) volcanics rocks, according to Playford (1962) (10).

Northeast-striking, high-angle faults in the White Pine, Grant, and Horse Ranges are probably Mesozoic to Eocene in age, according to Moores and others (1968, 1969), based on a paleogeologic map of the pre-Eocene and Oligocene depositional surface (11). Moores and others (1968) also reported that normal faulting of moderate displacement was initiated in Middle to Late Eocene time. They cited Kellogg's (1964) evidence for Eocene faulting in the Egan Range to support their hypothesis that normal faulting began at the same time in the White Pine, Grant, and Horse Range areas. Faulting continued during the Oligocene, but major movement on these normal faults was Miocene. In the northern Schell Creek Range, Dechert (1968) reported that some high-angle faults of unspecified trend are Mesozoic, although most are Tertiary (12).

In the Fish Creek Range, the north-striking Jackson normal fault cuts post-Permian, pre-Cretaceous thrusts but is overlain by the Cretaceous Newark Canyon Formation (Nolan, 1962) (13). This normal fault is therefore Mesozoic, probably Cretaceous. The northwest-striking Ruby normal fault is also probably younger than the thrusts (Nolan, 1962). Some of its motion preceded the deposition of the Cretaceous Newark Canyon Formation, and it helped to localize Eocene hornblende andesite intrusions (Nolan, 1962). Probable Early Tertiary north- to northeast-striking normal faults cut the Cretaceous Newark Canyon Formation and are cut, in turn, by Eocene andesites (Nolan, 1962).

In the Hawthorne and Tonopah quadrangles of western Nevada, Ferguson and Muller (1949) suggested that principal movement on normal faults took place during basin-range faulting, probably beginning in the Early Tertiary (14). Northeast- and northwest-striking high-angle faults in the Sand Springs Range of Churchill County supposedly formed shortly after intrusion of Cretaceous granite, because some faults offset the granite but not the associated dikes (Beal and others, 1964) (15). Other faults in the area have been active until recently.

In the Antler Peak quadrangle, Cretaceous orogenic movements caused block faulting and the formation of local basins in which Cretaceous continental sediments were deposited (Roberts, 1964) (16). Some north-striking normal faults are Eocene and Late Eocene or Early Oligocene in age (Roberts, 1964). The Eocene faults are dike filled, and since the Late Eocene or Early Oligocene intrusions follow the fault zones, the faulting may have begun in the Eocene. Late Eocene or Early Oligocene faults cut the intrusions.

Near Winnemucca, Nevada, block faulting may have begun in the Early Tertiary, because Early Tertiary sediments were deposited in intermontane basins perhaps formed by block faulting (Hawley and Wilson, 1965) (17). In the Getchell area of the Osgood Mountains, the north-striking, predominantly dip-slip Getchell fault system was active during both Cretaceous and Quaternary time (Berger and Taylor, 1974) (18). The fault system apparently controlled emplacement of dikes dated as 88-91 million years old; Quaternary alluvium is offset along a southern extension of the fault system (Berger and Taylor, 1974). In the Jackson Mountains, north-striking, high-angle, dip-slip faults involve only pre-Tertiary rocks as young as Early Cretaceous but not rocks of Cretaceous or Tertiary age; therefore, they are probably Cretaceous or Early Tertiary (Willden, 1963) (19).

A Late Mesozoic to Early Tertiary age is given to northeast- and northwest-striking high-angle faults in the Rowland quadrangle of northeastern Nevada (Bushnell, 1967) (20). The faults are possibly pre-intrusive (Late Cretaceous), based on the shape of one intrusion, and while some faults do not disturb the Late Cretaceous granite, others do but do not dislocate Miocene volcanic rocks. Farther north at the Nevada-Idaho border in the Jarbidge quadrangle, northeast-striking faults may be Late Eocene in age (Coats, 1964) (21). They cut Paleozoic rocks; but the restricted distribution of the Late Eocene Meadow Fork Formation, the large size of boulders in it, and its abrupt change in thickness suggest that the unit accumulated in a narrow trough with steep walls, possibly bounded by northeast-striking faults.

Eardley (1963) reported that some of the basin-range faults in western Utah began in the Eocene or Oligocene and continued to be active during the Pliocene and Early Pleistocene. In the Ashbrook district of northwestern Utah, north- and east-striking normal faults predated possible Late Eocene or Early Oligocene intrusions and ore deposits but closely followed the Laramide revolution, according to Peterson (1942) (22). North-striking normal faults in the Raft River Basin dated from the Early Tertiary, but most had formed in the Middle and Late Cenozoic to Recent (Nace and others, 1961) (23). The faults displaced structures as young as Late Cretaceous or Early Tertiary in age, and some were active at about that time (Nace and others, 1961). Paleocene normal faults in the Lakeside Mountains were related to uplift of the Northern Utah Highland, according to Doelling (1964) (24). Basin-range block faults occurred later in the Lakeside Mountains.

Possible Early Cenozoic high-angle faults are found in the Pilot Range of northern Utah where they cut known Mesozoic structures but have little or no topographic expression (O'Neill, 1969) (25). They produce up to 7,700 feet of stratigraphic separation. In the Silver Island Mountains that straddle the northern part of the Utah and Nevada border, block faulting began in the Early Tertiary and continued to the Late Tertiary (Schaeffer, 1960; 1962) (26). Northwest-, northeast-, north-, and east-striking internal normal faults in the Silver Island Mountains may have created basins in which early volcanic rocks, probable Early Tertiary sediments, and later rocks were deposited. Intrusion followed early block faulting. Schaeffer noted that there is a 45 to 90 degree difference between the strikes of major internal normal faults and the youngest phase of northeast-striking block faulting, which he identified as basin-range type. He concluded that the primeval topography of ranges and basins was analogous to today's topography and that so-called basin and range topography may have formed several times since the Early Tertiary.

South of the Great Salt Lake in the Oquirrh Mountains, west-, north-, and northwest-striking high-angle faults of large displacement may be Late Cretaceous to Middle Tertiary in age (Gilluly, 1932) (27). The faults are mineralized and crossed by a rhyolite dike and, therefore, were in existence before Late Eocene or Oligocene igneous activity. They are no older than the folding of Late Cretaceous age. Movement has continued to Recent time (Gilluly, 1932). Northwest-striking block faults date from the Early or Middle Tertiary (Gilluly, 1928). Gilluly reported that the faults are all later than folding in the range, which he dated as latest Cretaceous or earliest Tertiary. At least one of the faults appears to be mineralized, and Gilluly dated mineralization as pre-Miocene and possibly pre-Eocene Wasatch Formation. Movement on the faults was renewed later in the Tertiary.

On the west slope of Mount Timpanogos in the southern Wasatch Range are northwest-striking normal faults whose age cannot be determined accurately from local field evidence but which are probably Eocene to Recent, based on regional evidence (Olsen, 1955 [citing Eardley, 1951, and Hunt and others, 1953]) (28). Two large north-northwest-striking normal faults on the eastern side of the range are at least Eocene in age because they offset Late Cretaceous thrusts and the earliest volcanic rocks of the Tibble Formation, which are probably Eocene (Baker, 1964) (29). One branch of one of these faults does not displace younger Eocene volcanic rocks. Both large faults are terminated by the Wasatch fault zone and have little effect on the present topography in the Wasatch Range (Baker, 1964).

The East Tintic and Boulter Mountains area also has Eocene normal faults. Contours on the surface that existed prior to deposition of Eocene volcanic rocks in the East Tintic Mountains show it was similar to the present surface in general relief, but Eocene ore bodies are not cut by faults (Morris and Anderson, 1962) (30). North-striking normal faults of small displacement in the central East Tintic Mountains are Middle or early Late Eocene, since they are younger than the larger stocks but were the structural control for the late dikes and plugs (Morris, 1964a; 1964b) (31). Foster (1959) stated that basin-range block faulting in the East Tintic Mountains area took place from Late Eocene through Early Miocene (32).

To the west in the Thomas and Dugway Ranges, normal faults of unspecified trend may have formed during or very soon after Cretaceous or Early Tertiary thrusting (Staatz and Carr, 1964) (33). Nolan (1935), in his paper on the Gold Hill quadrangle which includes the Deep Creek Mountains of west-central Utah, gave evidence for several stages of north- to northwest-striking normal faulting associated with stages of thrusting of Cretaceous or Paleocene (Early Eocene in his paper) age (34). These thrusts and normal faults are older than an Eocene or Oligocene quartz monzonite that cuts them. They are also overlain uncônformably by the Eocene(?) White Sage Formation. The faults are younger than Triassic rocks, and since Nolan believed there was no known Early Mesozoic deformation in the area, he dated the faults as Cretaceous or Early Tertiary. More stages of north- to northwest-striking normal faults that began in the Cretaceous or Early Eocene continued into the Eocene (Nolan, 1935). These faults cut the Eocene(?) White Sage Formation but are older than fourth cycle faults that are cut off by the Late Eocene or Early Oligocene intrusion. However, the normal faults of this stage are rather rare and of small throw. Bick (1966) also found evidence for Late Mesozoic to Late Eocene faulting in the Deep Creek Range (35). The north-striking Reilly Canyon normal fault had motion before and after formation of the North Pass thrust, but this normal fault is older than the Late Eocene to Middle Miocene(?) Ibapah stock.

To the southeast in the Sevier Valley, there was Early or Middle Eocene and Middle or Late Eocene normal faulting (Spieker, 1949) (36). Eocene normal faulting of unspecified trend apparently occurred on the west side of the Gunnison Plateau (Spieker, 1949). The Paleocene Flagstaff Formation is faulted against the Eocene Green River Formation. Since these two formations lie on opposite sides of the fault and both lie on the Jurassic Arapien Shale (Zeller, personal communication [cited in Spieker, 1949]), faulting must have occurred between the deposition of the Flagstaff and the Green River Formations. On the east side of the Gunnison Plateau, a N. 35° E. vertical fault had offsets in Eocene time. Initial faulting offset the Middle Eocene(?) Green River Formation but not the Late Eocene(?) Crazy Hollow Formation. Minor normal faulting in the Late Eocene and Early Oligocene in the nearby southern Pavant Range was reported by Crosby (1959); major normal faulting occurred during the Miocene (37).

Early to Middle Tertiary block faulting along a north-striking fault on the east flank of the San Francisco Mountains occurred prior to the intrusion of a Tertiary quartz monzonite stock, since the stock obliterated part of the fault (East, 1966) (38). The fault is overlapped at its ends by Early Tertiary conglomerate and mid-Tertiary volcanic rocks. In the Star Range of Beaver County, north-striking normal faulting began in Late Cretaceous or Early Tertiary time (Baer, 1962) but had later movement that elevated the range (39). Normal faults cut thrusts but were used by Tertiary intrusions for entry.

According to Averitt (1962), movement on the Hurricane normal fault zone has occurred intermittently since Early Tertiary time (40). The Eocene Wasatch Formation and overlying Eocene to Miocene(?) volcanic rocks show the greatest displacement across the fault. Lovejoy (1974) reported that faulting along the Grand Wash and related faults probably began during Laramide time (41). On stratigraphic evidence he dated the uplift of the nearby Beaver Dam Mountains as Laramide; on structural evidence he determined that the Cedar Pocket Canyon and Gunlock faults are essentially contemporaneous and that these faults are the same age as the uplift of the Beaver Dam Mountains. Since the Cedar Pocket Canyon and Gunlock faults are northern continuations of the Grand Wash fault, Lovejoy concluded that the Grand Wash fault also dates from the Laramide.

Middle Tertiary

Nolan (1943) reported in his paper on the Basin and Range Province in Utah, Nevada, and California that block faulting began in the Early Oligocene and continued to the present. He based this conclusion on the work of Stock and Bode (1935) in the Death Valley region. Many other authors have used an Oligocene age for the beginning of basin-range faulting, based only on Nolan's conclusion. Figure 3 shows the distribution of Middle Tertiary normal faulting.

The localities on which Stock and Bode (1935) based their Early Oligocene date for the age of basin-range topography are in the Amargosa Range (1). The basal limestone breccia of the Early Oligocene Titus Canyon Formation contains material that has been derived from Paleozoic rocks in the immediate vicinity, probably to the west, based on the northeast dip of cross-bedding. This suggested to Stock and Bode that the unit accumulated on the flanks of a mountain range that was in a position similar to the present Grapevine and Funeral Mountains and that this indicated an Early Oligocene age for the present basin-range topography. Reynolds (1974) apparently disagreed with the interpretation of Stock and Bode because he stated that uplift of the Grapevine Mountains block occurred between 20 and 16 million years ago (Early and Middle Miocene). Between 16 and 13 million years ago (Middle Miocene), there was northeast-striking normal faulting in northeastern Death Valley; between 11 and 7 million years ago (Late Miocene) there was north-striking faulting; and from 7 million years ago to the present there has been north-northwest normal or right-lateral faulting, according to Reynolds (1974).

Local structural basins had been formed in Nevada by Oligocene time (Van Houten, 1956 [citing Axelrod, 1950]). According to Van Houten, Oligocene mud, sand, and gravel were deposited in local basins that had been outlined by faulting by the Oligocene in southwestern Nevada and adjacent states.

Albers (1967) reported that basin-range dip-slip faults in southwestern Nevada between Reno and Las Vegas are Middle and Late Tertiary in age and trend predominantly north-south (2). In the Lathrop Wells quadrangle of southwestern Nevada, north-striking steep faults range from Oligocene to Recent in age (Burchfiel, 1966); the evidence for an Oligocene age is citation of Stock and Bode's conclusions (1935) (3).

In the northern Nevada Test Site, there were two periods of normal faulting in the Middle and Late Tertiary (Ekren and others, 1968, 1971) (4). The earlier normal faults had predominantly northeast and northwest strikes and formed during the Early and early Middle Miocene (26.5-17 million years ago). These faults occur in both pre-Tertiary and Tertiary rocks; so they probably began to form after the oldest Tertiary rocks (25 million years old) were deposited. Lavas erupted from vents localized by these faults 18 million years ago and were then cut by faults of the same trend. These northeast- and northwest-striking faults were truncated by Middle and Late Miocene (17-7 million years), north-striking normal faults. Late Miocene rhyolites were intruded along some of the north-trending fractures. Carr (1974) also reported that basin-range faulting in the Nevada Test Site was well established prior to initiation of major volcanism about 15 million years ago (Middle Miocene). He said many of these faults were repeatedly reactivated from 15 to 6 million years ago.

At Goldfield, northeast-striking, east-dipping shingle faults formed about

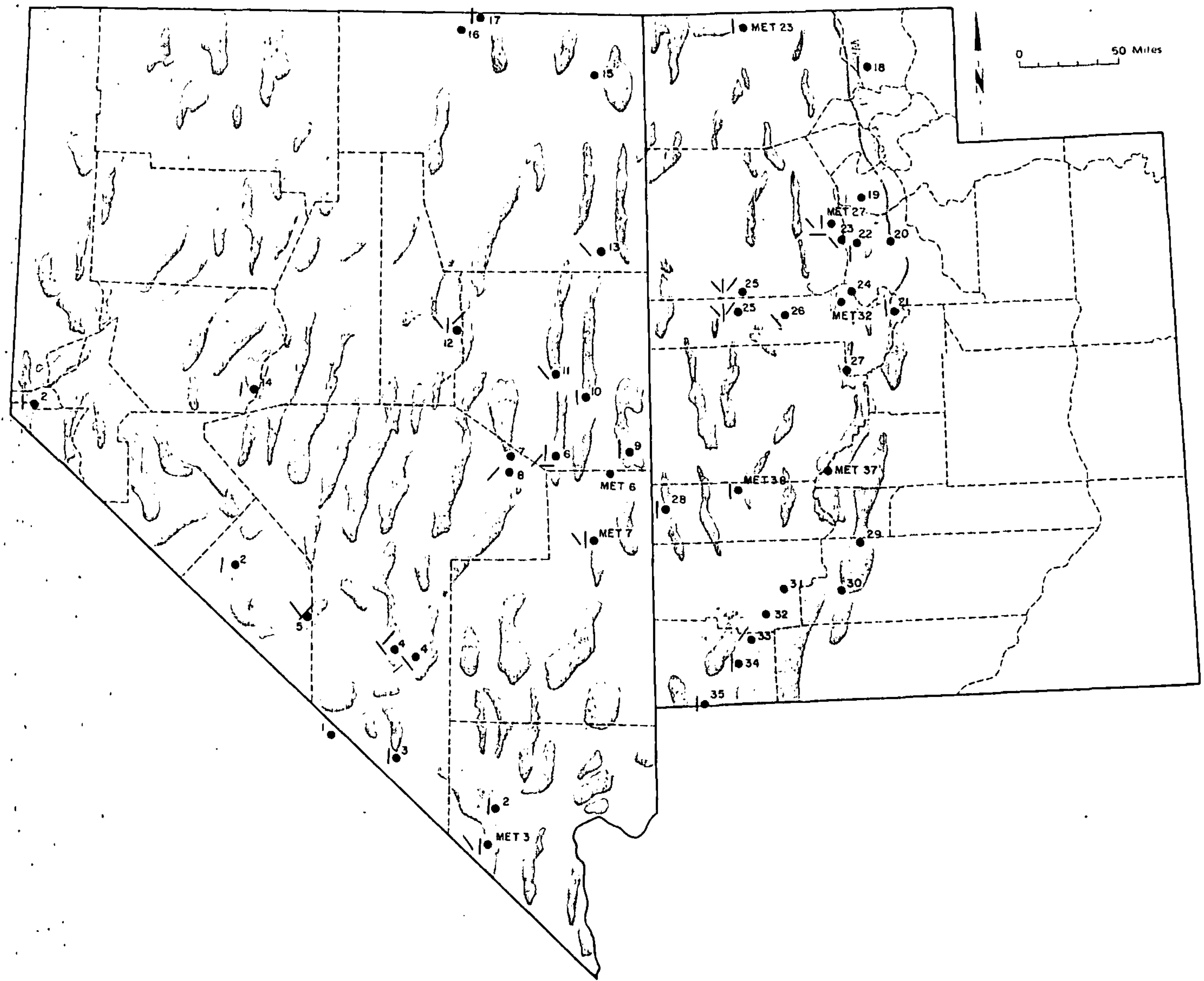

Figure 3. Localities of Middle Tertiary normal faulting in Nevada and Utah. Lines indicate the strike of faulting to the nearest 45 degrees. Numbers correspond to references in the text; letter-number combinations refer to localities on figure 2.

21 million years ago (Early Miocene) near the end of pre-mineral volcanism (Ashley, 1972) (5). Northwest-striking shingle faults formed about 21-20 million years ago, cutting a rhyodacite ash-flow tuff but preceding hydrothermal alteration and ore deposition (21-20 million years ago) (Ashley, 1972). Basin-range faulting began 2 to 4 million years after ore deposition (Middle Miocene) (Ashley, 1972).

In the southern Egan and Schell Creek Ranges, normal faulting dates from the beginning of the Cenozoic, but normal faults were more numerous and of larger displacement in the Oligocene and Miocene (Kellogg, 1960, 1962) (6). Early Oligocene north- and west-striking normal faults in the southern Egan Range originally had dips of 31 to 58 degrees. Late Tertiary and Quaternary tilting of the range also tilted the Oligocene normal faults so that they are now low-angle normal faults (Kellogg, 1960, 1962). These normal faults probably all formed during the initial uplift of the range in latest Eocene or earliest Oligocene time, according to Kellogg (1960). Lumsden (1964) stated that the Horse Camp basin in the White Pine and northern Horse Range area began to form in Oligocene to Miocene time (7). The basin postdates Oligocene volcanism, but it contains 10,000 feet of Mio-Pliocene(?) clastics, limestone, and breccia.

In the White Pine, Grant, and Horse Ranges, normal faulting that began in the Eocene and continued through the Oligocene was particularly active in the Early to Middle Miocene (Moores and others, 1968) (8). To the east in the southern Snake Range, normal faulting occurred in several episodes from the Middle Tertiary to the Quaternary (Drewes, 1958) (9). Drewes based the Middle and Late Tertiary age on the regional picture and noted that normal faults cut Late Tertiary(?) clastics.

In the north-central Schell Creek Range, normal faulting followed deposition of Early Tertiary sedimentary and volcanic rocks but preceded deposition of Late Tertiary sediments; it lasted through the Quaternary (Young, 1960) (10). The N. 20° E. Kalamazoo normal fault predates at least part of the North Creek Formation (Late Tertiary), which overlies it locally, but cuts thrusts and postdates the Eocene(?)-Oligocene(?) volcanic rocks. At the Ward mining district in the central Egan Range, north-northwest, high-angle normal faults along the present range fronts began to form in the Early Oligocene (Heidrick, 1974) (11). Deformation continued into the Miocene as evidenced by faulted intrusive vents, inclined Oligocene ignimbrites, and tilting of the range (Heidrick, 1974).

In the Diamond Mountains of Eureka County, Brew (1971) stated that north-, northeast-, and northwest-striking high-angle normal faults within the range are Middle Tertiary or earlier (12). In the Dolly Varden Mountains of southeastern Elko County, northwest-striking normal faults developed during the course of Oliogcene volcanism (Snow, 1964) (13). Post-Oligocene basin-range faults are the youngest structures. In the southern Desatoya Mountains, faulting occurred throughout the Middle and Late Tertiary (Barrows, 1972) (14). A north-trending elongate trough formed near the end of the Early Miocene owing to faulting and possible downwarping; Middle Miocene lake sediments filled the basin (Barrows, 1972).

In the Delno district of northeastern Elko County, Olsen (1961) stated that major movement on normal faults immediately followed the Laramide orogeny, coming before Late Miocene and continuing into the Recent (15). Bushnell (1956) concluded that basin-range block faulting in the Rowland quadrangle of northern Elko County is mid-Tertiary in age (16). In the Jarbidge quadrangle of northern Nevada and southern Idaho, a N. 17° E. Oligocene or Miocene normal fault does not displace the Late Miocene Jarbidge Rhyolite, but the hanging wall contains Late Eocene rocks (Coats, 1964) (17).

In the Cache Valley of northern Utah, north-striking, high-angle normal faults that bound the present valley are Middle Tertiary to Quaternary in age (Williams, 1962) (18). Major faults displace rocks as young as the Early Tertiary Wasatch Formation and locally the Oligocene-Pliocene Salt Lake Group. There is no displacement of the Pleistocene Lake Bonneville Group. Unconformities within the Salt Lake Group indicate that there was faulting and tilting during its deposition (Williams, 1962). Marine and Price (1964) thought the Jordan Valley graben has probably been filling since the Middle Tertiary (19).

Along the Wasatch front northeast of Provo, Rigby and Hintze (1968) dated the Wasatch fault zone as Oligocene (30 million years ago) to Recent (20); Hintze (1962) also dated basin-range normal faulting in the southern Wasatch Range as Oligocene to Recent (21). North-striking normal faulting occurred during and after the Oligocene in the northern Cedar Valley of northern Utah (Larsen, 1960 [citing Stokes and Heylmun, 1958]) (22). In the Stockton and Fairfield quadrangles, there are Middle and Late Tertiary northwest-striking normal faults, according to Rigby (1959) (23). Accumulation of valley-fill deposits in the East Tintic Mountains area suggests there was intermittent normal faulting near the margins of the range in Early and Middle Miocene time (Morris, 1957) (24).

In the Thomas and Dugway Ranges, some north-, northeast-, and northwest-striking normal faults cut Mesozoic or Early Tertiary thrusts but predate the "older volcanic group" (Staatz and Carr, 1964) (25). One lead-alpha determination on the older volcanic group yielded a 20 million year age (Jaffe and others, 1959). North- and northwest-striking, basin-range normal faults tilted at least some of the older volcanic group but have only locally affected the "younger volcanic group" (Staatz and Carr, 1964). Rocks of the younger volcanic group have been dated at 16.2 million years (Park, 1970) and 6.0 million years (Armstrong, 1970). According to Staatz and Carr (1964), some elevation and tilting of the ranges probably occurred between Eocene and Middle Miocene time as did development of lines of weakness that controlled later basin-range faulting. Shawe (1972) stated that the present mountain ranges in the Thomas, Keg, and Desert Mountains areas formed by block faulting in Middle to Late Tertiary time; some of the basin-range faults strike north-northwest (26).

Basin-range uplift and tilting of Oligocene(?) age is demonstrated in the Canyon Mountains area by Oligocene(?) valley-fill deposits (Campbell, 1974) (27). Northward tilting is indicated by the deposits that remain only on the south side of a major valley. Episodic uplift through Late Tertiary time is documented by the remnants of at least five pediments (Campbell, 1974).

In the Needles Range of southwestern Utah, Conrad (1969) found evidence for Oligocene north-striking faults (28). Bedding and size gradation of boulders in the Oligocene Beers Spring Formation suggest a source to the west, probably created by local differential uplift and depression along north-striking faults.

Based on the mapping of the Late Oligocene Isom Formation on the southern Sevier Plateau, minor block faulting seems to have begun by Late Oligocene time (Rowley, 1968) (29). Faulting that produced the High Plateaus of Utah took place after Late Cretaceous or Early Eocene folding, probably in the Middle Tertiary but possibly earlier (Hunt, 1946) (30). In the Red Hills area, block faulting may have begun in the Oligocene (Threet, 1963), since part of the Paleogene upper Quichapa Formation is widespread to the west but poorly developed to the east of the Colorado Plateau margin (31).

Post-Eocene, pre-Miocene(?) normal faulting on the west side of the Colorado Plateau near Hurricane Cliffs is indicated by faults that cut the Eocene Wasatch Formation but not Miocene(?) lava (Hunt, 1956) (32). Kurie (1966) found evidence for a post-Eocene but pre-Late Cenozoic Hurricane fault (33). It cuts the Wasatch Formation, and its presence is indicated by the paleogeology at the base of the Late Cenozoic lavas. Gardner (1941, 1952) concluded that the least important disturbance on the Hurricane fault of southwestern Utah and northern Arizona was post-Eocene and pre-Miocene; it formed a pattern for later faults (34). The fault cuts the Eocene Wasatch Formation, but the scarp was leveled by erosion before being covered by Miocene(?) lavas.

To the south in the western Grand Canyon, movement on the north-striking Grand Wash fault began in Early Miocene time (Hamblin, 1970) and lasted until after 6 million years ago (35). The Late Miocene Muddy Creek Formation is not displaced across the southern trace of the fault.

Late Tertiary and Quaternary

Figures 4 and 5 show the distribution of Late Tertiary and Quaternary normal faulting in Nevada and Utah. Unnumbered data points are taken from Loring (1972). Numbered fault localities have been discussed in the preceding paragraphs.

DISCUSSION OF THE AGE OF NORMAL FAULTING IN THE GREAT BASIN

The original distribution of sediments and the effect of erosion play

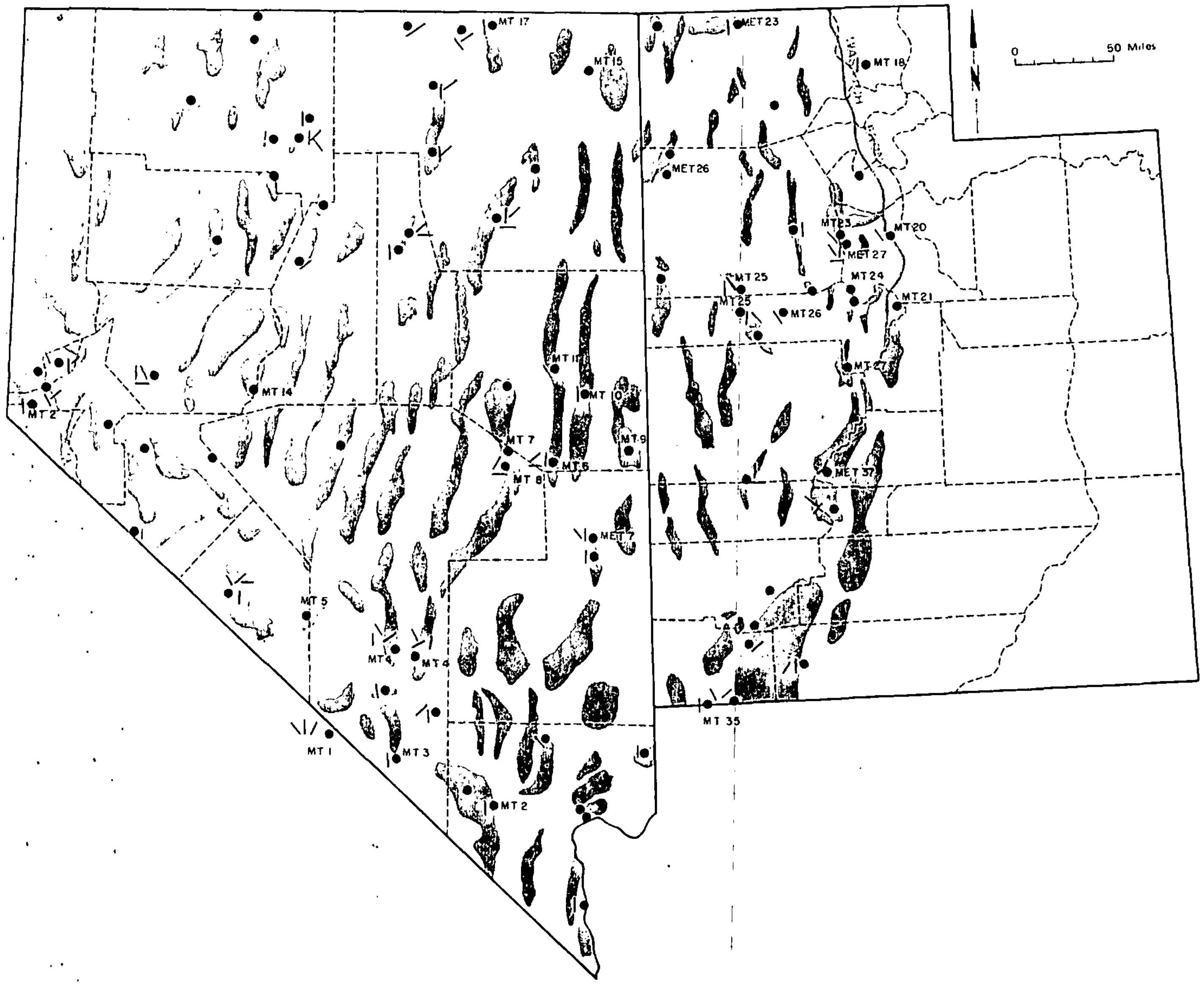

Figure 4. Localities of Late Tertiary normal faulting in Nevada and Utah. Lines indicate the strike of faulting to the nearest 45 degrees. Letter-number combinations refer to localities on previous figures; unnumbered localities are taken from Loring (1972). Numbers preceded by MET are for localities from figure 2; those preceded by MT are from figure 3.

an important limiting role in the determination of ages of normal faulting. Because roughly half of Nevada and western Utah is composed of basins filled with Late Tertiary or Quaternary sediments, the chances of finding stratigraphic evidence for pre-Late Tertiary fault motion in the region are greatly reduced. Furthermore, since not every range has a complete Mesozoic and Tertiary section, the chances of proving older faulting are even less. The problem of the presence or absence of pertinent stratigraphic evidence for dating the initiation of faulting must be kept in mind when comparing figures 2 through 5; that there are more localities for Late Tertiary and Quaternary normal faulting does not necessarily mean normal faulting was less extensive in Late Mesozoic-Early Tertiary and Middle Tertiary times.

The limitations of the original extent and preservation of rock units are particularly important in evaluating whether there was a shift with time in the distribution of normal faulting. For instance, in southwestern Nevada, most localities have faulting dated as Late Tertiary or Quaternary with only a few older examples. But in the Spring Mountains, for example, there are no rocks of Cretaceous through Oligocene age (Albritton and others, 1954). In the Lathrop Wells quadrangle, there are none from Mississippian through Oligocene age (Burchfiel, 1966). In the Hawthorne and Tonopah quadrangles, there are none between Jurassic and Miocene (Ferguson and Muller, 1949). Similar stratigraphic limitations occur in northern and west-central Nevada, suggesting that apparent shifts of normal faulting with time in Nevada and Utah may not be due to tectonic processes but may be the result of the limited occurrences of Early Tertiary stratigraphic criteria.

A comparison of figures 2 through 5 indicates no significant shift with time in the distribution of normal faulting. In general, it seems that the faulting has occurred in the same areas of the Great Basin during Late Mesozoic-Early Tertiary and Middle Tertiary times and that there has been no migration in the faulting between the Early and Middle

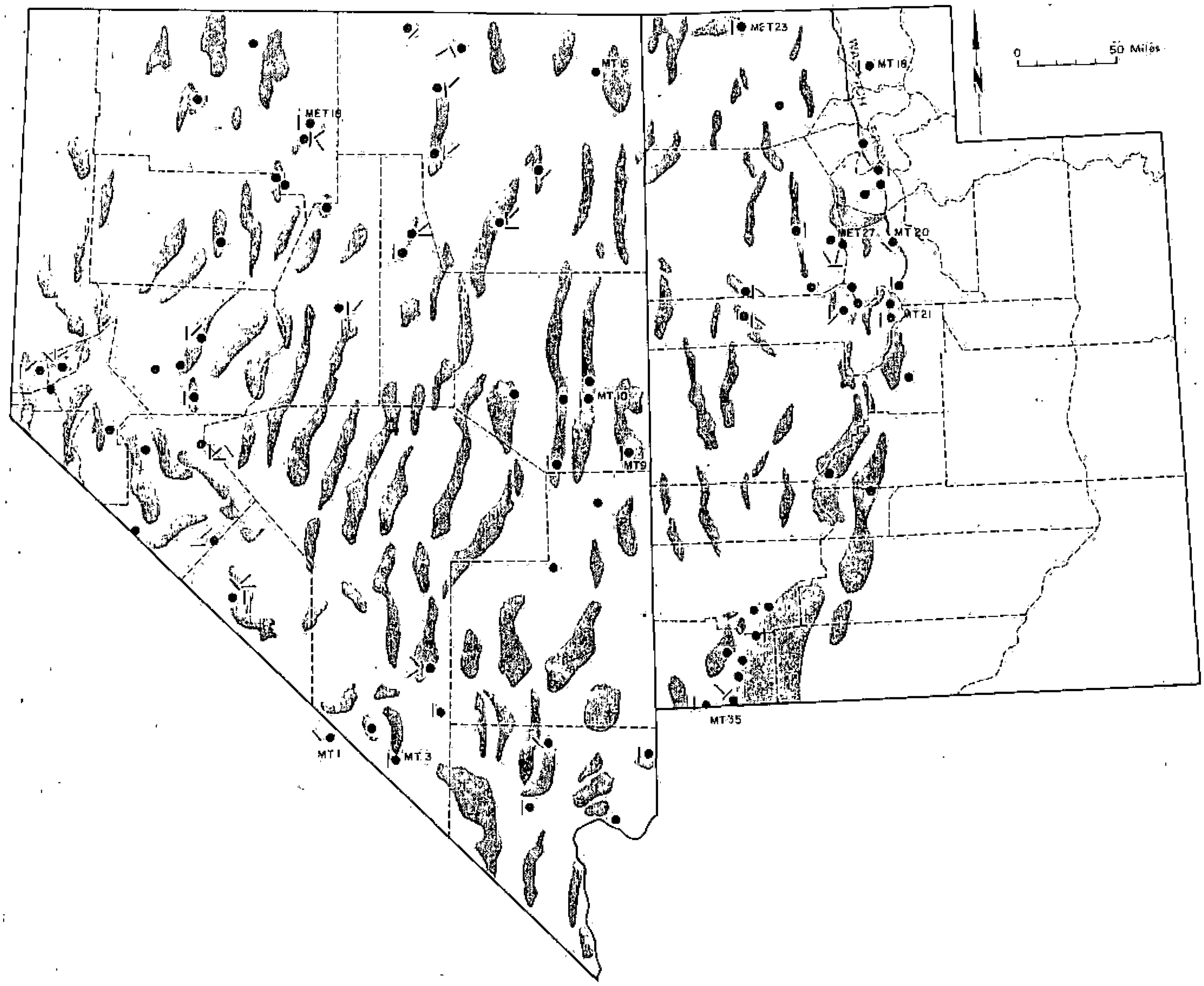

Figure 5. Localities of Quaternary normal faulting in Nevada and Utah. Lines indicate the strike of faulting to the nearest 45 degrees. Letter-number combinations refer to localities on previous figures; unnumbered localities are taken from Loring (1972). Numbers preceded by MET are for localities from figure 2; those preceded by MT are from figure 3.

Tertiary. Late Tertiary fault localities outnumber older fault localities, particularly in Nevada. Late Tertiary faults also are found in areas in west-central, southwestern, and northern Nevada that have only sparse reports of Early and Middle Tertiary faulting. However, it would be difficult to say that there was an actual shift in faulting westward with time, because Late Mesozoic-Early Tertiary fault localities, although few, are reported from the same general areas as Late Tertiary faults. As has been pointed out, the preponderance of Late Tertiary fault localities may be due to the lack of Early Tertiary rocks in much of the Great Basin. In general, Quaternary fault localities fall in areas where there was Late Tertiary faulting, and the converse is also generally true. Quaternary faulting has been reported in almost all areas of the Great Basin with the exception of central Nevada. Thus, there does not appear to be any consistent pattern in the initation of normal faulting within Nevada and Utah.

The apparent absence of faulting of Quaternary and other ages in central Nevada is not real and is most likely due to a scarcity of published reports about the area, at least those reports which give fault ages. A large part of the area which lacks fault ages lies within the Nevada Test Site; this may explain why few papers deal with it. As Stewart's (1971) paper showed, however, normal faulting is widespread in central Nevada.

RELATIONSHIP OF NORMAL AND BASIN-RANGE FAULTING

It is apparent from the data just presented that normal faulting has occurred in the Great Basin since the close of the Cretaceous. The major questions are how much of this normal faulting represents basin-range faulting and when did basin-range faulting begin.

Fenneman (1931) described the Basin and Range Province as a physiographic province, topographically distinguished by isolated, roughly parallel, mountain ranges separated by desert basins. Although Nevada, western Utah, southern Oregon, southwestern Arizona, and parts of California, Texas, New Mexico, and Mexico are included in the province, there is minor disagreement as to its exact borders, particularly in Mexico.

In spite of the fact that the basins and ranges are now known to be structurally controlled, the actual definition of basin-range structure is not clear. Gilbert (1928) defined basin-range structure as being the fault block structure of the present ranges in the Great Basin, noting that the boundaries of the tectonic Basin and Range Province are distinct from those of the Great Basin drainage district. Using this restricted definition, however, the age of basin-range structure is immediately limited by rates of erosion, for once the range is eroded, the faults can no longer be called basin-range faults.

Mackin (1960) questioned whether the term basin-range structure should be restricted to Gilbert's definition of block faulting that produced existing ranges or be broadened to apply to Cenozoic block faulting without regard for the relationships of the faulting to present topographic form. As Mackin noted (1960, p. 106-107): ". . . if commonly held rates of erosion are accepted as true, 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."

Using either Gilbert's or Mackin's definition of basin-range faulting, one would conclude that the Late Tertiary and Quaternary normal faults indicated on figures 4 and 5 are most likely basin-range faults. There would probably be little disagreement among geologists familiar with Great Basin tectonics that basin-range faulting is at least Late Tertiary in age. But as Mackin pointed out, erosion eliminates the obvious criteria for identifying older basin-range faults—the mountains and basins themselves. In the absence of Early or Middle Tertiary mountains or even basin-type fill, it may be difficult to describe normal faults of that age as basin-range faults.

There seem to be two alternative explanations for the Late Mesozoic and Early and Middle Tertiary normal faulting described in the literature and summarized in this paper. One is that the early normal faulting represents the initiation of regional extension in the Great Basin whose culmination was the Late Tertiary-Quaternary structural-geomorphic Basin and Range Province. These Early and Middle Tertiary "basin-range faults" may not fit Gilbert's definition because they are not now accompanied by mountains. Perhaps they were never range-front faults. But they may have been the first extensional features formed in the tectonic episode that eventually formed the present basins and ranges. This explanation would then conclude that the extensional deformation that created the Basin and Range Province in the Great Basin began at the end of the Cretaceous or early in the Cenozoic.

The alternative explanation for the pre-Late Tertiary normal faults described in this paper is that they are not basin-range faults and that they are unrelated to extensional basin-range tectonism. This faulting would then represent a period of extension that followed the regional compression of the Sevier orogeny and that preceded the regional extension of the Late Tertiary "Basin and Range" orogeny. Perhaps this early faulting was a secondary effect of volcanism within the Great Basin, or some prolonged after-effect of the Sevier orogeny.

CONCLUSIONS

The evidence presented in this paper suggests that regional normal faulting in Nevada and Utah occurred during the latest Mesozoic and Early and Middle Tertiary as well as during the Late Tertiary and Quaternary. There was no apparent spatial migration of normal faulting through the Tertiary.

Although Late Tertiary and Quaternary normal faults appear to be more numerous than older ones, it is difficult to evaluate whether this is true. The fact that the younger faults outnumber older ones could be a function of the extensive Late Tertiary and Quaternary volcanic and sedimentary cover of the Great Basin, which provides criteria for dating young faults but masks older faults and rocks.

The Late Tertiary and Quaternary normal faults described in this paper would probably be considered basin-range faults by most workers. But the problem of whether the Late Mesozoic to Middle Tertiary normal faults are also related to basin-range tectonism remains unanswered.

If the extension that created the Late Tertiary-Quaternary Basin and Range Province did begin in the Early Cenozoic or even the Late Cretaceous, then there would have to be modifications of a number of proposed origins of the province based on plate tectonics. Atwater (1970) suggested that the Basin and Range Province is part of a transform boundary between the North American and Pacific plates related to the San Andreas transform, which she dated as apparently no older than Middle Tertiary. She dated basin-range deformation as ranging between 20 and 5 million years old. Christiansen and Lipman (1972) agreed with Atwater's (1970) theory on the origin of the Basin and Range Province. McKee (1971) related basin-range faulting in the Great Basin to the subduction of the East Pacific Rise off western North America and the resulting extension of the overlying crust, dating both the faulting and subduction of the rise as Middle Miocene. Scholz and others (1971) concluded that the Great Basin is an ensialic interarc basin and that crustal extension is due to a spreading mantle diapir beneath the crust. They dated the beginning of basin-range faulting at about 25 million years ago. A Middle to Late Tertiary age for the initiation of the San Andreas transform boundary, for the initiation of extension due to a subducted East Pacific Rise, or for the spreading of a mantle diapir in an interarc basin leaves these models unable to account for Early Tertiary or Late Mesozoic extension in the Great Basin. Perhaps extension in the Great Basin began in the Early Tertiary or Late Mesozoic as back-arc spreading behind a subduction zone off western North America, similar to what Karig (1970, 1971a, 1971b) has described behind active trenches in the western Pacific Ocean.

If the Late Mesozoic to Middle Tertiary normal faulting described in this paper does not represent the beginning of basin-range tectonism, then a new model must be developed to account for it. This Early Cenozoic extensional episode would fall between the compression of the Great Basin in the Sevier orogeny and the extension of the same area in the Late Tertiary and younger "Basin and Range" orogeny. This early extension could be related to volcanism in the Great Basin or to some after-effect of the Sevier orogeny. Its relationship to plate activity in western North America may very well depend on when the subduction of the Farallon plate (Atwater, 1970) ceased, a question still not satisfactorily resolved.

ACKNOWLEDGMENTS

Gregory A. Davis and Richard B. Loring critically reviewed the original draft of this manuscript. Continental Oil Company provided drafting assistance.

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