BOSTON COLLEGE
GRADUATE SCHOOL

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entitled GEOTHERMAL ENERGY IN NEW ENGLAND

submitted to the Department of GEOLOGY-GEOPHYSICS

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in the Graduate School of

Boston College has been read and approved by the Committee:

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APRIL 21, 1975
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GEOTHERMAL ENERGY IN NEW ENGLAND

A THESIS

Submitted by

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BOSTON COLLEGE
May, 1975

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ABSTRACT

This study of sites in New England for geothermal potential deals with the locations of natural thermal resources in the New England and New York region and explains them in terms of localized geology and estimates risks and costs for the actual reclamation of natural thermal energy. There are discussions regarding heat flow, geothermal gradients, methods of exploration and reclamation of geothermal power as well as shallow temperature measurements.

At present there is almost no practical usage of geothermal energy in the New England area simply because geothermal areas are not as pronounced in the northeastern section of the United States as they are in those other areas of the country which are active or semi-active volcanic regions having recognized geothermal potential. Such areas are noted for their extremely high heat flow, which is manifested by the presence of volcanoes, geysers, fumaroles, steam vents and thermal springs.

In general, the heating of the crust of the earth to abnormally high values depends upon volcanism, radioactivity and ground water circulation. Although there has been no active volcanism in New England since Mesozoic to Early Cenozoic time, the area does possess a number of sites where heat flow is higher than normal. In the Conway Granite of New Hampshire there are at present three known sites where radioactivity has produced near-surface heat anomalies. In Roy and Decker's (1965) list of the twenty-two measured heat flow sites in the New England area, the highest values were in areas of most recent volcanism and the lowest values were in areas of least recent volcanism.

Thermal springs having a slightly higher than average temperature are a

potential, although limited, source of natural heat extraction. Their heat may be caused either by contact of the waters with magma or by the recirculation of the waters from great depths where the rock is much warmer than at the surface. In the latter case, investigation of ground water in the immediate vicinity of deep-seated faults has suggested that if the fault is deep enough to permit ground water to percolate through heated rock, closed water circulatory systems may permit thermal energy to be piped to the surface. In the New England area there are at least two well-known thermal springs. These could possibly serve as additional regional sources of energy.

Studies by some geophysicists have shown that it is possible to delineate such phenomena as shallow salt domes and surface faults by measuring temperature at a depth of approximately three meters. This method of shallow heat flow study is discussed in relation to New England's major fault zones with the possibility of finding naturally heated ground water. Specific data from such a study over the Clinton-Newbury Fault are included and analyzed.

Although the surface manifestation of New England's thermal springs, raioactive rocks and deep-seated fault zones may, in most cases, exhibit temperatures only several degrees higher than the average, the importance of this study lies in the recognition and understanding of the reasons for these anomalies, so that these thermal resources may be utilized to their best advantages.

INTRODUCTION

SHORT ENERGY HISTORY

Fossil fuels have long been the mainstay of world economy, having helped to give rise to the Industrial Revolution which began in England between 1760 and 1780, where it was accompanied by an agrarian revolution. Credit for the revolution actually goes to the rising population which needed to update the processes which fed it. Cantor (1970) credits one historian with claiming the Industrial Revolution to be probably the most important event in world history. Toynbee (1920) accounts substitution of the factory for the domestic system as the consequence of the mechanical discoveries of the time. The years between 1760 and 1830 produced, at any rate, the largest impetus to the depletion of the natural resources of fossil fuels up to that time. Monumental fuel deficits were incurred by wars, especially the First and Second World Wars as well as the Korean, Vietnam and the Arab-Israeli wars. In the case of the Second World War, Germany possessed unusually large reserves of coal which supported important metallurgical, engineering, chemical and electrical industries.(Blum, 1970). One could logically place much of the blame for the Second World War directly on the easy availability of Germany's coal supply. Obviously, the depletion of natural fossil fuels has feasted on cooperation as well as on disagreements among nations..

It has been said that from the standpoint of human history, the epoch of the fossil fuels will be quite brief. One can hardly disagree when realizing that the world's consumption of energy for industrial purposes alone is doubling approximately once per decade (Hubbert, 1971).

Today, the spiraling population density of the globe depends upon industry to be clothed and fed, and world industry depends, in turn, upon dwindling fossil fuel reserves. One must realize that in the depletion of precious hydrocarbon stores, the people of the world face not only an energy but a food shortage as well, since one depends upon the other. Countries hard-hit by famine today are the victims of food shortage certainly, but the direct cause is insufficient energy resources. As the agrarian revolution in England proved in the Eighteenth Century and as is painfully evident in the have-not nations now, it is necessary to update the processes which feed the people of the world. With this type of an updating comes newer techniques of mass-produced farming, and with these techniques comes a greater need for the energy necessary to power these processes.

The United States, with its overabundance of foodstuffs, leads the world in two important areas concerned with energy economics. America has the highest national per capita income of the world as well as having the highest per capita consumption of energy. In fact, while we have only 6 percent of the world's population, we consume some 33 percent of the world's total energy production (U.N., 1971).

It is evident that the United States has supported its population increase, its economic growth and its high standard of living by means of an expanding usage of low cost energy derived from a bountiful endowment of domestic fossil fuel resources.

It is predicted that United States energy consumption is to grow at an average rate of 4.2% per year in the 1971-1985 time period and, in 1985, domestic supplies will satisfy only about 70% of the country's consumption. In 1970, domestic supplies satisfied about 88% (Kruger et al., 1973).

NEW ENGLAND'S FUEL CRISIS

The New England region of the United States has its own type of energy problem. Hard-hit by the nation's fuel shortage because it lacks such resources, New England, along with the rest of the Northeast Corridor, must depend upon transported fossil fuels. Its industrial concentration and population density is the highest in the nation owing mainly to its industry and high concentration of educational institutions. The area is also geographically far-removed from the oil-rich areas of the country.

The growing need for increased amounts of energy cannot be met by conventional methods and conventional supplies for much longer. Hubbert (1969) predicts that if present trends continue, oil production will reach its peak in 1995, the year which he foresees as the approximate deadline for alternative forms of energy that must replace petroleum as a result of the sharp decline of fossil fuel production after that date.

MAJOR OIL FIRMS

Alternative sources of energy were sought in the past but only now are receiving renewed attention of scientists the world over, especially those employed by energy firms and universities. Some oil companies, however, are directing their attention increasingly to geothermal energy. The number of geothermal wildcat wells drilled by major oil firms has markedly increased since 1972.

TABLE:1 Geothermal Wildcats of Oil Companies Since 1972
(Outside Of Geysers KGRA)

1972	AREA	COMPANY	WELL NAME
	Mendocino County, California	Sun Oil	Torchio-Ferro
	Lake County, California	Getty Oil	Kettenhofen 1 (deepen)
	Steamboat Springs, Nevada	Gulf Oil	------------
1973	Imperial Valley, California	Chevron Oil	Nowlin Partnership 2
		Phillips Oil	Sinclair 3 Sinclair 4
	Sonoma County, California	Signal Oil	Bianchi 1
	Surprise Valley, California	Gulf Oil	SV-1 ST SV-2 ST
	Honey Lake, California	Gulf Oil	Honey Lake 1 Honey Lake 2
	Lakeview, Ore.	Gulf Oil	Favell-Utley-1-ST
1974 (to Aug. 31)	Imperial Valley, California	Chevron Oil	J.D. Jackson C.B. Jackson Hulse
	Mendocino County, California	Sun Oil	Macii-State Torchio-Ferro 2
	Plumas County, California	Phillips Oil	Filippini A-1
	Valles Caldera, New Mexico	Union Oil	Baca 11 Baca 12
	Brady, Nevada	Phillips-Southern Pacific	Desert Peak 1-29
	Oreana, Idaho	Anschultz Corp. (O & G)	------------
	Beowawe, Nev.	Chevron-ATR	Ginn

(After Fuchs et al., 1975)

As illustrated in Table # 1, the number of wildcat geothermal wells drilled by major oil companies outside of known geothermal resource areas increased from 3, in 1972, to 9, in 1973, to 9 as of August 31, 1974.

An exception to this rule is Texaco, which, as of February, 1974, was concentrating less than 1 percent of its research and development efforts towards geothermal study (Sullivan, 1974).

Logically, the major oil companies will invest more capital in the research and development of geothermal energy in the near future. It is also true that major oil companies will invest amounts of money in geothermal to a much greater degree as it becomes more and more profitable.

THE POLITICAL SPECTRUM

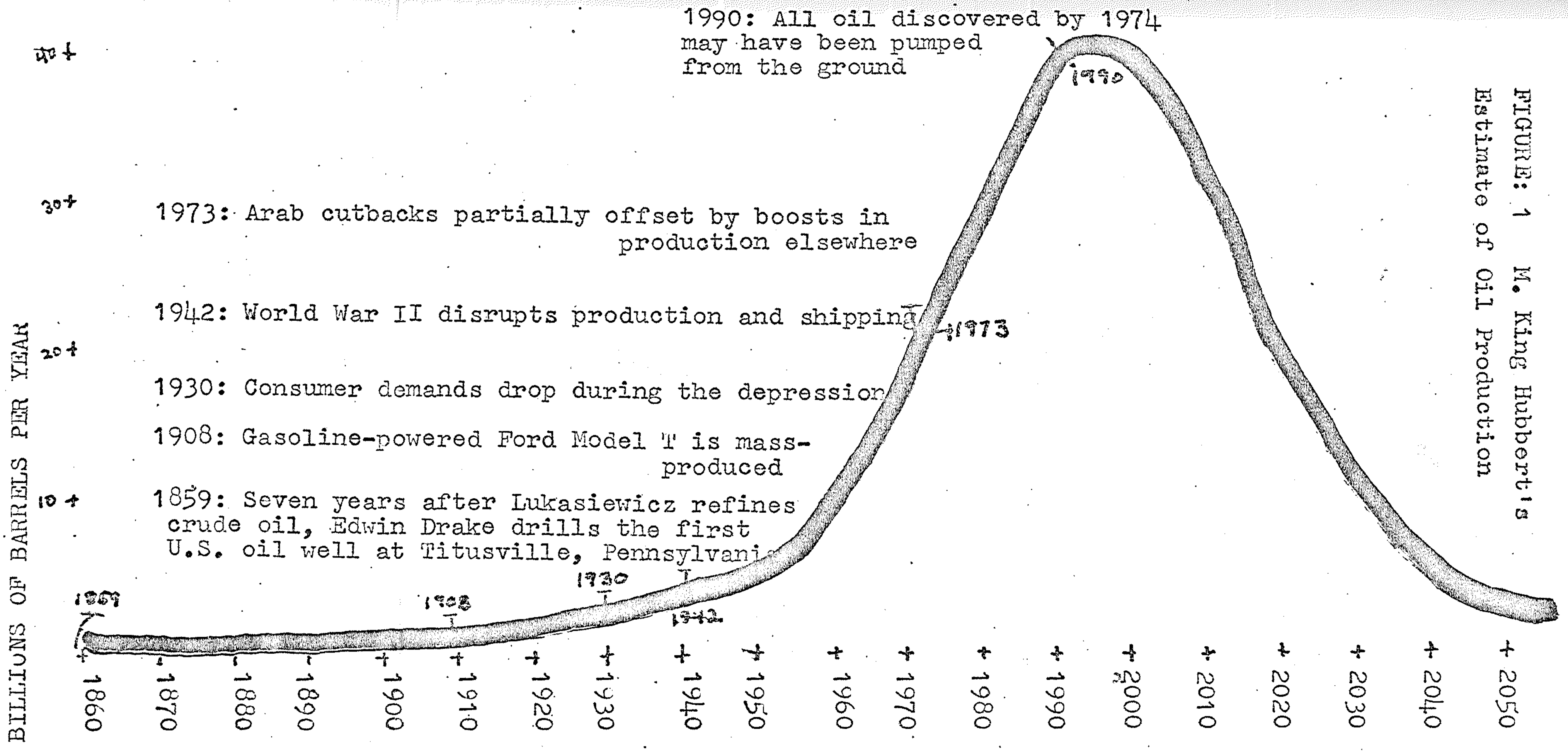
Senator Henry M. Jackson (D-Wash.), ex-chairman of the United States Senate Interior Committee, was the author of a massive energy research and development bill in late 1973. The bill appropriated $20 billion for a program to develop the nation's untapped energy sources during the next decade. This became the Geothermal Steam Act of 1970, which was passed in January, 1974. At this time federal lands first became available for geothermal exploration. Today, however, in the most prospective portion of the United States~~,~~ the West- 75% of the land is held by the government (Fuchs et al., 1975).

Eventually, Watergate-related troubles within the Republican Party led to a succession of replacements in the United States Energy Commission and the nation's energy problem lost some prominence as it was shelved alongside other national distress items such as unemployment, inflation, world hunger and its effect on United States food stockpiles and the remaining issues of the day.

Massachusetts' Senator Michael Harrington (D-Salem) contends that oil companies should be forbidden to own any share of alternate energy. In the face of the economic strife caused by the major oil companies during the 1973-1974 period, his contention is noteworthy.

The adoption of the Geothermal Steam Act of 1970 established the development of United States geothermal resources as a national goal (Barnea, 1972). However, the federal government has so far failed to implement the Act, thus preventing exploration in about three-quarters of the western United States. A final determination to proceed with leasing and a firm time schedule are still lacking (Fuchs, et al., 1973).

FIGURE: M.King Hubbert's Estimate of Oil Production



1990: All oil discovered by 1974 may have been pumped from the ground

1973: Arab cutbacks partially offset by boosts in production elsewhere

1942: World War II disrupts production and shipping

1930: Consumer demands drop during the depression

1908: Gasoline-powered Ford Model T is mass-produced

1859: Seven years after Lukasiewicz refines crude oil, Edwin Drake drills the first U.S. oil well at Titusville, Pennsylvania

(After Hubbert, 1969)

FIGURE: 1 M. King Hubbert's Estimate of Oil Production

GEOTHERMAL RESEARCH AND PROJECTIONS

The United Nations, through technical assistance programs, are helping Kenya and Ethiopia tap large stores of geothermal energy concentrated in the African Rift Valley. United Nations efforts are also underway in Turkey, Chile, El Salvador and Nicaragua. The search for new geothermal power sources is currently underway or being actively studied in at least 30 other countries (Koenig, 1973).

Research demonstrates that the cost of developing geothermal energy is likely to be less than for conventional forms. Capital and operating costs per unit of generating capacity at the few geothermal fields now operating are significantly below those of fossil fuel and nuclear power plants (Fuchs et al., 1973). This is offset by the fact that since power rates charged to consumers are set as a percentage of capital as well as operating costs, the lower capital cost of a geothermal power plant may actually defer a utility from developing geothermal energy.

It is difficult to project a figure of geothermal potential as a future world energy source due to the lack of information and experimental research at this time. However, Donald E. White of the United States Geological Survey has estimated (1971) that the stored thermal energy in the world's major geothermal areas amounts to about 4×10^{20} joules. After a 25% conversion factor the production of electrical energy would be about 10^{20} joules, or 3,000,000 megawatt-years (mwy). If this depletable source of energy were used up over a 50 year period, the average annual production would be 60,000 mw (Hubbert, 1971). This is comparable to the world's potential tidal power, which is listed as 3×10^{12} watts (See table 2).

Broadly speaking, it can be said that the world's total consumption of energy for industrial purposes is now doubling approximately once per decade. At the present rate of development it is likely that by the end of this decade the production of electric power from steam fields will be quadrupled (Barnea, 1972).

Geothermal energy is inexpensive, pollution-free and can be more swiftly harnessed than most of its rivals. Setting up a geothermal power station, for instance, only takes 3 years, whereas a hydro or nuclear power station takes 8 to 10 years (Winder, 1974). The drawbacks are clearly defined also. Geothermal can deliver only electricity and heat, but not fuel for transportation unless the transportation system is electrified.

TABLE: 2

FLOW OF ENERGY TO AND FROM THE EARTH

ENERGY FLUX AT THE EARTH'S SURFACE IS DUE TO:

1) Intercepted solar radiation
2) Thermal energy, conveyed to the surface from the warmer interior by the conduction of heat and by the convection in hot springs and volcanoes.
3) Tidal energy, from combined kinetic and potential energy of the earth-moon-sun system.

PHENOMENON	ENERGY RELEASE	
SOLAR RADIATION	173,000	x 10^{12} watts
(Direct reflection)	52,000	"
(Direct conversion to heat)	81,000	"
(Evaporation, precipitation)	40,000	"
WINDS, WAVES, CONVECTION & CURRENTS	370	"
PHOTOSYNTHESIS	40	"
TIDAL ENERGY	3	"
NUCLEAR, THERMAL AND GRAVITATIONAL ENERGY	35	"
(Conduction in rocks)	32	"
(Convection in volcanoes and hot springs	3	"

(After Hubbert, 1971)

CHAPTER I: WORLD GEOTHERMAL RESERVES

GEOTHERMAL DEFINITIONS

The high-enthalpy geothermal systems of the world are known only in regions of active or recent volcanism, crustal rifting and recent mountain building. The major volcanic and geothermal belts are the same general regions which are characterized by frequent earthquakes of great magnitude. These are the Circum-Pacific margin, the islands of the mid-Atlantic Ridge, the rift zones of east Africa and the adjacent Middle East and the irregular belt of mountains and basins which extends from the Mediterranean basin of Europe and north Africa across Asia to the Pacific (Koenig, 1973). Figure 1-1 is a world map which displays these areas.

Geothermal resources, in general, include energy plus any associated mineral products which can be extracted from steam and hot water emitted from the earth. The most important item is geothermal energy, used to generate electric power by releasing steam from naturally hot areas through drill holes, then channeling it to a generator unit (USGS, 1972). The heat of many geothermal reservoirs comes from a large body of molten rock pushed up into the earth's crust from great depths by geologic forces. This body of magma heats the rocks in the crust near the surface, which in turn heats the water in fissured or porous rocks to high temperatures. Being at depths of as much as six miles, the water is under high pressure and is therefore liquid (Barnea, 1972). Where the hot water can escape through a fissure it begins to boil and a part of it then flashes off as steam. The geothermal energy can then

FIGURE: 1-1

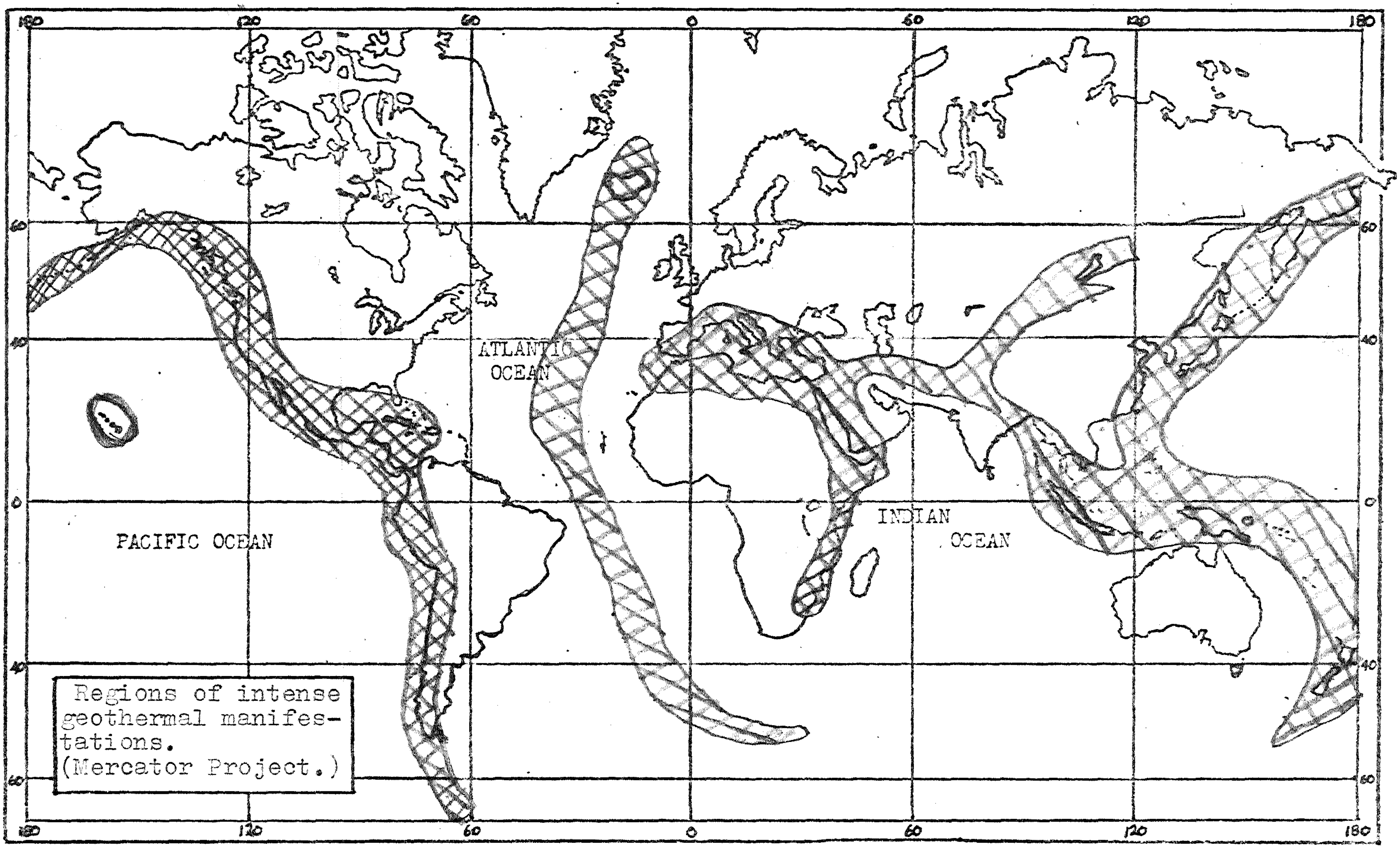


FIGURE: 1-1 Regions of intense geothermal manifestations; the distribution accords generally with recent volcanism and youthful mountain-building, and in part outlines boundaries of mobile crustal plates. These are also the main earthquake zones of the globe. (After Koenig, 1973) be tapped by a well driven into the fissure or down to the porous layer. The combination, however, of geologic events needed to produce a naturally occurring, high-quality source of steam is unusual and the number of known sources is correspondingly small. This has sometimes led to the conclusion, and in the writer's opinion an erroneous conclusion, that geothermal energy has little chance of contributing significantly to the future energy demands of the world (Nat. Res. Council, 1969; Chem. & Eng. News, 1970).

Geothermal investigation of provinces or regions, rather than single locations, is thought to be most desirable and should be feasible in those areas which have been extensively drilled for oil (Birch, 1954). There are two main requirements, difficult to meet, in the successful search for geothermal resources:

1) Approximate thermal equilibrium (which may require an undisturbed period of many months)
2) Availability of cores of the major formations penetrated by the well for laboratory study

World production of power using the earth's natural heat as an energy source has now reached about 1 million kw and can probably be increased at least 10 times under present economic conditions (USGS, 1972). In a special National Science Foundation report in 1972, Walter J. Hickel, chairman, states that, with the research and development recommended in that report, he is confident that the United States can be producing from its geothermal resources at least 132,000 mw in 1985 and 395,000 mw by the year 2000. Under the United States, the heat stored to a depth of about 10 km is said to be about 6 x 10^{24} cal or equivalent to the heat content of 9 x 10^{14} short tons of coal (White, 1972). In the same paper White classifies high geothermal gradient areas three ways:

1) Areas in which the geothermal gradient is higher than "normal" but where notable hydrothermal activity is absent; in some of these areas molten magma may exist within accessible depth

2) Hot spring areas, in which natural thermal fluids are discharged at the surface

3) Hydrothermal areas of composite type that have little surface expression but with high temperature fluids that exist beneath capping rocks of low permeability

It is not surprising that types 2 and 3 offer the best immediate possibilities for economic development for the reasons that high temperatures occur relatively near to the surface and hot, natural fluids are present as energy-transporting media.

For so short a period of time has geothermal energy been in use that there is doubt concerning the forecasts of geothermal usage and recovery from hydrothermal reservoirs. On the conservative basis of a 1% estimate, the estimated recoverable reserves are:

	HEAT CONTENT (cal)
A) Potential reserves to depths of 3 km, recoverable at or near present costs.......	2×10^{19}
B) Additional resources to depths of 10 km, recoverable at much more than present costs..	1×10^{22}

(From White, 1972)

Irregardless of depth, Keller (1971) defines a good geothermal reservoir as having three characteristics:

1) Storage capacity
2) Elevated temperature
3) Fluid permeability

In general, however, three main types of geothermal deposits have been listed by Fuchs et al. (1973). These are vapor-dominated, hot water and geopressurized systems listed in table 1-1.

TABLE: 1-1

TYPES OF GEOTHERMAL DEPOSITS

1) VAPOR DOMINATED OR DRY STEAM TYPE	Of prime commercial interest since superheated steam is fed directly into a rotary turbine generator. These systems are believed to be rare.
2) HOT WATER SYSTEM (OR COMBINATION STEAM-HOT WATER SYSTEM	By far the most common geothermal deposit. As fluid moves to surface and pressure drops, steam is produced by boiling or flashing. At the surface this steam-water mixture must be separated before steam is fed into turbines, owing to the mineral-saturated water's effect on turbine blades, including pitting, corrosion, clogging and accumulation in the mechanism. Hot water and steam-hot water systems are economically less-attractive as energy sources due to large volumes of water that must be handled to operate even a moderate-sized turbine.
3) REGIONAL OR GEOPRESSURIZED SYSTEM	Normal heat flow of the earth is trapped by insulating, impermeable clay beds in a rapidly subsiding geosyncline. i.e., the Tertiary Gulf Coast Basin of the United States. The enormous size of these low-temperature, geopressurized systems offers a large potential, but still theoretical, future energy source. Currently, cost of production from these deep systems appears to exceed greatly the value of the energy that can be produced.

(From Fuchs et al., 1973)

The present heat withdrawal of some established geothermal fields has been found to be considerably in excess of the natural heat flow and some are very high. The computed rates of heat withdrawal for six world sites are listed in table 1-2.

TABLE: 1-2

GEOTHERMAL FIELD HEAT WITHDRAWAL RATES

LOCATION	HEAT FLOW PERCENT*	SOURCE
Reykir, New Zealand	300	(Banwell, 1964)
Hengill, New Zealand	400	(Banwell, 1964)
Wairakei, New Zealand	400	(Banwell, 1964)
Reykjavik, Iceland	900	(Bodvarsson and Zeoga, 1964)
Larderello, Italy	1000 (estimated)	(Boldiszar, 1963)
The Geysers, California	17000	(McNitt, 1963)

*Percentage of the natural heat flow of particular location
(After White, 1972)

Banwell (1964) concluded that 70-90% recovery is possible over periods of 20-100 year drawoff times, providing that the channel spacing is less than about 200 ft. Banwell's theoretical discussion of the subject is informative but White (1972) has commented on initial assumptions:

1) "The efficienvy and percent of heat recovery only to heat stored above 100°C (rather than to that stored above mean surface temperature, which is commonly used by others). Banwell's calculated efficiencies are therefore correspondingly high."

2) "Banwell's idealized models assume all faults and fractures to be so permeable that permissible rates of fluid withdrawal or circulation have no restrictive upper limit; his model also assumes a uniform rate of flow across all surfaces."

It is also true that the rate of withdrawal of the fluid bust be at least in the range of about 25 times that of the natural discharge of the system. Any circulation rate increase will be immediately confined to the largest channels of highest permeability and will eventually be responsible for a loss in heat content of the recovered fluid. Because heat dissipates rapidly, geothermal fluids cannot be transported far from their point of recovery without suffering diminished thermal properties and, in the case of steam for electric power generation, the maximum transportation distance is probably on the order of 2 to 3 km (Koenig, 1973).

TABLE: 1-3

CLASSIFICATION OF GEOTHERMAL ENERGY SOURCES

TYPE I...	Regions of normal geothermal gradient (about 20°C/km). Temperatures great enough to produce high-grade steam exist only at depths of about 10 km or more, where there is probably no free water. This situation exists under most of the earth's surface.
TYPE II..	Local areas of higher-than-normal geothermal gradient, which cannot at present be exploited economically because the temperature and hardness of the source make it difficult to penetrate and its low permeability prevents the ground water circulation required to produce natural steam. These are usually regions in which there has been either volcanic activity or intrusive flow in recent geologic time. In the United States such sources are common in the west, including several in New Mexico.
TYPE III.	Hot-spring areas, characterized by shallow ground water and convective heat transfer. In general, water temperatures are too low to be of interest for power generation.
TYPE IV..	Regions in which impermeable rock near the surface covers underlying formations that are permeable to circulating ground water. At depth, heat transfer is convective, but near the surface it occurs only by conduction through the rock. All present power production from geothermal energy originates in type IV sources. The major ones are Larderello in Italy, Wairakei in New Zealand and The Geysers and Salton Sea areas in California.

From White, 1965)

TABLE: 1-4

GEOTHERMAL ENERGY RESOURCES OF THE CONTINENTAL UNITED STATES

Type of Source	Depth range in km for useful power	Geothermal gradient °C/km	Temperature range at useful depth °C	Total thermal energy, gigawatt years	Available electrical energy, gigawatt years	Number of years operation at 3000 gigawatts (a)
I	15-30	20	300-600	$5x10^9$	10^9	$3x10^5$
II	3-10	100	300-1000	10^8	$2x10^7$	$7x10^3$
III	0-3	--	100-200	$2x10^4$	10^3	0.3
IV	0.5-3	--	200-500	$2x10^4$	$4x10^3$	1.3

(a) The projected electrical requirement of the United States for the year 2000

(From Robinson et al., 1971)

TABLE: 1-5

UNITED STATES GEOTHERMAL ENERGY RESOURCES POTENTIAL

YEAR	1975	1985	2000
POWER (gw)	0.75	132	395
ELECTRICAL ENERGY[1] (thousands of gwh)	5.913	1041	3114
OIL EQUIVALENT[2] (millions of Bbls/day)	0.242	4.213	12.60
FORIEGN TRADE IMPACT[3] (billions of dollars)	0.051	8.919	26.67

1. 90% load factor
2. 3,412 BTU/KWH and 5,800,000 BTU/Bbl of oil used at 40% conversion efficiency
3. $5.80 per barrel ($1.00 per million BTU)

(After Hickel, 1972)

TABLE: 1-6

AMOUNT OF PRODUCIBLE GEOTHERMAL ENERGY IN THE UNITED STATES
(Mw/cen of electricity)

Energy Price (mill/kwhr)a	Known reserves		Probable reserves		Undiscovered	
	Amount	Areas	Amount	Areas	Amount	Areas
2.90- 3.00	1,000	1	5,000	1	10^{4}	1
3.00- 4.00	30,000	1-2	400,000	1-4	2×10^{6}	1-5
4.00- 5.00	--	--	600,000	1-6	12×10^{6}	1-7
5.00- 8.00	--	--	--	--	2×10^{7}b	d
8.00-12.00	--	--	--	--	4×10^{7}c	d

AREAS: 1) Clear Lake-The Geysers; 2) Imperial Valley; 3) Jemez area, N.M.; 4) Long Valley, Calif.; 5) Remainder of Basin and Range area of western U.S.; 6) Hawaii; 7) Alaska

a. In 1972 dollars

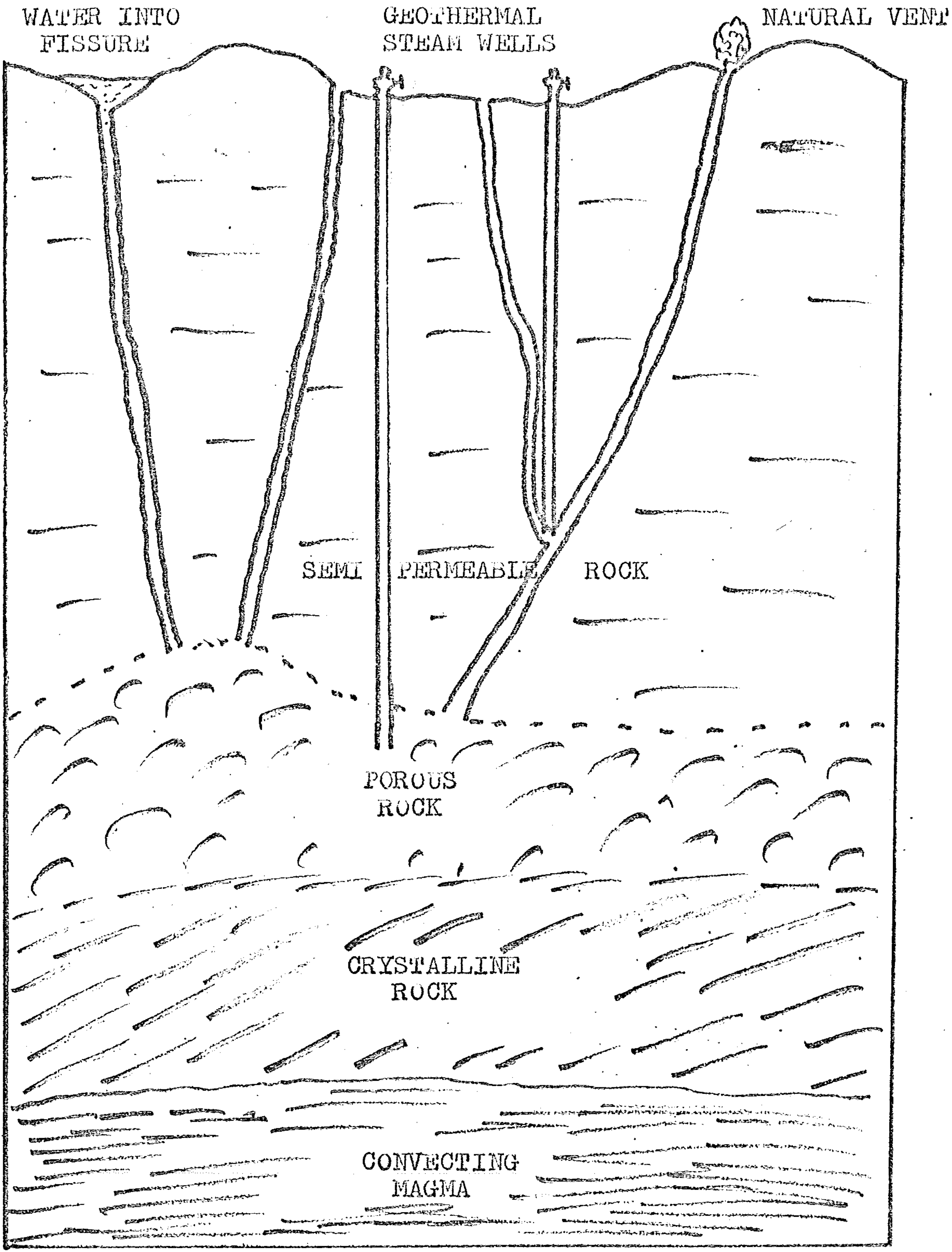
b. Hot, dry rock at less than 6.1 km (20,000 ft) depth

c. Hot, dry rock at less than 10.7 km (35,000 ft) depth

d. Development of hot, dry rock energy is assumed over 5% of the area of the western third of the U.S. Hot, dry rock systems development is based on hydrqulic fracturing or cost-equivalent technology. Present drilling technology is assumed but new, low-cost deep drilling could substantially improve the economics.

(After Rex and Howell, 1973)

FIGURE: 1-2



GEOLOGICAL SETTING of a geothermal energy source. Heat comes from magma, or molten rock, that has been pushed up into the earth's crust. By convection of the magma the heat moves through crystalline rock to a porous rock layer containing water that has percolated down from the ground, sometimes to great depths. Over the porous rock is relatively impermeable rock that serves as a cap to contain the heat. Deep in the ground, the water is under high pressure and is therefore liquid, although its temperature may be some 500°F. It expands and rises in a natural vent; as pressure drops, water begins to boil and produce steam. A well can tap the vent or the porous layer. (After Barnea, 1972)

GROUND WATER

Ground water is important in geothermal systems not only because it is the heat transporting medium but also because ground water in open pore space increases electrical conductance. In resistivity surveys, an increased conductivity is one indication that, in areas of higher-than-normal geothermal gradient, the possibility of discovering a geothermal reservoir at some depth is very good. Geysers, fumaroles, mud pots, solfataras and thermal springs depend upon the natural plumbing systems of groundwater for their volume, intensity, areal extent and heat. Deep-seated aquifers are, in many cases, sites of surficial thermal activity.

Almost two-thirds of the recognized thermal springs in the United States issue from a variety of rock types thought to be underlain by deep-seated sources. Ground water is heated through contact with subterranean volcanic sources (Miller, 1963). Although many of the country's natural springs have been or are being used as sites for health spas, only those which issue water significantly warmer than normal are generally looked upon favorably as supplies of warm tap water or for heating purposes. Natural springs in the New England and New York areas are discussed in chapter five.

Low-temperature geothermal fields have been used for some kind of domestic purpose for many thousands of years at least. It is only recently, however, that their importance has been increasingly realized. The low-temperature hot water fields generally consist of large bodies of water in the approximate temperature range

TABLE: 1-7

THERMAL SPRINGS REPORTED IN THE UNITED STATES

STATE	NUMBER OF THERMAL SPRINGS
1. Alaska	79
2. Arizona	21
3. Arkansas	6
4. California	211
5. Colorado	46
6. Florida	1
7. Georgia	8
8. Hawaii	10
9. Idaho	203
10. Massachusetts	1
11. Montana	41
12. Nevada	200
13. New Mexico	38
14. New York	1
15. North Carolina	1
16. Oregon	126
17. Pennsylvania	1
18. South Dakota	4
19. Texas	3
20. Utah	65
21. Virginia	20
22. Washington	18
23. West Virginia	30
24. Wyoming	285

(After Waring, 1965)

of 120° to $180^{\circ}F$. Usually found in sedimentary deposits and in strata of tightly folded anticlines and deep-seated fault systems, such water used from low temperature fields can prove useful and economical in the long run. In the U.S.S.R., for instance, water usage from low temperature geothermal fields is reported to have represented a saving of about 15 million tons of fuel in 1970 (Barnea, 1972).

WORLD GEOTHERMAL SITES

In 1777, at Larderello, Italy, borax was recovered from natural steam and hot water vents. In 1905 the world's first power-generating station was built there using natural steam. In New Zealand attempts to harness geothermal energy were made in 1925 but no real development occurred until about 1946. The year 1925 also saw hot water in Iceland being supplied for space heating. By 1930, in Reykjavik, natural hot water was widely used for homes and industry. Industry in Japan in 1974 benefited from the operation of a geothermally powered zinc plant in Akita (Rutledge, 1974). The Mitsubishi Co. claims it as the third geothermal station in Japan.

The United States claims two main geothermal areas in The Geysers and the Imperial Valley, both in California. Of these, only The Geysers geothermal plant, built in 1955, is currently in operation. These are important dry steam fields. The Valle Caldera field in New Mexico is also an important dry steam field. Two wet steam fields are in Boise, Idaho and in Klamath Falls, Oregon.

The Geysers Field, the world's largest operating geothermal field, in Sonoma County, California, is about 80 miles north of

San Francisco. The first wells to supply steam for electric generating purposes were drilled at The Geysers in 1921-22. The project was abandoned in 1928 (Fuchs, et al., 1973) but it was revived in 1955, when Magma Energy Co. began a program of drilling and economic evaluation. These investigations resulted in a contract with Pacific Gas & Electric in 1958 to supply geothermal steam for a 12.5 mw power plant that went on line in 1960. This original plant was eventually supplemented by nine other generating plants through mid-1973, with a present total generating capacity of 396 mw (table 1-9). Suppliers of steam are the Magma-Thermal Power Project and Union Oil Co. venture to be joined in the future by Signal Oil & Gas and Pacific Energy Corporation. As of December, 1973, four other plants were either planned or under construction.

By 1975 The Geysers project a power production capability sufficient to supply the needs of the city of San Francisco, with ultimate power potential estimated to be 1,000-2,000 mw. Consulting engineers have appraised future net revenue from one portion of The Geysers at $150,000 per acre over a 15 year period.

At The Geysers, steam arises from a reservoir of highly fractured, slightly metamorphosed graywackes, shales and basalts of the Jurassic-Cretaceous Franciscan formation. The heat source is believed to be a buried igneous mass of Pleistocene age a few miles northeast of the field. Wells are completed at depths of 4,000-8,000 ft, producing, on the average, 150,000 lb/hr of 570°F steam (Fuchs et al., 1973). The steam production from northwest-trending shear zones is in a zone about 5 miles long and 2 miles wide.

Recent exploration suggests that the future productive area may be twice as large as the present field. The steam fed into turbines is relatively pure and superheated and is either evaporated into the atmosphere or condensed into pure water, some of which being used for artificial recharge of ground water.

TABLE: 1-8

STATUS OF GEOTHERMAL EXPLORATION AND DEVELOPMENT, 1972

NATION	ELECTRIC POWER GENERATION/ CONSTRUCTION	EXPERIMENTAL POWER STATIONS	SIGNIFICANT DIRECT UTILIZATION	OTHER GEOTHERMAL FIELD DISCOVERIES	ADDITIONAL EXPLORATION UNDER WAY[c]
Chile				X	
China		X			
Ethiopia					X
Guadaloupe (Fr. W. Indies)				X	
Hungary			X		
Iceland	X		X	X	
Indonesia					X
Italy	X				X
Japan	X	X[b]	X	X	X
Kenya			X		
Mexico	X[a]	X	X	X	X
New Zealand	X		X	X	
Nicaragua				X	
Philippines		X		X	
El Salvador	X[a]			X	
Taiwan				X	
Turkey				X	
U.S.S.R.	X	X	X	X	X
United States	X	X[b]	X	X	X
Zaire		X[b]			

a) Under construction; b) Inactive; c) Other geothermal exploration/ interest: Algeria, Argentina, Bulgaria, Burundi, Colombia, Costa Rica, Czechoslovakia, Ecuador, Fiji Islands, Greece, Guatemala, India, Israel, Malawi, Morocco, New Britain, New Hebrides, Peru, Poland, Portugal (Azores Is.), Rwanda, Spain (Canary Is.), Tanzania, Tunisia, TFAI (French Somaliland), Uganda, Venezeula, Yugoslavia, Zambia

(From Koenig, 1973)

TABLE: 1-9

GEOTHERMAL FIELDS PRODUCING IN 1973

COUNTRY	FIELDS	YEAR COMMERCIAL PRODUCTION STARTED	1973 MW CAPACITY
Italy	Larderello	1912	365.0
	Monte Amiata	1959	25.5
New Zealand	Wairakei, Broadlands	1960	170.0
United States	The Geysers	1960	396.0
Japan	Matsukawa	1965	20.0
	Otake	1967	13.0
U.S.S.R	Pauzhetsk	1967	29.0
Iceland	Namafjall	1969	3.0
China	Kwantung Province	1958	?
Mexico	Cerro Prieto	1973	75.0
			1,059.5

(From Fuchs etal.,197

TABLE: 1-10

GEOTHERMAL POWER PRODUCTION DEVELOPED OR UNDER DEVELOPMENT

COUNTRY	FIELD	PLANNED CAPACITY (1977 MW)
Chile	El Tatio	20
El Salvador	Ahuachapan	30
Guadeloupe	La Bouillante	30
Iceland	Namafjall	3
	Hveragerdi	17
Italy	Larderello	415
	Monte Amiata	25
Japan	Hashimanta-Onuma	10
	Hatchobaru	50
	Katsukonda	50
	Onikobe	25
Mexico	Cerro Prieto	78
	Pathe	4
New Hebrides	?	?
New Zealand	Wairakei	160
	Kaucrau	10
	Broadlands	?
Philippines	Bicol, Legaspi	10
Taiwan	Tatun	10
Turkey	Kizildere	30
United States	Salton Sea	50
	The Geysers	633
	Brady's Hot Springs	10
U.S.S.R	Pauzhetsk	20
	Kunashiry	6

(After Fuchs et al., 1973; Koenig, 1971)

TABLE: 1-11

CHARACTERISTICS OF SELECTED GEOTHERMAL FIELDS

FIELD	RESERVOIR TEMP °C	RESERVOIR FLUID TYPE	ENTHALPY Cal/g	AVERAGE WELL DEPTH m	FLUID SALINITY ppm	MASS FLOW PER WELL kg/hr	NON-CONDENSIBLE GASES %
Larderello	245	Steam	690	1,000	<1,000	23,000	5
The Geysers	245	Steam	670	2,500	<1,000	70,000	1
Matsukawa	230	Mostly Steam	550	1,100	<1,000	50,000	<1
Otake	200+	Water	~400	500	~4,000	100,000	<1
Wairakei	270	Water	280	1,000	12,000	---	<1
Broadlands	280	Water	400+	1,300	---	150,000	~6
Pauzhetsk	200	Water	195	600	3,000	60,000	-
Cerro Prieto	300+	Water	265	1,500	~15,000	230,000	~1
Niland	300+	Brine	240	1,300	260,000	~200,000	<1
Ahuachapan	230	Water	235	1,000	10,000	320,000	~1
Hveragerdi	260	Water	220	800	~1,000	250,000	~1
Reykjanes	280	Brine	275	1,750	~40,000	~400,000	~1
Namafjall	280	Water	260	900	~4,000	400,000	6

(From Kruger et al., 1973)

CHAPTER II: GEOTHERMAL GRADIENT AND HEAT FLOW

GEOTHERMAL GRADIENT

Magmatic, radioactive, tectonic and convective heat are the natural sources of heat in rocks. The diversity of rock in the crust is best indicated by a diversity in the values of geothermal gradient. As there is a prevalence of high values of heat flow within the Basin and Range province of the United States, a region noted for thermal springs and widespread Tertiary volcanism, there also exists, according to recent geophysical studies; an abnormally thin crust and low seismic velocity in the underlying mantle (Herrin and Taggart, 1962; Pakiser, 1965; Pakiser and Zietz, 1965).

Levorsen (1967) defines geothermal gradient as: (mean annual surface temperature)/(depth in feet), where the average surface temperature is taken to be 25°C or 77°F. Except for about the top meter which is subjected to diurnal and seasonal changes, the temperature within the earth steadily rises with depth at a variable rate which depends on the location. Even in volcanically quiet areas, geothermal gradients vary considerably depending on differences in heat sources of the local crust (Jacobs et al., 1974). The range is from less than 10°C/km to greater than 50°C/km. The rate of increase of the earth's temperature with depth depends on differing kinds of rock, inhomogeneity within rock materials, amount of crack space in dry rock and liquid pressures in the cracks of saturated rocks.

In most rocks, cracks originating from forces such as stress due to heat and pressure are of greater importance than the differences produced by the variety of the atomic structures in the component minerals. Heat conductance and stress resistance in rocks is related to their composition; thus, the mineral content of a rock constitutes important information when coupled with its thermal conductivity.

Simmons and Nur (1968), in their studies on granites, showed that the presence of open cracks significantly affects many properties, including the thermal conductivity, which increases as the open pore spaces are filled with liquid.

HEAT FLOW

The product of the geothermal gradient and the thermal conductivity is known as heat flow. Its value is reasonably constant the world over; the average terrestrial value being approximately 1.5 HFU (Heat Flow Units in μcal/cm^{2}sec)(Lee and Uyeda, 1965; Simmons and Horai, 1968). The vertical component of heat flow Q_z is calculated from the fundamental relation,

$$Q_z = k(dT/dz) = (1/R)(dT/dz),$$

where z is vertical depth, k is thermal conductivity, T is temperature and R is resistivity. This relation may also be used in the form of finite differences of temperature ΔT and depth Δz, with $\langle k \rangle$ a mean conductivity, or $\langle R \rangle$ a mean resistivity for this interval, or in the integrated form:

$$Q_z \int_{z_0}^{z} R dz = \int_{T_0}^{T} dT$$

where Q_z is assumed independent of depth and R is a function of z alone (Bullard, 1939, p. 481). The value of Q_z is then found as the slope of the least-squares line giving T as the function of the 'resistance integral' $\int R dz$ (Roy et al., 1968).

The construction of temperature profiles of the earth's crust and mantle is far more ambiguous than other geophysical problems. The available parameters are:

1) Heat flow values
2) Radioactive content of different crustal layers
3) Coefficient of thermal conductivity
4) Thickness of the earth's crust and its layering

Heat flow studies to date deal with the outside of the earth's crust, which is very nonhomogeneous. Actually, there is very little difference in thermal conductivity of various rock types. Most of the differences in heat flow are due to local sources of heat. One possible model listed by Combs and Simmons (1973) assumes that the crustal layering and the heat source distribution for areas differ but the mantle contribution to the heat flux at the surface is constant.

In most of the outer crust of the earth, conduction is the dominant mode of heat flow, owing to its crystalline and solid-state nature. Fourier's Law for thermal gradients is expressed as:

$$r = q / k$$

where the thermal gradient (r) is in $^{\circ}C/km$, heat flow (q) in $\mu cal/cm^2 sec$ and thermal conductivity (k) in $\mu cal/cm\ sec\ ^{\circ}C$. Mineralogy, porosity and fluid content determine overall thermal conductivity of rock and temperature gradients may change greatly with depth, thus near-surface thermal gradients cannot reliably be projected below explored depths due to possible changes in those three determinants (White, 1973).

Besides radioactivity, heat flow values in excess of normal can also be attributed to exothermic chemical reactions, friction along faults or migration of waters of different origins into areas of near normal geothermal gradient. Increased heat flow due to these phenomena usually are of restricted extent and limited in duration (Combs and Muffler, 1973, p. 101).

RADIOACTIVITY

> By good fortune, the heat generated by the disintegration of radioactive minerals, combined with that given to the interior of the earth during its early history, has provided energy for earthquakes and volcanism.
> (Wilson, 1962)

The radioactive content of an approximately 6 km thick layer of crust is responsible for the radioactivity of the surface bedrock. This radioactivity is believed to impart a certain amount of heat to the surface (Jacobs et al., 1974). The important short-lived radioactive isotopes are U^{236}, Sm^{146}, Pu^{244} and Cm^{247}; all of which have half-lives sufficiently long enough to have heated up the earth during the 10^7 to 10^8 years after the initial formation (Jacobs et al., 1974). MacDonald (1959) estimates that if all this heat was retained by the earth, a temperature increase of the entire planet on the order of 2000 to 3000 ^oC may be possible today.

Birch et al. (1968), Roy et al. (1968a) and Lachenbruch (1971) described a linear relationship between heat flow Q and heat production A of the surface rock in plutons from many localities in the United States. The relationship has the form cussed at greater length in Chapter V.

In practice, heat flow measurements, whether taken for the purpose of determining local gradient or the general gradient of an area, may be considered unreliable unless the holes are 200-300 m deep (Birch, 1966). The gradients measured in the shallow parts of drill holes (even in regions of gentle topography) commonly depart remarkably from those measured deeper in the drill holes, particularly in regions of low to normal heat flow. These "anomalous" shallow gradients have been attributed to conductive effects such as water circulation (Diment, 1964; detailed discussion by Birch, 1966).

Shallow temperature measurements, however, when conducted at about 1.5 to 2 m depth, just out of the range of temperature fluctuation due to diurnal and seasonal temperature effects, have been shown to be reliable in the detection of thermal anomalies due to shallow salt structures and surface faults (Poley and Van Steveninck, 1970). A more detailed discussion on theory and usage of this technique follows in Chapter VI.

TABLE: 2-1

AVERAGE HEAT FLOW (μcal/cm^2 sec)

OCEANS:	Basins	1.3
	Ridge Axes	1.4
	Ridge Flanks	0.8
CONTINENTS:		
	Shield areas and stable platforms	1.0
	Paleozoic mountain belts	1.4
	Mesozoic mountain belts	1.7
	Cenozoic mountain belts and active compression zones	2.5

(After McBirney, 1963)

TABLE: 2-2

HEAT FLOW VALUES

NON-VOLCANIC REGIONS:	$Q = 0.6 - 1.0$ (μcal/cm^{2}sec)	LOW heat flow
	$Q = 1.0 - 1.5$	NORMAL heat flow
	$Q = 1.5 - 3.0$	HIGH heat flow
	$Q = 3.0 +$	EXTREMELY HIGH heat flow
OCEANIC CRUST REGIONS:	$Q = 0.5$	VERY LOW heat flow (Origins not clear)
	$Q = 1.0 - 1.5$	LOW heat flow (Typical of Ocean basins and trenches)
	$Q = 1.6 - 2.5$	MEAN heat flow (For ocean rises and island arc areas)
	$Q = 2.5 - 8.0$	HIGH TO EXTREMELY HIGH heat flow (Mid ocean ridge crests, rifts and volcanic intrusions)

(From Lubimova, 1968)

TABLE: 2-3

THERMAL CONDUCTIVITIES OF SOME COMMONLY ENCOUNTERED ROCK TYPES

Granodiorites	6×10^{-13} to 6×10^{-14} (cal/cm^{2}sec)
Gabbro	5×10^{-14} to 1×10^{-14}
Continental Peridotites	$(0.1 - 0.01) \times 10^{-15}$
Oceanic Peridotites	$(0.3 - 0.05) \times 10^{-15}$

(From Lubimova, 1968)

TABLE: 2-4

HEAT PRODUCTION BY IGNEOUS ROCKS

TYPE OF ROCK	HEAT PRODUCED BY U, ergs/g yr	HEAT PRODUCED BY Th, ergs/g yr	ASSUMED CONTENT OF K, 10^{-4}g/g	HEAT PRODUCED BY K, ergs/g yr	TOTAL HEAT PRODUCTION, ergs/g yr
Granites	117	84	300	34	235
Acidic (general)	126	109	340	28	273
Intermediate	43	36	263	29	108
Intermediate	81	81	263	29	191
Basalts	25	41	57	6.4	72
Basic Lavas	26	28*	49	5.5	59
Hualalai Basalt	15	16*	56	6.3	37
Twin Sisters Dunite (neutron activation)	0.034	0.036*	0.1	0.01	0.08
Dunites	0.42	0.44*	0.1	0.01	0.87

(From Jacobs et al., 1974, p. 207)

CHAPTER III: GEOTHERMAL EXPLORATION AND RECLAMATION TECHNIQUES

PART A: GEOTHERMAL EXPLORATION

The current state-of-the-art of geothermal exploration may be compared to that of oil exploration in the early part of this century when the technique giving the highest probability of finding an oil reservoir was to drill a well at the site of a surface showing. The same may be said for geothermal exploration at this time, with the exception that there have been numerous attempts to apply seismic, gravity and magnetic techniques.
(Banwell, 1970)

Geothermal power is obtained by extracting heat that is temporarily stored in the earth by such sources as volcanoes and the hot water filling the sands of deep sedimentary basins (Hubbert, 1971). The actual extraction of such energy depends upon techniques of location and reclamation, whether generalized or specially suited to particular locations. According to Dobrin (1952), the five major geophysical prospecting methods are gravity, magnetics, seismic reflection, seismic refraction and electrical resistivity. Gravity and resistivity measurements mave been the techniques most used in geothermal prospecting (Douze and Sorrells, 1972).

The following is a list and description of geological and geophysical methods of exploration, prospecting and extraction technology with a short discussion regarding their degree of usage in geothermal exploration:

A. Geology
B. Geochemistry
C. Seismology
D. Gravity
E. Magnetics
F. Electrical Resistivity
G. Thermal Sensing: Remote and Direct

A. GEOLOGY

Geological studies focus on local structure (particularly faulting), degree and kind of rock alteration, type, character and extent of thermal manifestations, presence, type and age of igneous rocks in the area and availability of recharge waters for existing reservoirs. Contemporary fracturing and fault movements, evidenced by earthquake activity as well as youthful, acidic volcanism, evidenced by cinder cones, calderas, lava flows and shallow intrusives, are geologic criteria significant in the search for geothermal energy (Fuchs, et al., 1973). Geothermal reservoirs are not uniformly distributed in the crust of the earth but essentially all fields explored to date are near the margins of crustal plates (Muffler and White, 1972), where scientists consider that crust is being either created or consumed (see, for example, Dewey and Bird, 1970). Current theory holds that in these areas molten rock is generated and buoys upward in the crust, providing the basic heat which is transferred conductively to the crustal meteoric water system (Combs and Muffler, 1973). The general location of a geothermal system is determined by the location of a deep igeous mass (at perhaps greater than 5 km) that is the probable source of heat which drives the overlying meteoric convective system (White, 1968).

Geologic exploration for geothermal resources has also been aided by airborne side-looking radar, which has the advantage of "seeing" through cloud cover and vegetation (Hubbert, 1971).

B. GEOCHEMISTRY

Geochemistry involves sampling waters for dissolved mineral content, as well as investigations for epithermal and telethermal mineral deposits such as mercury and fluorspar. The detection of passage or presence of hydrothermal fluids, evidenced by recent rock alteration and adequate groundwater with favorable recharge conditions are factors (Fuchs et al., 1973). Chemical analyses of soil gases are made, in some cases, and highs of hydrocarbon concentration are sought. Analyses of soil radioactivity and soil fluorescence have also been made to test for correlation with subsurface structure (Dobrin, 1952, p. 406). The chemicals dissolved in water samples are rough indicators of subsurface temperature, water sources and reservoir fluid characteristics.

C. SEISMOLOGY

Of all current geophysical techniques, seismic ones are by far the most widely used because they give the most detailed information and the most unique picture of the subsurface (Dobrin, 1952). In geothermal prospecting, seismic study involves the measurement of microseisms and natural ground noise. Faults, natural conduits for geothermal fluids, often are sites of minor and frequent movement. In geothermal areas, several hundred micro-earthquakes per day have been observed. Ground noise surveys measure frequency and amplitude of natural ground movements believed to be the result of rheological deformation and phase changes associated with geothermal fluids. Passive seismic measurements are made with six or more low-frequency seismometers telemetered to a central low-speed magnetic tape recorder.

In the Imperial Valley of California, for instance, field studies indicated that there is a high empirical relationship between hot water deposits at depth and an anomalously high seismic background level at the surface (Goforth et al., 1972). The method consists of measuring the power spectrum of the vertical background noise in the survey area; the presence of a geothermal reservoir is them indicated by a sharp increase in the noise level (Douze and Sorrells, 1972). Clacy (1968) noted that, in the Rotorua, Taupo volcanic region of New Zealand, areas of continuous high seismic noise and dominant low frequency were found in conjunction with aquifers.

Recent studies done in regions of geyser activity are also of value. In the passive seismic observation of a number of Icelandic geysers, Rinehart (1973) found that each geyser studied has a characteristic seismic signature generated by the interactions among its plumbing system, water supply and heat source. The pattern of any one geyser was also found to repeat itself closely from cycle to cycle. A 1972 U.S.G.S. seismic survey of Yellowstone National Park turned up geothermal seismic noise predominantly in a 2-8 hz band and found that the seismic signature of Old Faithful is in the 8-24 hz range. It is assumed that only surface activities of the geysers produce such frequency levels and that much lower frequencies are generated by the deeper convective systems associated with the geothermal activity (Iyer, 1974).

D. GRAVITY

Gravity methods are designed to detect variations in the gravitational pull of the rocks which lie as much as several miles below the earth's surface. Since differences may be only on the order of 1 part or less in 10 million, it has been necessary to develop gravity instruments that measure changes less than one ten-millionth the total force of gravity. From these data, one can estimate the location and magnitude of the corresponding density variations in the underlying rocks (Dobrin, 1952). In prospecting for geothermal reservoirs, however, the use of gravity surveys has been inconclusive. Positive gravity anomalies due to increased density caused by hydrothermal alteration of the country rock are associated with some reservoirs, but are absent or even negative in others (Goforth et al., 1972, p. 77).

E. MAGNETICS

Magnetic prospecting involves the study of variations in the earth's magnetic field attributable to anomalous magnetic properties in relatively shallow subsurface rocks. Variations may result from changes in depth of buried magnetic rock materials, from changes in susceptibility, or from both (Dobrin, 1952). Magnetic lows resulting from demagnetization of magnetite, which begins at about 250°C, are associated with some geothermal reservoirs, but like the gravity surveys for geothermal sources, are absent or negative in others (Goforth et al., 1972, p. 77). In general, magnetic surveys are probably the geophysical tool least useful in defining geothermal drilling targets (Griscom and Muffler, 1971).

In some cases, very young intrusives and volcanic rocks associated with geothermal systems display positive magnetic anomalies. In most cases, however, so many factors influence the character of a magnetic map that it is difficult to interpret in terms of geothermal resources (Combs and Muffler, 1973).

F. ELECTRICAL RESISTIVITY

One recognized characteristic of all the known geothermal zones is their low electrical resistivity. This is due to the high temperature and salinity of the fluids and the high porosity of the enclosing rocks. High temperatures have been found in all types of rocks associated with geothermal zones; the undisturbed resistivities are in the range of 3.0 to 3000 ohm-meters. True resistivity within the geothermal source itself is always in the range of 0.5 to 5.0 ohm-meters (Meidav, 1971).

An electrical prospecting technique that is being increasingly used in geothermal exploration is the dipole-dipole array. This technique has been used by Risk, MacDonald and Dawson (1970) to outline the Broadlands field in New Zealand at depths of 1 to greater than 3 km. Greater depths can be attained (Keller, 1970) using very powerful sources and exceptionally well-grounded current electrodes. Effective dipole-dipole investigations require complicated data analysis and careful interpretation, but the method is logistically simple and is insensitive to rugged topography (Harthill, 1971; Combs and Muffler, 1973). Keller (1971, 1974) attributes electrical resistivity surveys with effectiveness in estimating both reservoir capacity and temperature because porous rocks containing hot ground water are commonly far more conductive than surrounding rocks. The most usual prospecting application of resistivity surveys is in the search for shallow mineral deposits and in engineering surveys (Dobrin, 1952).

Rex et al., (1971), in a combined geological, geochemical and geophysical survey in California, states: "Of all the conventional geophysical tools, electrical resistivity surveys appear to be the most used and useful technique for geothermal exploration." This is disputed by Goforth et al., (1972), who content that surveys "...keying on the decrease in electrical resistivity with increasing temperature and saline content have been useful in determining the lateral extent of known reservoirs but have not been responsible for the discovery of any new reservoirs." There is also some difficulty in interpretation which arises in trying to separate effects of highly saline ground waters from the temperature phenomena (Fuchs et al., 1973).

G. THERMAL SENSING: REMOTE AND DIRECT

There are three categories of thermal sensing: airborne, remote ground-based and direct. The first category covers the greatest area but is the least accurate, whereas the third offers the least amount of area covered but is the most accurate. The second category falls between these two in terms of area and accuracy.

Difficulties in the use of thermal sensing arise from the fact that background heat from solar radiation is about 20,000 times average earth heat flow from within. Further, differences in surface color, vegetation, texture and moisture content produce surface temperature variations many times greater than the increased heat flow expected from even shallow subsurface anomalies (Fuchs, 1973). In airborne surveys, nighttime data collection has been proven superior to daytime data collection. The plane, however, must be flown in straight lines and must make passes in the same direction to eliminate differences arising from flying with and against the wind (Stingelin, 1969). Wind movements along the ground have been found to interfere with thermal images, although this imagery generally enhances faults, lineaments and fracture traces. Surface weathering and vegetation camouflage infrared images, limiting their effectiveness. Conversely, some geothermal areas fail to produce thermal images. In the "blind" geothermal area near Marysville, Montana, airborne thermal imaging surveys recognized only two groups of warm trees. It was later noted that the trees had contracted some sort of tree illness (Blackwell, 1974).

Ground-based thermal infrared surveys prove most useful in the study of localized or nearby control areas. Lange and Avent (1973) used a radiation thermometer with precision in the -20° to $+75^{\circ}C$ range. They concluded that the study of steep slopes, which defy high-altitude airborne infrared surveillance accuracy, for the most part became simpler. Difficulties arise in heat measurements of snow and ice covered terrain, as it does in areas of heavy vegetation. Furthermore, observations must be carried out during clear weather and preferably in daylight hours due to the nightly ponding of cold air on some surfaces. Ground-based infrared surveys are difficult to carry out on volcano summits.

Direct thermal sensing is carried out usually with thermocouples or thermistors and, in some cases, mercury maximum or electric thermometers. Thermistors, electrical resistors whose resistance varies with temperature, measure temperature at one point. Two thermistors are needed to measure the temperature change with depth. Their voltage output is greater than that of thermocouples and their calibration time is shorter. A thermocouple can be calibrated to measure temperature differences as a function of depth directly, but thermocouple output voltage is small, making accurate determinations of small temperature differences difficult (Bullard, 1963). Thermometers are sometimes used for heat flow measurements.

The temperature gradient in boreholes can be determined by mercury maximum thermometers enclosed in sealed glass envelopes. They have, however, the disadvantage of taking a considerable time to come to equilibrium (Jacobs et al., 1974). The equilibration time complicates the gathering of many thermal measurements in this manner. There are, however, electrical thermometers which permit readout values instantly. Some provide digital output with 0.01°C resolution from -100°C to +200°C, the most commonly used range. The Hewlett-Packard Co. is marketing thermometers of this type presently.

TABLE: 3-1

INDIVIDUAL SURVEY COSTS

Reconnaissance Evaluation	$3-5,000/prospect
Photographic Geology	$1,000/prospect
Geologic Mapping	$4,000-6,000/month
Gravimetry	$4,000-6,000/month
Aeromagnetics	$2,000-5,000/prospect
Hydrochemistry	$5,000/25 samples
Infrared Surveys	$10-40/line mile, $8,000 minimum
Microearthquakes (MEQ)	$1,500/day, Average $15-20,000
Ground Noise (GN)	$1,000/day, Average $ 8-15,000
Electrical Resistivity (Dipole)	$1,000/day, Average $ 8-16,000
Electrical Resistivity (Soundings)	$1,000/day, Average $ 3- 8,000
Electromagnetic (EM) Soundings	$1,500/day, Average $ 5-10,000
Age Dating	$1,000/sample
Temperature Gradient Drilling (ΔT) (200-500 ft)	$4-10/ft $8-20,000 for 2,000 ft
Heat Flow	" +50% ΔT Hole
Deep Drilling	$50/ft, $350,000/hole

COST OF EXPLORATION - $/ACRE

	Acres 2,000	50,000
Reconnaissance	$1.00	0.20
Hydrochemistry	.50	0.20
Microearthquakes (MEQ)	5.00	0.50
Geologic Mapping	1.00	0.70
ER - EM - MT	3.00	1.00
ΔT Drilling	3.00	1.50
	$13.50	4.10
Interpretation and Overhead	2.00	2.00
	$15.50	$6.10
	$10.80/acre	

(From Koenig, 1974)

TABLE: 3-2

DRILLING COSTS FOR WELLS OF DIFFERENT DEPTHS

DEPTH RANGE (ft)	COST RANGE ($)
6,000 - 8,000	$300,000 - 520,000
8,000 -10,000	425,000 - 770,000
10,000 -15,000	635,000 - 1,055,000
15,000 -20,000	940,000 - 2,750,000

SOURCE: Data compiled by K.E. Brunot, now with Phillips Petroleum Company. NOTE: Costs are tangible and intangible, for exploratory, development and reinjection wells. Add approximately $100,000. for each exploratory well. In hot-water systems, one reinjection well is drilled for each development well and each successful exploratory well. (From Rex and Howell, 1973)

TABLE: 3-3

COSTS AT DIFFERENT DRILLING DEPTHS FOR HOT, DRY ROCK SYSTEMS

Energy Price Range (mill/kwhr)	Average Well Depths (ft)		
	Western U.S.	Mid Continent	Eastern U.S.
3.00 - 4.00	14,000 - 16,000	--	--
4.00 - 5.00	16,000 - 17,000	--	--
5.00 - 8.00	17,000 - 20,000	15,000 - 17,000	--
8.00 -12.00	20,000 - 30,000	17,000 - 22,000	15,000 - 18,000

[illegible] (From Rex and Howell, 1973)

[illegible]

PART B: GEOTHERMAL RECLAMATION TECHNIQUES

The actual harnessing of geothermal energy has taken many forms, from the simple concept of using naturally heated water for minor domestic heating purposes to forced steam systems. Hydrofracturing of rock at depth is a method advanced for the forced circulation and subsequent heating of cool water.

In the Klamath Falls, Oregon area, Peterson (1967, 1974) cites the usage of hot springs for the hot water supply of greenhouses, buildings such as schools and a medical center, homes and an inland fish hatchery. In most of these cases the mechanism for drawing out the heat lies in the form of radiator-type coils inserted to some depth in well casings. A water pump is located at the top of the wellhead and simply forces cool water down through the pipes. The water is heated and passes this heat out at the radiators which do the space heating. Temperature control can be obtained through the use of a motorized or solenoid valve operated by a thermostat. A rough estimate of the heat withdrawn from wells in the Klamath Falls geothermal zone amounts to about 3,000 to 4,000 BTU/sec. (There are 252 calories per BTU.) averaged over the year.

Another example of relatively low-temperature geothermal utilization is a system in the town of Melun, on the outskirts of Paris, France. A 3,000 room apartment building sits atop a pair of drillholes approximately 1800 m deep. Oil prospecting disclosed a 158°F hot water reservoir at 1800 m depth beneath the Paris Basin. Water is pumped down one of the anti-fouling titanium pipes inserted in the holes. The water then permeates through the subsurface strata and returns, heated, to the surface via the second pipe. The heated

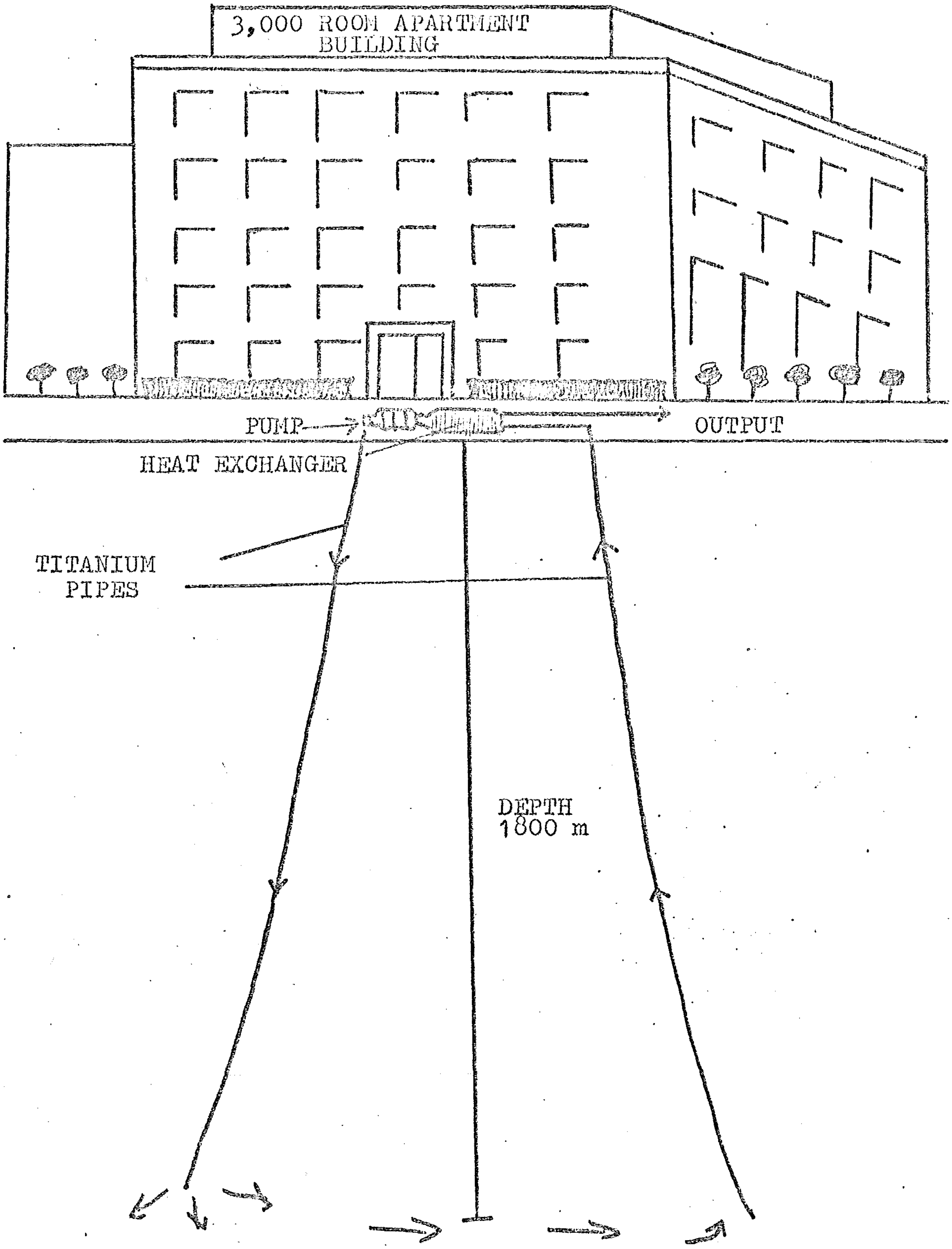


FIGURE: 3-1 GEOTHERMICALLY HEATED APARTMENT BUILDING IN MELUN, FRANCE

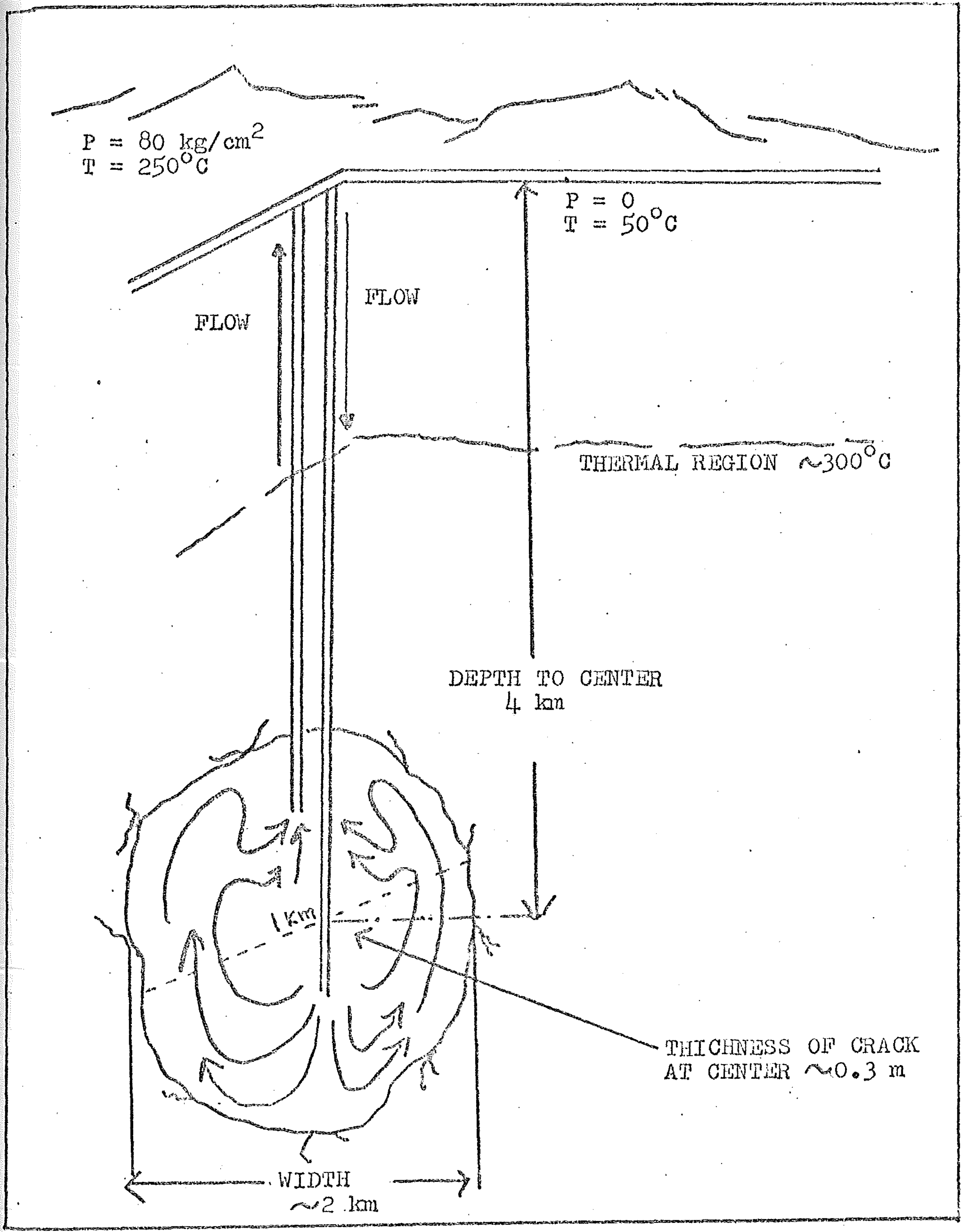
(After Kunze, 1974)

water passes through a heat exchanger and is fed throughout the entire giant building. Figure 3-1 illustrates the basic technical geothermal system in Melun. Sullivan (1974) estimates that about two-fifths of the building's annual hot water and heat needs are fulfilled but the reservoir is said to be large enough to provide service for 1 million apartments for 1300 years. The 1800 m depth gives sufficient heat for 3,000 apartments in a type of geothermal system that can probably be utilized anywhere (Kunze, 1974).

There are some homes and businesses in Iceland which utilize heat from near-surface pipes using essentially the same principle as those in Klamath Falls, Ore. The only difference is that in Iceland, where volcanism is much more recent, hot water for municipal heating was pioneered in the 1930's and approximately 50 percent of the population of 200,000 receives geothermal heating and this is to rise to over 60 percent this decade. Iceland's location, straddling a northern portion of the mid-Atlantic Ridge, provides it with centers of basaltic volcanism for the island's geothermal fields.

The reclamation of deep-seated geothermal energy which has no surface manifestations requires adequate drilling techniques to reach the thermal reservoir as well as the technology for transfer of the heat. The present drilling methods are costly, especially in areas of hard rock. In the Imperial Valley, for instance, to drill and complete a 3,000 ft well cost $125,000. For a 5,000 ft well the cost was $200,000. To drill and complete a 7,000 ft well in the Geysers area the cost was $350,000 (Cromling, 1973). Even the prices for drilling rights have soared in the last ten years.

FIGURE: 3-2
Proposed System For Developing The Los Alamos Geothermal Energy Source (From Robinson et al., 1971, p. 46)

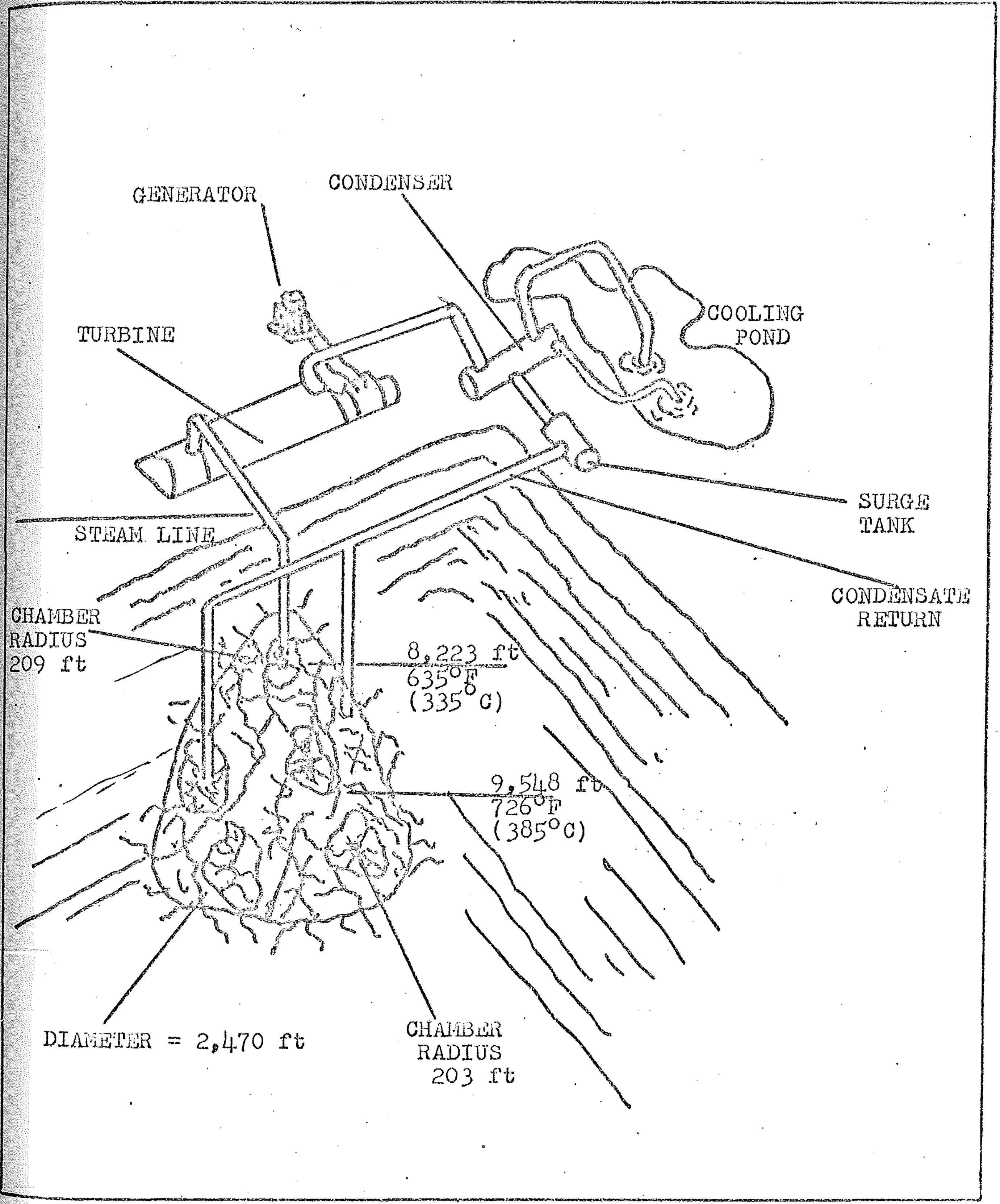


Drilling right prices around Pacific Gas & Electric's plant there skyrocketed from $.20 per acre in 1964 to the almost $1,360 an acre that Shell Oil recently committed itself to pay (TIME, 1974).

To try to alleviate some of the obvious problem with drilling deep holes, the Los Alamos Scientific Laboratories in New Mexico worked on the problem and the rock-melting drill was invented in 1960. Electrically heated, laboratory-scale drills were subsequently shown to penetrate igneous rocks at usefully high rates, with moderate power consumption. With these devices the potential exists of producing holes up to several meters in diameter and several tens of kilometers long or deep (Robinson et al., 1971). The system is said to be insensitive to composition, hardness, temperature and structure of the rock. It has also been shown to produce a self-supporting glass lining in most formations owing to the high amount of silica in the earth's crust. The problem of debris removal is also solved by this method. As the device heats and melts through the rock, it cracks surrounding rock and forces molten rock into those cracks. Lithofracturing, or the cracking of rocks, produces, also, an added area for fluids to contact. This principle was studied at Los Alamos for the purpose of stimulating a geothermal rock zone at depth, where there was no aquifer present and no steam. It is necessary to have a closed, pressurized circuit of water through a large zone fractured in hot, permeable rock (Harlow and Pracht, 1972) in order to extract heated fluid in this case. A perfect circuit may not be obtained due to leakage or other factors. For this problem Rex (1971) suggests a single cycle or "huff-puff" system in which water is forced in and then pumped

FIGURE: 3-3

A POWER PLANT USING THE PLOWSHARE GEOTHERMAL CONCEPT



(From Burnham and Stewart, 1973)

out. The rock must, however, be able to retain pressure for this system to work. Since cold water is more viscous than hot water, it would tend to sink and force up the hot water. Cooling the rock causes contraction, which in turn causes new cracks to form, which:

A. INCREASES the hot rock-water interface area,
B. ENHANCES heat transport by convection of water directly to and from hot rocks,
C. ENLARGES the area at the edge of the cracks for conduction from greater distances and
D. ALLOWS the cracks to penetrate into deeper rocks, where the temperature is greater.

The uncertainties of this method are mainly that the rocks may not contract enough to raise the permeability significantly and that any leakage in the system would sap pressure from the main circuit. Figure 3-2 illustrates the Los Alamos hot, dry rock lithofracturing method. If the Los Alamos plan workd, the energy could provide all the additional power the nation will require until thermonuclear fusion and solar sources are developed (Rex, 1974).

The Plowshare geothermal concept described by the American Oil Shale Corporation et al. (1971) entails the generation of power from the energy contained in deposits of hot, dry rock. The rock is first fractured by a number of nuclear explosions and water is then injected. Steam is then drawn off at the surface. The economics of this concept equate one cubic mile of rock at 350°C, when cooled to 150°C, to the energy equivalent of 300 million barrels of oil, worth approximately $1 billion today (Burnham and Stewart, 1973). (See figure 3-3.)

There are some hazards connected with the injection of fluids into the earth. A fundamental characteristic of many geothermal resource areas is their close association with regions of high geologic activity, which is manifested most commonly as earthquakes. Studies have shown that, if fluid pressure is changed in tectonically stressed areas, faults can vary their normal patterns of earthquake activity (Hickel, 1972).

In retrieving heat energy from hot rocks at depth, there must be some sort of heat transporting fluid or medium. In the cases of the shallow thermal wells in Oregon and Idaho, the medium is water which is passes through pipes. In the case of the steam-producing wells, the medium is water in the gaseous state. In the case of thermal springs the medium is, again, water. The operation of any geothermal processing plant must process the steam or water and return the cooled liquid into the ground. Those geothermal sites which are fortunate enough to be situated near or over aquifers have their water supplied naturally. The adequacy of fluid supply is likely to be more critical than adequacy of the heat reservoirs in limiting future utilization of geothermal energy.

Artificial recharge of aquifers has become a technical achievement. In Valley City, North Dakota, for instance, river water was diverted into the top ground surface of the sand and gravel aquifer. The system at work now is described by Kelly (1967) as being simple, efficient, dependable and low-cost for operating. It now supplies the city with water for domestic and industrial purposes. This type of cooling-recharge system for geothermal power plants is most economical for their purpose.

A more sophisticated method of heat transport was developed at the Los Alamos, New Mexico, Scientific Laboratories. Known as the Grover Heat Pipe, the device is explained as being a self-contained engineering structure which exhibits a thermal conductance greatly in excess of that which could be obtained by the use of a homogeneous piece of any known metal (Cotter et al., 1965). The two-phase fluid flow with capillary circulation allows heat to vaporize liquid at one end of the pipe, travel in the gaseous state to the other end and condense. then returns to the evaporator through a wick of suitable capillary structure.

The principle can theoretically be applied to a wide range of shapes, sizes, temperatures and materials. The development of the Heat Pipe for the reclamation of thermal energy from hot rocks at depth, especially if the use of water as a thermal transporting medium is not feasible, is seen as overly promising.

TABLE: 3-4

EQUATIONS OF HYDRAULIC AND THERMAL FRACTURING

---

1. Radius of Hydraulically-Induced Fracture:

$$R_f = K/(I_p)\frac{1}{3}$$

R_f = Hydraulic fracture radius
I_p = Injection pressure
K = S/P (Separation over Pressure)

2. Separation of Fracture:

$$B = 8(1-V^2)(p_o-\gamma h)\alpha^2 \; a'/\pi E$$

B = Maximum separation of hydraulically induced fractures
V = Fluid Velocity
p_o = Injection pressure at the well site
γ = Average specific weight of (rock + contained water)
h = Depth of hydraulically induced fracture
$\alpha = (a/a')^{\frac{1}{2}}$
a = Fracture radius
a' = Radius of the stress-altered region
$\pi = 3.1416$
E = Young's Modulus (stress/strain)

(From Sun, 1969)

3. Thermal Fracturing Propagation Equations:

A. Conservation of mass for water:

$$\partial \rho w\theta/\partial t + \nabla \cdot \rho wu\theta = \rho wS$$

B. Conservation of momentum for water:

$$\nabla P - gPw + (\mu\theta/K)u = 0$$

C. Conservation of heat energy in water and rocks:

$$\partial\{[b_R \rho_R \; (1-\theta)+bw\rho w\theta] \; T\}/\partial t + \nabla \cdot \rho wbw\theta uT = \nabla \cdot [K_R(1-\theta)\nabla T] + \rho wbwT_sS$$

θ = Porosity, open volume for water flow (per unit volume)
ρw = Water density, a function of temperature
ρR = Rock density
S = Source or sink of water from surface pipes (Vol/vol/time)
g = Acceleration of gravity
μ = Coefficient of water viscosity, a function of temperature
K = Permeability, a function of crack spacing
b_R = Specific heat of rock
b_W = Specific heat of water
u = Water velocity
P = Water pressure
T = Temperature
T_s = Source or sink temperature
K_R = Heat conduction coefficient for rock

(From Kennedy, 1944)

CHAPTER IV: GEOLOGY OF NEW ENGLAND

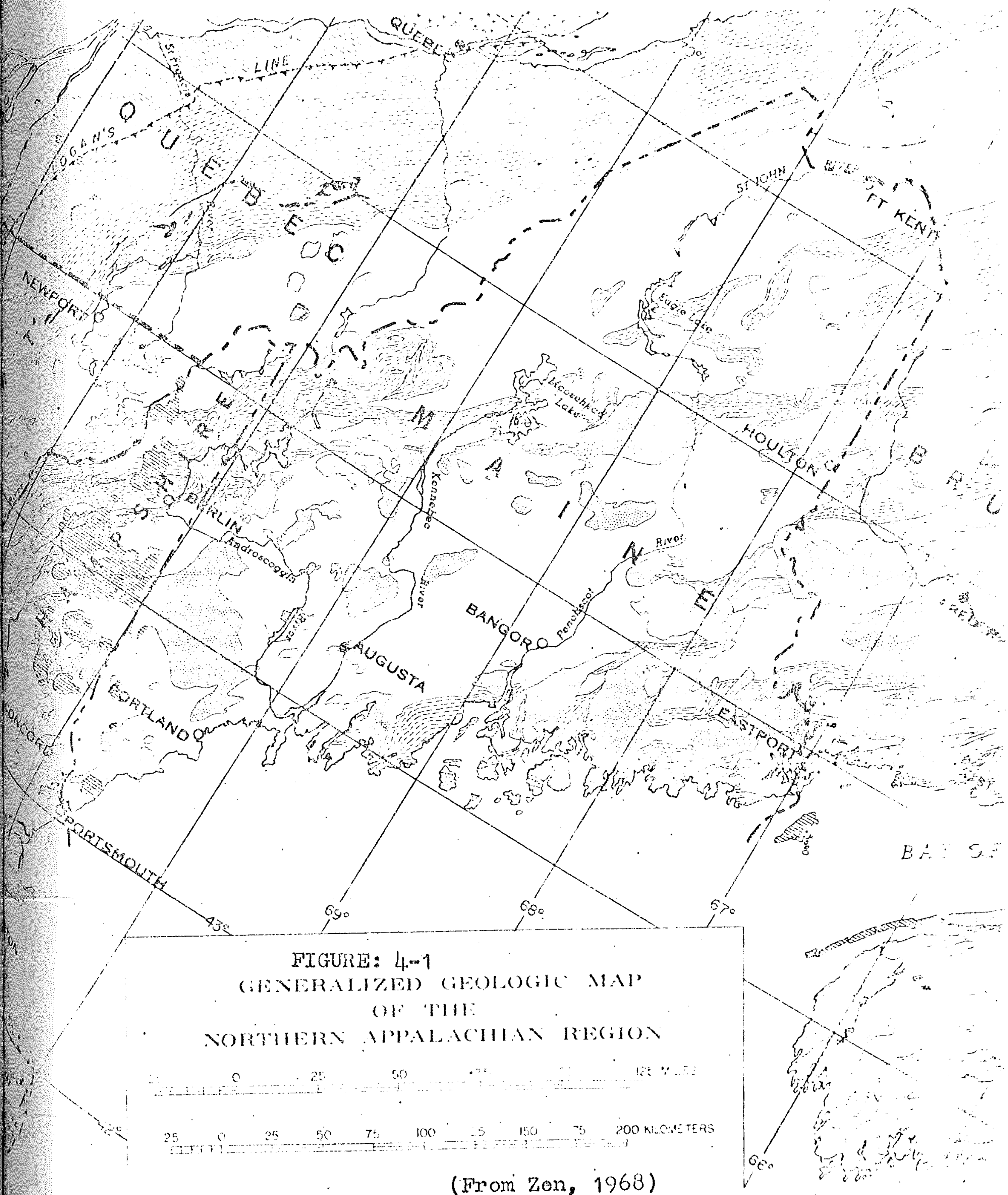
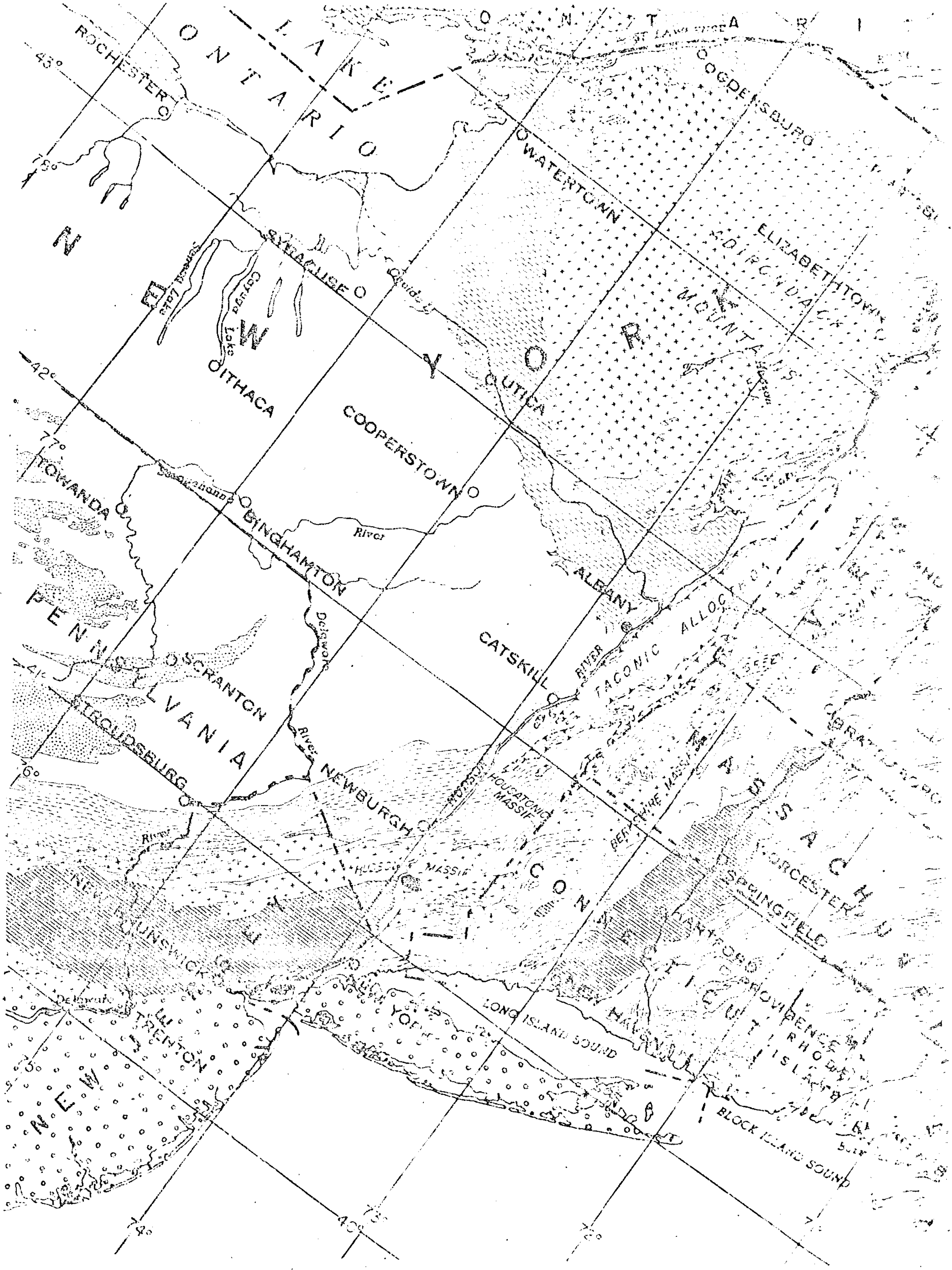
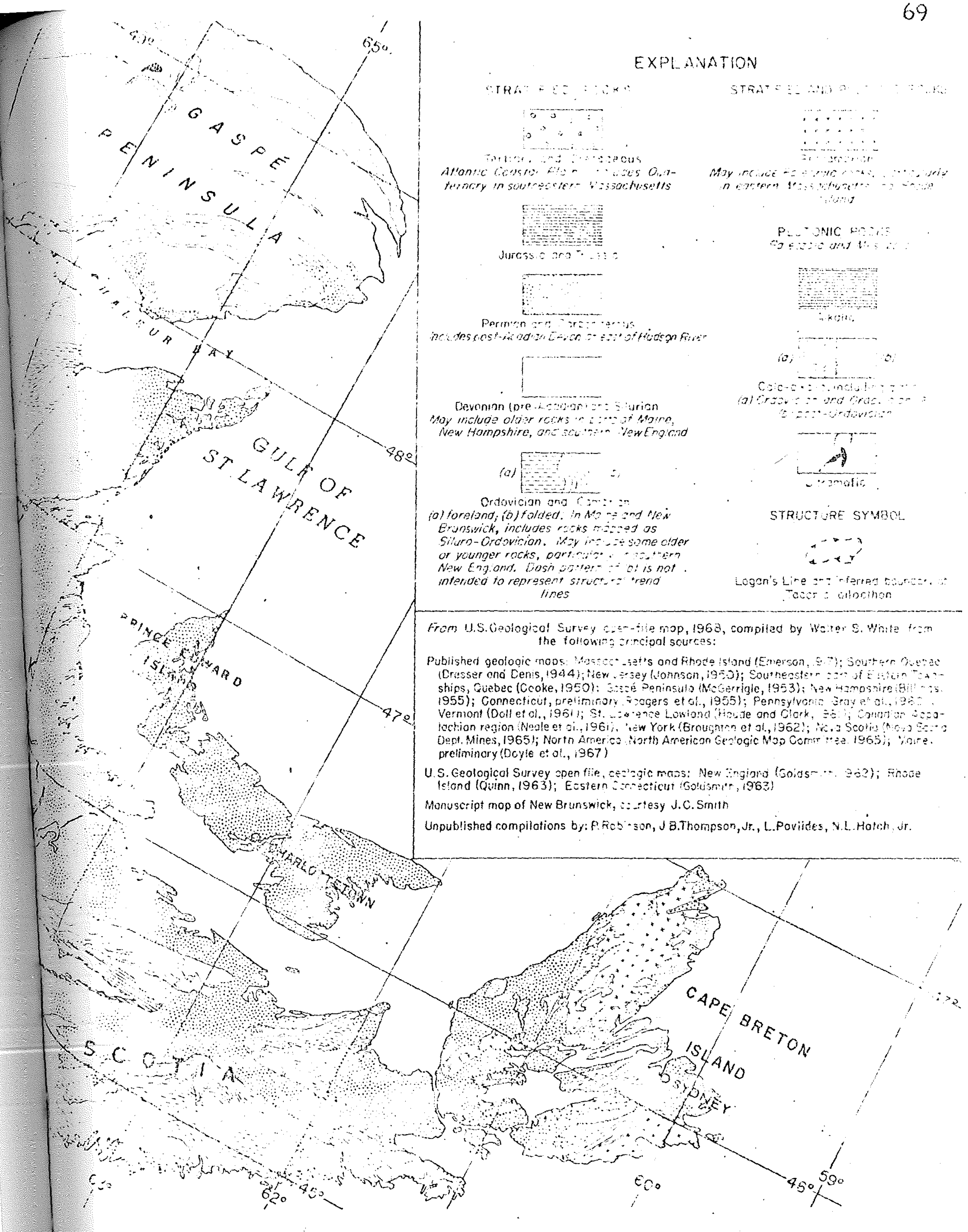


FIGURE: 4-1
GENERALIZED GEOLOGIC MAP
OF THE
NORTHERN APPALACHIAN REGION

(From Zen, 1968)


LAKE ONTARIO
ONTARIO
ST. LAWRENCE
ROCHESTER
OGDENSBURG
WATERTOWN
ELIZABETHTOWN
ADIRONDACK MOUNTAINS
SYRACUSE
Oneida L.
Seneca L.
Cayuga Lake
NEW YORK
UTICA
ITHACA
COOPERSTOWN
TOWANDA
Susquehanna
BINGHAMTON
River
ALBANY
CATSKILL
River
TACONIC ALLOCHTHON
PENNSYLVANIA
SCRANTON
STROUDSBURG
Delaware
River
NEWBURGH
HUDSON
HOUSATONIC MASSIF
BERKSHIRE MASSIF
HUDSON MASSIF
MASSACHUSETTS
WORCESTER
SPRINGFIELD
BRATTLEBORO
CONNECTICUT
HARTFORD
NEW HAVEN
PROVIDENCE
RHODE ISLAND
NEW BRUNSWICK
NEW YORK
TRENTON
Delaware
NEW JERSEY
LONG ISLAND SOUND
BLOCK ISLAND SOUND
43°
42°
41°
40°
78°
77°
76°
74°
73°
72°
71°



From U.S. Geological Survey open-file map, 1968, compiled by Walter S. White from the following principal sources:

Published geologic maps: Massachusetts and Rhode Island (Emerson, 1917); Southern Quebec (Dresser and Denis, 1944); New Jersey (Johnson, 1950); Southeastern part of Eastern Townships, Quebec (Cooke, 1950); Gaspé Peninsula (McGerrigle, 1953); New Hampshire (Billings, 1955); Connecticut, preliminary (Rodgers et al., 1955); Pennsylvania (Gray et al., 1960); Vermont (Doll et al., 1961); St. Lawrence Lowland (Houde and Clark, 1961); Canadian Appalachian region (Neale et al., 1961); New York (Broughton et al., 1962); Nova Scotia (Nova Scotia Dept. Mines, 1965); North America (North American Geologic Map Committee, 1965); Maine, preliminary (Doyle et al., 1967)

U.S. Geological Survey open file, geologic maps: New England (Goldsmith, 1962); Rhode Island (Quinn, 1963); Eastern Connecticut (Goldsmith, 1963)

Manuscript map of New Brunswick, courtesy J.C. Smith

Unpublished compilations by: P. Robinson, J.B. Thompson, Jr., L. Pavlides, N.L. Hatch, Jr.

THE MAJOR TECTONIC FEATURES OF NEW ENGLAND

In an assessment of the geothermal potential of a region such as New England, major structural features and their possible relationship to sources of deep, circulating hot waters must be considered.

The major tectonic and structural features of New England include anticlinoria and anticlinorial massifs, synclinoria, overthrust masses, domes, basin structures and larger fault systems (figure 4-2). An inventory of such structures follows:

a. Anticlinoria and anticlinorial massifs: The Green Mountain Anticlinorium of western Vermont, the Berkshire Massif of Massachusetts, the Housatonic and New Milford Massifs of Connecticut and the Hudson Massif of New York.

b. Synclinoria: The Connecticut Valley-Gaspé and Merrimac synclinoria, located in central New England and Quebec, the former lying west and northwest of the latter.

c. Taconic Allochthon: Thrust sheets of eastern New York and western Massachusetts and Vermont

d. Domes: There are at least 16 domes in Vermont, New Hampshire and the central part of southern New England which have deformed the nappes of central New England.

e. Basin structures: The Norfolk, Narragansett and Boston Basins deformed in Permian Time; and the Triassic Basin, developed in Mesozoic Time.

f. Fault Systems - The major fault systems are:

MAINE - The preliminary geologic map of Maine (1960) shows a number of faults which may be of greater importance and extent than was recognized at the time that the map was published. Five major faults and fault zones have been recognized in Maine; the longest extends from the vicinity of Westbrook to the northeast to Bangor and another from Casco Bay to near Bangor and may connect with the previous one which extends still further to the northeast into southwestern New Brunswick (Hussey and Osberg, oral communication, 1974). Another major fault extends from near Flagstaff Lake (western Maine) to Moosehead Lake; and finally, a series of faults of diverse orientation has been mapped near Houlton and Presque Isle, Me. There is also a cluster of generally southwest-northeast trending faults in western Me.

NEW HAMPSHIRE - The major faults of western New Hampshire and Vermont are, from west to east respectively, the Monroe Thrust, the Ammonoosuc Thrust and the Northey Hill Thrust.

VERMONT - The major faults of western Vermont are: the Highgate Springs Thrust, the Champlain-Orwell Thrust Fault system, the Hinesburg Thrust, the Pine Hill Thrust, the Dorset Mt. Thrust, the Maple Hill Thrust, the Hoosac and Hoosic Thrust and a variety of less well-known normal faults and thrusts such as that in the Bennington, Vt.-Williamstown, Mass. Valley.

EASTERN NEW YORK - The major fault system in the eastern part of the state is the Champlain Fault.

MASSACHUSETTS - Western Mass. has a number of thrust and normal faults that are either similar to or continuations of those described above for Vermont. In the eastern part of the state, the Clinton-Newbury Fault is probably the largest and most extensive, possibly connecting with the Lake Char Fault in Conn. Other faults in eastern Mass. include the Spencer Brook Fault, the Assabet River Fault, the Bloody Bluff Fault zone, the Mystic Fault, the Northern Border Fault and the Ponkapoag Fault.

CONNECTICUT - The major fault systems of Connecticut are the Lake Char Fault, which may connect with the Clinton-Newbury Fault in Massachusetts, and the Honey Hill Fault.

RHODE ISLAND - There are no major faults in Rhode Island, however, some faults offset the Narragansett Basin.

PLUTONIC AND VOLCANIC ROCKS

The plutonic and volcanic rocks of New England include the White Mountain Plutonic-Volcanic Series, the New Hampshire Plutonic Series, the Oliverian Plutonic Series and the Highlandcroft Plutonic Series. Billings (1956) summarizes them as follows:

a. White Mountain Plutonic-Volcanic Series...
It is consolidated from magma. Thicknesses of 10,000 ft. of the Moat Volcanics indicate the large quantities of magma as flows and pyroclastic rocks. The structural relationships are discordant bodies such as ring-dikes, stocks and a batholith. The series became progressively more siliceous with time, progressing from gabbro through diorite, monzonite, syenite and quartz syenite to granite.

b. New Hampshire Plutonic Series...
The origin of the magmas of this series is problematical. Although they may be differentiates from basalt, they may equally well be melted up older rocks or granitized sediments that moved up from greater depths.

c. Oliverian Plutonic Series...
Most published papers have considered the Oliverian plutonic series to be magmatic; however, there are facts that suggest to some observers that the Oliverian consists largely of metamorphosed volcanic rocks while some facts suggest to other observers that the Oliverian is magmatic. The series shows considerable range in composition and may be a product of the fractional crystallization of basalt but other possibilities cannot yet be ruled out.

d. Highlandcroft Plutonic Series...
The Highlandcroft plutonic series is considered to be magmatic. Indications point to its consolidation from a melt. Moreover, dikes of the Highlandcroft series cut the older rocks and some plutonic breccias have developed.

Refer also to figure 4-3 showing distribution of Devonian plutonic rocks in New England.

GEOTHERMAL FEATURES

Of the tectonic features of New England the most pertinent, for this report, are the Taconic Allochthon, the Merrimac Synclinorium and the Clinton-Newbury Fault zone. Each possesses some possibility of yielding abnormally high amounts of natural heat. The Taconic Allochthon is the site of numerous joint and fault systems resulting from the initial overthrusting and metamorphism. It possesses at least two reported thermal springs; one of which (Sand Spring in Williamstown, Massachusetts) is the northernmost which is known in the eastern United States (Waring, 1965). The Merrimac Synclinorium encloses an area intruded by the White Mountain Magma Series, of which the Conway Granite, having a high content of radioactive heat sources, is a constituent. The Clinton-Newbury Fault zone is perhaps the most prominent and possibly the most extensive fault zone in southeastern New England. If the fault penetrates to sufficient depth, as it seemingly must, and has been active in relatively recent geologic time (which is not definitely certain), there is a possibility of ground water being heated at depth and percolating along fractures to the surface or to levels near the surface.

Given the situation of global energy allocation and development, any natural heat energy which might be tapped from any of these sources for some sort of utilization would represent an enormously significant quantity. These possible sources of New England area geothermal energy are thoroughly discussed in the following chapter.

FIGURE: 4-2 TECTONIC MAP OF SOUTHERN NEW ENGLAND AND SOUTHWESTERN NEW YORK

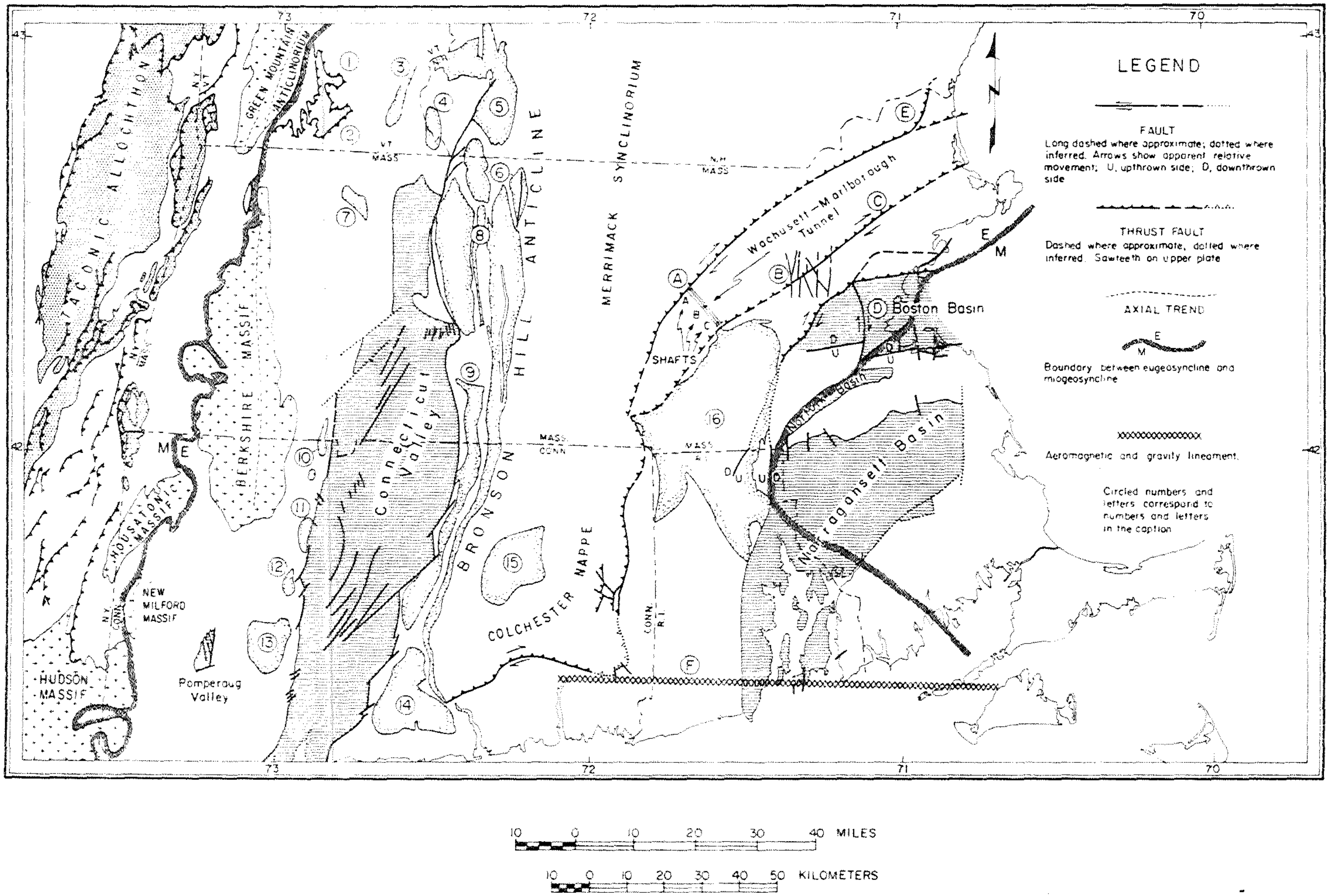
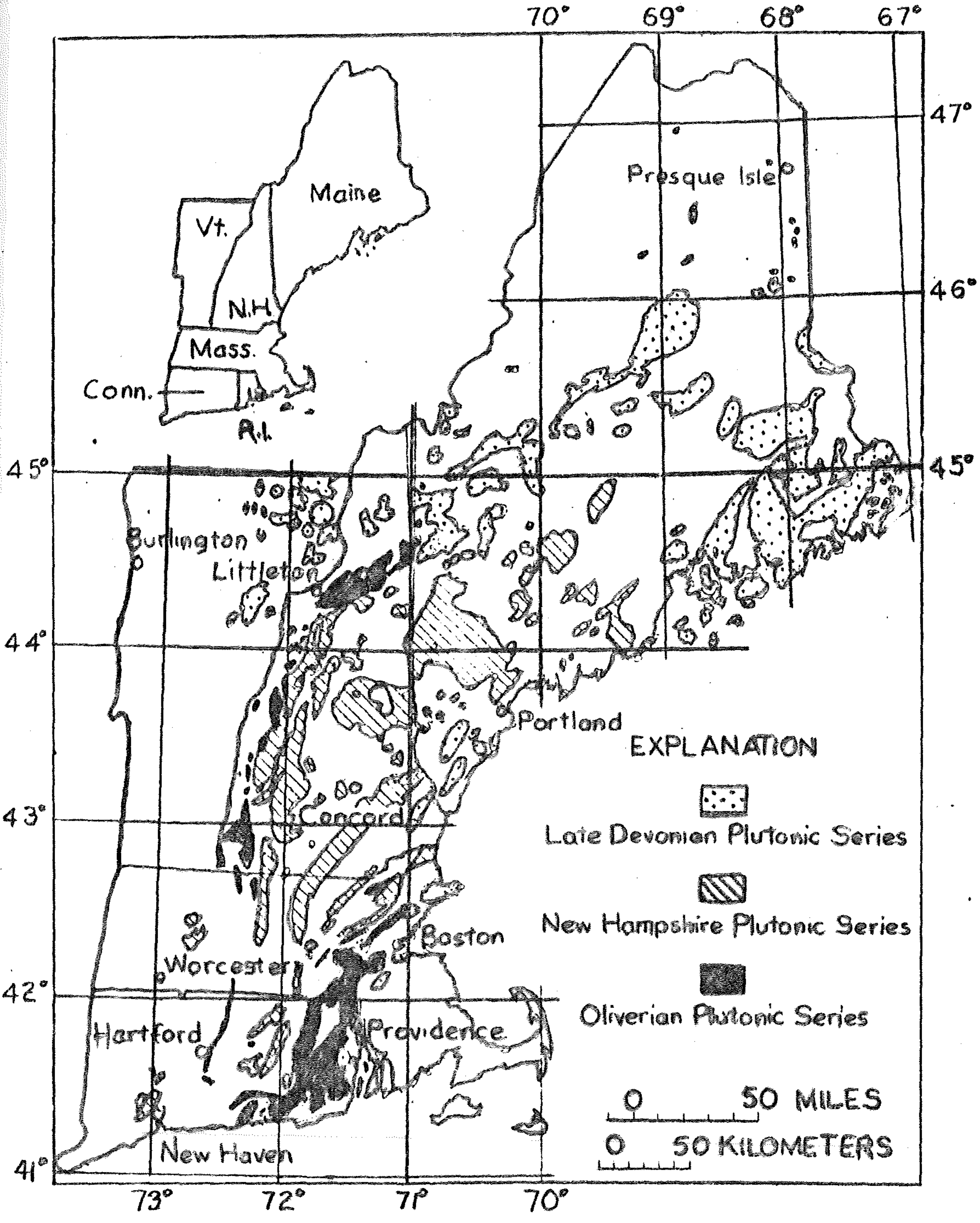


FIG. 1.—Tectonic map of southern New England and southeastern New York. *Domes:* (1) Lake Raponda dome, (2) Sadawga dome, (3) Guilford dome, (4) Vernon dome, (5) Swanzey dome, (6) Warwick dome and Tully body of Monson Gneiss, (7) Shelburne Falls dome, (8) Pelham dome, Kempfield anticline, and main body of Monson Gneiss, (9) Glatsonbury dome, (10) Goshen and Granby domes, (11) Collinsville dome (Stanley, 1964), (12) Bristol dome, (13) Waterbury dome, (14) Haddam dome, (15) Willimantic dome (Goldsmith, 1962), (16) Milford dome (Page, 1968).

FIGURE: 4-3



Distribution of Devonian rocks in New England. Outline of plutons based on compilations by Goldsmith (1964) and Doyld (1967).

(From Page, 1968)

TABLE: 4-1
TIME LINE OF GEOLOGIC EVENTS AFFECTING THE NEW ENGLAND AREA

MIOCENE: Miocene rocks are found in Martha's Vineyard.

CRETACEOUS: Deposition along coastal plain, conglomerates, sands, muds.

EARLY TRIASSIC: White Mountain Magma Series.
Tensional deformation.

----------- ALLEGHENIAN UNCONFORMITY ---------

PERMIAN: Alleghenian Orogeny.

PENNSYLVANIAN: Mississippian and Pennsylvanian deposition confined chiefly to basins, coal forms.

UPPER DEVONIAN: Post-tectonic, peraluminous granitic intrusions.

------------- ACADIAN UNCONFORMITY ----------

DEVONIAN: Acadian mountain building, plutonism and metamorphism.
Siluro-Devonian rocks are found east of the Green Mountain Anticlinorium and occur around the domes and in the Merrimac Synclinorium.
Slates and limestones.

SILURIAN: Siluro-Devonian volcanics along the coast of New England, as exemplified by the Lynn Volcanics.

LATE ORDOVICIAN: Quartz-pebble conglomerates, quartzites.

------------- TACONIC UNCONFORMITY ----------

MID-ORDOVICIAN: Taconic mountain building, plutonism and metamorphism.
Development of faults and grabens, tensional deformation.
Black mud and graywacke deposition.

Carbonate deposition, some metamorphism.

CAMBRIAN: East coast submerged, minor volcanism.
Eugeosynclinal rocks, intensely folded, sheared and variably metamorphosed.
Formation of nappes.

PRECAMBRIAN: Basement massifs emplaced

(Adapted from Atwood, 1940; Boucot, 1968, Cady, 1968; Dixon and Lundgren, 1968; Green and Guidotti, 1968; Harwood, 1975; Osberg et al., 1968; Page, 1968; Rankin, 1968; Skehan, 1961, 1969; Theokritoff, 1968; and Zen, 1968)

CHAPTER V: NEW ENGLAND GEOTHERMAL AREAS

PREFACE

Since the bedrock formations of the New England area range from Precambrian to Cenozoic in age and the evolution of its structures is intensely complex, any possibilities for the discovery of heated areas of crust would depend upon relatively recent volcanism, radioactivity or deep-seated faults, possibly in conjunction with natural springs. Such areas will be thoroughly examined for geothermal indicators.

The most recent volcanism in the New England area ranges from Cretaceous to Early Cenozoic or about 185-60 million years old and is represented by the White Mountain Magma Series in New Hampshire. The highly radioactive Conway Granite of this Series possesses a few observed locations of abnormally high heat flow.

Waring (1965) reports two natural thermal springs in the New England area. One is in Williamstown, Massachusetts and the other is in Lebanon Springs, New York. A third thermal spring has also been reported (Hansen, 1975, oral communication) approximately one mile from the Sand Spring system in Williamstown. A reconnaisance survey of these springs by the author reveals that these warm springs are part of larger geohydrologic systems.

Section A will be concerned mainly with the Conway Granite and section B will examine the Williamstown and Lebanon Spring thermal water systems.

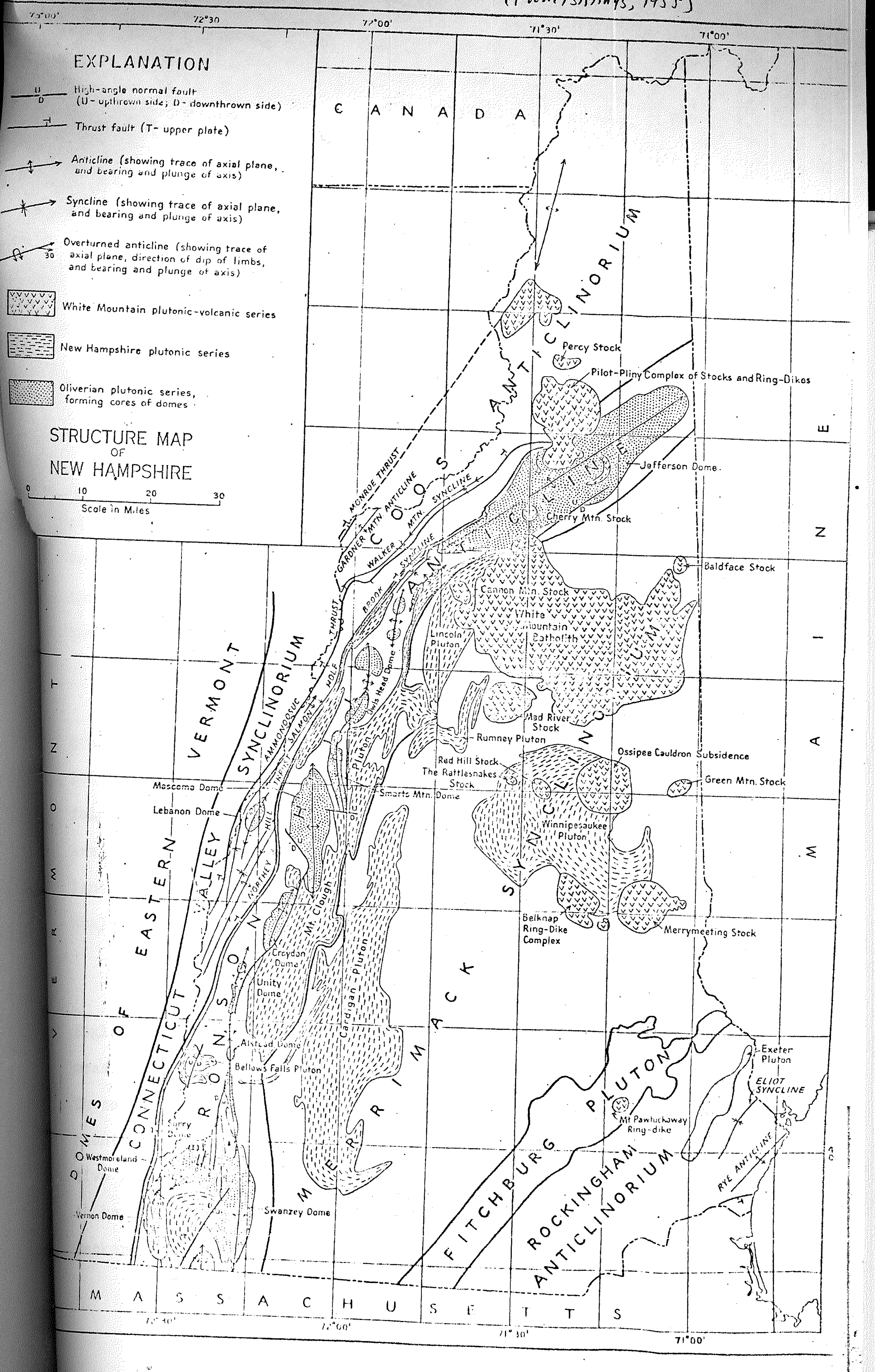
SECTION A. THE CONWAY GRANITE

GEOLOGY

Billings (1956) describes the distribution of the Conway Granite as being the most extensive single unit in the White Mountain Magma plutonic-volcanic series. It is found north and south as well as in and near the White Mountain batholith (fig. 5-1). In all, there are eighteen outcrops in New Hampshire of the Shite Mountain plutonic-volcanic series, the largest being the White Mountain batholith, located in north-central New Hampshire.

Birch et al. (1968) state that after about 10 km of Ordovician and Silurian sediments covered a broad strip of north-northeasterly strike, during a period estimated to be 100 m.y. in length, the deposition rate increased during the early Devonian and 15 km or more of sediments were deposited in about 50 m.y. Then deformation, uplift and erosion followed and were accompanied by the emplacement of the New Hampshire Plutonic Series, approximately 360 m.y. ago (Wilson, 1965; Handford, 1965). Regional metamorphism of surrounding rocks to high grades also occurred at this time and was followed by a Permian episode of metamorphism in central southern New England. Erosion and uplift continued into Triassic Time. Mafic volcanism accompanied the development of Triassic basins while the White Mountain Plutonic Series was emplaced along a generally N 10° W trend from near Boston to Montreal with the Conway Granite as one of the early intrusives. The depths of emplacement of White Mountain intrusives suggested by apatite fission track ages and Lovering's (1935) model indicate an uplift rate of 30 m/m.y. for the Mid-Mesozoic (190-120 m.y.) to present.

FIGURE: 5-1
STRUCTURAL MAP OF NEW HAMPSHIRE
(From Billings, 1955)



Hitchcock (1877) named the Conway Granite for massive, coarse-grained granite that forms cliffs and ridges on the east and west sides of the Saco River Valley near North Conway, New Hampshire. It is well exposed in the Redstone Quarries, 2.8 miles north-northeast of Conway, New Hampshire. Outcrops occur at the southeast edge of the White Mountain Batholith, in the central stock of the Ossippe Mountains, in Green Mountain and in the Whale's Back Stock (not seen on Billings' map, fig. 5-1, but located at the center of the New Hampshire-Maine state line).

MINERALOGY

Conway Granite is best described as being medium to coarse-grained, light pinkish to buff-colored, equigranular biotite granite. The biotite is the iron-rich lepidomelane. The quartz and feldspar grains are 7-12 mm in diameter and accessory minerals are hastingsite, fayalite, apatite, zircon, rutile, fluorite, allanite and molybdenite (Wilson, 1969). For modes and chemical analyses of the Conway Granite refer to tables 5-2 to 5-4.

HEAT FLOW

Heat flow measurements were made in twenty-two sites in New England and New York by Birch et al. (1968) and the three highest measured values were obtained in New Hampshire (see table 5-5). These high values (greater than 1.9 μcal/cm^2 sec) in the White Mountain Magma Series relate to the Conway Granite's high radioactive heat generation. The depth of high radioactivity is estimated to be 4-6 km deep on the southern and western margins (Roy and Decker, 1965).

Several methods of isotope dating were carried out in Redstone Quarry. They were Pb-Pb, Pb-alpha, U-Pb (both) and Th-Pb methods used on zircon or thorite; and K-Ar and Rb-Sr methods used on biotite. The average date arrived at for the Conway Granite by these methods was 185 m.y., or Early Jurassic age. Table 5-5 illustrates the heat production from radioactivity in a number of samples from the Conway Granite. Included is a summary of thorium and uranium in parts per million and potassium in percent. (It may be helpful to refer back to table 2-4 for a comparison of heat production by igneous rocks due to radiogenic ions. Thorium, uranium and potassium are listed.) The average world value for terrestrial heat flow is approximately 1.5×10^{-6} μcal/cm^2 sec (Lee and Uyeda, 1965; Simmons and Horai, 1968). The values found at investigated sites in New Hampshire, at least the highest ones, are 1.95 in North Conway, 2.21 in Waterville and 2.13 in Kancamagus. These heat flow values by Birch et al. (1968) were obtained in areas of natural heat flow values (theoretically excluding radiogenic heat production) of approximately 1.6×10^{-6} μcal/cm^2 sec.

A correction for the finite size of the body of Conway Granite establishes the best heat flow site as being at the center of the outcrop since the surrounding rocks are roughly half as radioactive as the Conway Granite. Similar correction by Birch et al. (1968) establishes that the values of heat flow at the Waterville and North Conway sites should be raised approximately 10% over their listed values.

TABLE: 5-1

DESCRIPTION OF WHITE MOUNTAIN PLUTONIC-VOLCANIC SERIES

1. Stratigraphic age	Younger than Lower Devonian rocks
2. Age relative to regional metamorphism	Younger
3. Consanguineous volcanics	Present
4. Foliation	Very rare
5. Lineation	Absent
6. Texture	Hypidiomorphic granular
7. Pegmatite	Rare
8. Structural relations	Discordant: ring-dikes, stocks and batholiths
9. Origin	Magmatic
10. Mineralogy:	
(a) Olivine	Present in gabbro as chrysolite (olivine) and in quartz syenite and granite as fayalite
(b) Pyroxene	Present throughout series; chiefly diopside-hedenbergite series; some augite in gabbro, a little aegerine-augite in special types
(c) Amphibole	Present throughout series; common hornblende in mafic end of series; hastingsite, soda hornblende and riebeckite in siliceous end of series
(d) Biotite	Persistent but relatively less important than other mafic minerals
(e) Muscovite	Absent
(f) Quartz	Generally confined to rocks with high ratio of potash feldspar to total feldspar
(g) Nephelite and sodalite	Present but rare

(After Billings, 1956)

TABLE: 5-2

APPROXIMATE AVERAGE MODE OF THE CONWAY GRANITE

MINERALS	% OF TOTAL VOLUME
Quartz	29
Potash feldspar	59*
Plagioclase	7
Olivine	
Pyroxene	
Amphibole	tr
Biotite	5
Opaque oxides	tr
Opaque sulfides	tr
Nephelite	
Sodalite	
Apatite	tr
Accessories and alteration minerals	12

* Chifly microperthite, but also some orthoclase and anorthoclase....the biotite is lepidomelane

(From Billings, 1956)

TABLE: 5-3

MODES OF CONWAY GRANITE

	BM-1	BM-2	73	68	330
QUARTZ	33	31	32	39	26
MICROPERTHITE	51	43	42	38	64
ALBITE	13	20	21	19	4
BIOTITE	2	6	4	5	5
ACCESSORIES	1	tr	tr	tr	1

Locations and details of the specimens:

BM-1	Average of two thin section modes, B&M Ledge Quarry
BM-2	Average of six macro-point counts on six sawed slices of granite from the B&M Ledge Quarry. Four slices were treated with HF acid and cobaltinitrite to aid in distinguishing K^- from Na^- feldspar.
73	Summit of Birch Hill, one mile N.35°W. of the B&M Ledge Quarry
68	Summit of Albany Ledge, one mile N.40°E. of the B&M Ledge Quarry
330	Elevation 1700 ft., 0.3 mile southwest of Hanson Top on Green Mt.

(From Wilson, 1969)

TABLE: 5-4

CHEMICAL ANALYSIS OF MINERALS IN CONWAY GRANITE

MINERALS	%
SiO_2	35.37
TiO_2	3.20
Al_2O_3	13.43
Fe_2O_3	4.32
FeO	27.26
MnO	0.26
MgO	4.03
CaO	0.69
Na_2O	0.88
K_2O	7.86
H_2O+	2.03
H_2O-	nd
BaO	nd
Cr_2O_3	nd
TOTAL	99.33

(From Wilson, 1969)

TABLE: 5-5

RADIOACTIVITY, HEAT GENERATION AND HEAT FLOW IN NEW HAMPSHIRE

STATION	N.LAT.	W.LONG	COLLAR ELEV., METERS	DEPTH†, METERS	NO. OF SAMPLES	Th, PPM	U, PPM	K,%	A**
KANCAMAGUS*	44°02'	71°29'	730	170-305	557	59	15.8	4.0	20.5
NORTH CONWAY*	44°04'	71°10'	195	120-215	145	52	12.6	4.3	17.5
NORTH HAVERHILL	44°06'	72°00'	180	150-240	---	--	----	---	----
WATERVILLE*	43°56'	71°32'	400	240-320	349	61	15.9	4.1	10.9

* Data from Conway Granite of White Mountain Magma Series

** A = Heat generation in 10^{-13} cal/cm^3 sec.

† DEPTH: This is the interval used for the computation of heat flow

	HEAT FLOW,[1] 10^{-6} cal/cm^2 sec.		
	UNCORRECTED	TOPOGRAPHY CORRECTED	GEOLOGY CORRECTED
KANCAMAGUS	2.40 .02	2.27	2.13
NORTH CONWAY	2.04 .04	1.89	1.95
NORTH HAVERHILL	1.41 .01	1.34	1.21
WATERVILLE	2.53 .06	2.15	2.21

1) Heat Flow: "Uncorrected" from combination of gradients and conductivities, with statistically determined standard errors. "Topography corrected" from temperature change in reference plane. Values at North Conway and Waterville: 1.77 and 2.01 respectively before correction for radioactivity contrast

(After Birch et al., 1968)

SECTION B. THE THERMAL SPRINGS OF WILLIAMSTOWN, MASSACHUSETTS AND LEBANON SPRINGS, NEW YORK

FIGURE: 5-2

LOCATION OF NEW ENGLAND AREA THERMAL SPRINGS

From Stearns et al. (1937)

SAND SPRING

The history of Sand Spring, Williamstown, Massachusetts, as a thermal spring is recorded by New England area Indians as being a landmark and campground for hunting and war parties among the five Indian nations and other tribes (Carlin, 1972). It lay near the intersection of an important north-south trail and the Mohawk Trail. Early settlers also used the spring for medicinal as well as domestic purposes. Graylock Hall, a popular health spa of its day, was built on the spring site in the 1880's and included a hotel which had 26 large baths and 6 sunken bathing pools which were fed by the thermal spring's mineral water. The baths supplied to the guests were warmed in the same fashion. The hotel was advertised as a "slice of metropolitan life and luxury" and lodged 250 people and seated 200 in its dining room.

The spring is actually located in the forested north part of Williamstown, Massachusetts near the conjunction of the three states of Vermont, Massachusetts and New York. It is the only reported thermal spring system in Massachusetts and only the second reported thermal spring in the entire New England area. According to Stearns et al. (1937) and Waring (1965) it is the northernmost such system that is known in the eastern United States and is approximately 30°F warmer than shallow well waters. The thermal waters are believed to percolate up through thick beds of white sand and sandstone from a depth of 3,000 ft (Carlin, 1972). The water temperature is reported to be a constant 76°F (24.44°C)(Waring, 1965) and steams in cold weather. Reportedly, the spring never freezes.

Stearns et al. (1937) reported Sand Spring to be 76° F and to flow at 400 gal/min as Waring reported in 1965. Hansen et al. (1974) list the temperature at 72°F.

GEOLOGY

Emerson (1916) gives the local geology of the Sand Spring area to be chiefly Stockbridge Limestone, a coarse, granular variety of limestone of various colors. Emmons (1842) describes Williamstown as the type locality for Stockbridge Limestone. Pumpelly et al. (1891) illustrate the Stockbridge Limestone of Williamstown bordered to the west by the Berkshire Schist and to the east by the Vermont Formation, which is clarified by Emerson (1916) to be Cheshire Quartzite. Dale (1923) suggests the contact of Berkshire Schist and Cheshire Quartzite with the Stockbridge Limestone in the immediate vicinity of Sand Spring. The thermal waters which permeate to the surface probably flow through these Precambrian and Lower Paleozoic rocks at the formation contacts. The thermal waters, upon reaching the surface, are only moderately mineralized and, according to Stearns et al. (1937) and Waring (1965) the water penetrates to considerable depth, is heated, and returns along fractures to the surface. It has not yet been determined if the spring's tepid water has undergone cooling by subsurface lateral flow or by mixing with cooler water from either groundwater runoff or cool spring water. Hanson et al. (1974) list analyses for the waters of Williamstown (Table 5-6). It is suspected by the author that these springs of the Sand Spring system are much warmer at depth. Chemical analyses

TABLE: 5-6

CHEMICAL ANALYSES OF SPRINGS IN WILLIAMSTOWN, MASSACHUSETTS

Local Well #	S2	S2	S3	S6	S7	S8	S9
Date Sample Taken	10-63	8-69	10-69	8-70	8-69	8-69	10-69
Temp. °C	21.0	22.0	11.0	8.1	22.0	17.8	8.9
SiO_2 (mg/l)	13.0	12.0	0.5	4.2	12.0	7.2	0.6
Fe (ug/l)	20.0	20.0	10.0	---	20.0	20.0	10.0
Mn (ug/l)	0	0	0	---	0	0	0
Ca (mg/l)	21.0	23.0	24.0	18.0	25.0	46.0	36.0
Mg "	11.0	8.8	4.2	3.0	8.9	11.0	11.0
Na "	3.3	2.0	1.3	0.3	2.0	1.9	1.9
K "	1.3	0.9	0.2	0.1	0.9	0.6	0.8
HCO_3 "	116.0	118.0	84.0	68.0	114.0	177.0	154.0
CO_3 "	0	0	0	0	0	0	0
SO_4 "	8.6	8.1	7.5	6.0	8.1	11.0	6.5
Cl "	2.0	1.0	0.4	0.1	1.3	0.8	0.6
F "	0.1	0.1	0.2	0.0	0.1	0.1	0.2
NO_3 "	0.4	1.0	1.0	4.2	0.4	0.7	1.1
Dissolved solids (calc)	----	114.0	80.0	69.0	115.0	166.0	135.0
Dissolved solids (residue at 180 C)	110	116	79	----	114	167	130
Hardness (Ca-Mg in mg/l)	98	94	77	58	99	160	135
Non-Carbonate Hardness (mg/l)	3	0	8	2	6	15	9
Alkalinity as $CaCO_3$ (gm/l)	--	--	--	--	---	--	--
Specific conductance (Micro MHOS)	197	199	153	134	199	291	252
Ph	8.2	7.8	7.7	7.7	8.1	8.0	8.1
Color	2	4	2	---	4	4	2
Data Source	1	1	1	1	1	1	1

Source of Data: 1) U.S. Geological Survey
2) State Health Department

From Hansen et al. (1974)

by Fournier and Rowe (1966) show that most hot spring waters are greatly supersaturated with silica in respect to the solubility of quartz and other silicates. Drill hole data also show that veins of hydrothermal quartz occur at depth but not near the surface. Existing data on compositions of hot spring solutions and solubility of silica phases suggest that the solubility of quartz at depth is the major control. In table 5-6, the warm springs of the area are wells S2, S2a, S7 and S8. In each of these it is easy to note the correlation of higher silica content with rising temperature. Wells S2 and S2a are the actual "Sand Spring" wells. Table 5-7 lists a potability analysis of water from these two wells.

In 1893 a bottling works was added to the existing balneological hotel and spa. In addition to the pure water being bottled, soft drinks were mixed with the waters and carbonated ginger ale was pioneered at the site (Carlin, 1974).

In 1972 Michael Meehan began to bottle and sell the water again. However, due to a poor market, bakruptcy followed. Mr. Robert Carlin bought out the product and stock but Meehan retained the house. The actual bottling ceased in late 1972.

The feasibility of Sand Spring being utilized for industrial or domestic heating purposes appears to be very good: the water is at a relatively elevated temperature constantly and issues forth in quantity (400 gal/min). In a rough estimate of geothermal temperatures and applications, Lindal (1973), Beall (1973) and Beall and Yarosh (1973) report 20°C or 68°F as suitable for the

FIGURE: 5-3

DISTINCTIVE QUALITY

SINCE 1762

GREYLOCK MOUNTAIN Springs

NATURALLY PURE

Spring Water

MILDLY ALKALINE MINERAL WATER
FROM THE FAMOUS MINERAL SPRING
IN THE HEART OF THE BERKSHIRES

THE SPRING WHICH RISES FROM 3000' UNDERGROUND IS NATURALLY FILTERED THRU WHITE SAND. IT MAINTAINS AN EVEN TEMP. OF 72° YEAR ROUND AND HAS A FLOW OF 400 GAL. PER MIN.

SAND SPRINGS RD., WILLIAMSTOWN, MASS.

NET CONTENTS 128 OZ. (1 GAL.)

Dome Mountain

"PRIDE OF BERKSHIRES"

Natural Spring Water

BOTTLING LABELS of Sand Spring's thermal water. Label on left was the older label used by Michael Meehan in 1972 and the label on the right was used by Robert Carlin after foreclosure. Although actual bottling has been discontinued, older stock is still being sold in area supermarkets. According to Meehan (1975) it was the warmest water bottled for these purposes in the United States.

TABLE: 5-7

CHEMICAL DETERMINATIONS OF WATER SAMPLES FROM SAND SPRING

TESTS:	SAMPLE A	USPHS: MAXIMUM ALLOWABLE
1. Color (APHA units)	2.00	15.00
2. pH	7.70	----
3. Hardness ($CaCO_3$) mg/l	102.00	----
4. Alkalinity mg/l	80.00	----
5. Nitrate Nitrogen mg/l	0.15	45.00
6. Nitrite Nitrogen mg/l	0.00	----
7. Iron mg/l	0.01	0.30
8. Manganese mg/l	0.00	0.05
9. ABS (Detergent) mg/l	0.00	0.50
10. Chlorides mg/l	1.60	250.00
11. Turbidity	0.20	5.00
12. Odor	0.00	4.00

COMMENTS: Satisfactory according to U.S. Public Health Service Drinking Standards

(From O'Connell, 1973)

hatching of shrimp, fish and the farming of both, as well as the agricultural application towards the cultivation of lettuce, tomatoes and cucumbers. These reports also cite $30^{\circ}C$ or $86^{\circ}F$ as a suitable temperature for warming swimming pools, for use in biodegredation and fermentation processes, for supplying warm water for year-round mining in cold climates and for de-icing. The temperature of Sand Spring falls into this category and therefore could be usefully investigated for non-electric heat generation and utilization.

LEBANON WARM SPRING

The only other reported thermal spring system referred to by Stearns et al. (1937) and Waring (1965) in the New England area is located approximately 17.3 miles south-southeast of Sand Spring, in Lebanon Springs, New York. Both Sand Spring and Lebanon Warm Spring are located in the Taconic Allochthon System, a massive thrust sheet shoved from east to west during the Taconic Orogeny (refer to chapter IV). During that period of time, layers of massive limestones and sand deposits were metamorphosed along with the other sedimentary materials deposited in the Early Paleozoic. Deep-seated faults resulted from the allochthonous movements and the Taconic Range was created. The probability of these thermal springs acquiring their heat from contact with these deep-seated fault zones is high. Since the underlying strata are permeable and, in the case of the sandstones and limestones somewhat porous, groundwater has a good chance of being funnelled down to the depths necessary for appreciable heating to take place.

TABLE: 5-8

POTABILITY DETERMINATIONS OF WATER FROM LEBANON THERMAL SPRING

Number of springs..... 1
Flow Rate.............. 30,000 gal/hr
Temperature............ 76°F
Water Character....... Chalybeate

AMOUNTS (gr/gal)

Sodium Carbonate	2.41	Silica	3.25
Calcium Carbonate	4.04	Organic Matter	10.21
Calcium Sulfate	----	Magnesium Carbonate	----
Potassium Sulfate	1.04	Sodium Sulfate	----
Iron Carbonate	----	Calcium Chloride	----
Magnesium Sulfate	1.06	Potassium Chloride	----
Sodium Chloride	0.96	Magnesium Chloride	----
Sodium Sulphide	0.02	Magnesium Bromide	----
Iron Oxide	0.94	Sodium Bromide	----
Alumina	0.45	Sodium Iodide	----
		Free Carbonic Acid	----
		TOTAL	24.38

GASES	Volume (in^3)
Sulphureted Hydrogen	----
Carbonic Acid	0.48
Oxygen	2.00
Nitrogen	3.52

(From Peale, 1886)

TABLE: 5-9

CHEMICAL DETERMINATIONS OF LEBANON WARM SPRING WATER SAMPLES (ANALYSIS BY PROFESSOR H. DUISAND, CHEMIST TO THE IMPERIAL CONSERVATORY OF THE ARTS AND SCIENCES, PARIS)

GASES	VOLUME (in^3/gal)
Oxygen	2.00
Nitrogen	3.50
Carbonic Acid	0.50
Sulphuric Acid	traces

FIXED MATTERS	VOLUME (g/gal)	PERCENT
Sulphates of Sodium	0.02	1.298
Carbonate of Sodium	2.41	15.649
Sulphate of Potash	1.04	6.753
Chloride of Sodium	0.96	6.233
Carbonate of Lime	4.05	26.292
Sulphate of Magnesia	1.06	6.883
Alumina	0.45	2.629
Oxide of Iron	0.94	6.103
Silicic Acid	3.25	21.100
Organic Compounds	1.22	4.870

(From Salls, 1974)

TABLE: 5-10

WATER POTABILITY DETERMINATION (LEBANON WARM SPRING, N.Y.)

TESTS:	AMOUNT (mg/l):
1. Sodium	7.2
2. Fe-Mg	(Chemical Oxygen Demand)
3. pH	7.8
4. Alkalinity	125
5. Total Hardness	145
6. Chlorine	7
7. Nitrate	0.2
8. Nitrite	4
9. Ammonia	0
10. Turbidity	0.5
11. Color	0

(Department of Public Health, Columbia County, N.Y., 1974)

GEOLOGY

"Lebanon Warm Spring" is located in Columbia County, New York and is 27 miles southeast of Albany, New York. There are presently no published geological maps of the Lebanon Springs area which give details of the type of rocks or structure (Fisher, 1975). The State Geologic Map of New York (1961) shows the generalized geologic relations on a scale of 1:250,000 or about 4 miles to the inch. However, according to Dale (1923), Lebanon Springs is located on the geologic contact between the Berkshire Schist and the Stockbridge Limestone, a granular, calcitic limestone with lenses and beds of granular dolomite. The State Geologic Map of New York (1961) describes the Berkshire Schist in the area to be of the variety of Austerlitz Phyllite and black Wallomsac Slate. According to Waring (1965), Lebanon Warm Spring issues from the base of gravel beds of glacial drift material near a contact of Paleozoic, faulted limestone and talc slate and is nearby evidences of local faulting and derangement of the strata. The water temperature of the thermal spring is reported to be 76°F by Stearns et al. (1937) and 75°F by Waring (1965). The author found the temperature of water issuing from the outside pipe system to be approximately 65°F. This value, however, was undoubtedly influenced by thermal dissipation in the large pool and plumbing system. The outside air temperature at the time of the reading was 34°F. The flow rate is a constant 500gal/min (Stearns et al., 1937; Waring, 1965) and its volume has not visibly decreased (Stouter, 1975).

HISTORY

Lebanon Warm Spring was a celebrated colonial resort and has been fairly well-known since then as a health spa. It is recorded that the Marquis De Lafayette, among other dignitaries of the time, stayed at the spring's Columbia Hall, a 400 room hotel which was built in 1794 and was razed in 1928 (because, of all reasons, there was great difficulty in heating the large structure).

The water is said to be soft and tasteless but possesses "medicinal properties of great merit" (Salls, 1974). A two-week regimen, for example, of drinking six glasses of the thermal water, walking a mile, drinking six more glasses of the thermal water, finishing with a cup of coffee and molasses, was reputed to cure kidney stones, arthritis and a long list of other maladies, if religiously adhered to daily (Cummings, 1975). The author found the water to be quite potable, having very little taste with a slight sweetness.

The property is owned by Mrs. Anna Zieter, whose late husband, Victor, did much to restore the area. In about 1906, the Rutland Railroad laid about a mile of porcelain-lined pipe from the spring down to the railroad depot, where the warm water was used to recharge boilers of the railroad steam engines. Over the years, after the railroad line was abandoned, over 30 families have tapped into the line and have utilized the water for various domestic uses. When a question arose as to the right to utilize the spring's water, Mrs. Anna Zieter and the Town of Lebanon

Springs negotiated a compromise agreement whereby the town's residents are permitted to utilize the hot water but are responsible for maintaining their own pipeline system. It appears that the question as to who owns geothermal resources is a novel legal question and is in need of further study.

Waring (1965) states that surface water at Lebanon Springs penetrates to considerable depth and returns to the surface via cracks and fractures. As is the case with Sand Spring, natural heat recovery from the Lebanon Thermal Spring, which falls into the 20-30°C range, is feasible.

Both Sand Spring and Lebanon Warm Spring issue from deep-seated joint and fault systems developed in the Taconic Allochthon. While Adams (1924) calculated that water rising along a crack in the rock from a depth of 3.5 km, corresponding to a release of pressure of about 1,000 megabars, will be subjected to an increase in temperature of more than 20°C while in transit to the surface of the ground, Devane (1975) states that pressures of the order of 10^9 bars are only possible, in modern scientific thinking, at the center of the earth.

OTHER SPRINGS

In a Vermont Geological Survey report Adams (1848) mentioned Morgan Spring, near the center of Bennington, Vermont, as possibly being a warm spring. Stearns et al. (1937) reported that the particular spring was listed again in 1934 as a thermal spring, and listed the temperature of Morgan Spring as 53°F (11.67°C), which is 8°F above the mean annual temperature. Bennington is located along the western margin of the Green Mountain Anticlinorium. Also known as the Green Mountain-Reading Prong Arc, it consists of a discontinuous, essentially linear series of anticlinorial folds overturned and overthrust westward (Skehan, 1969). According to Savage (1974), the water of Morgan Spring is cold but it never freezes and is sometimes used to implement the water supply of the town. The geothermal potential of the spring is not known. However, the fact that it never freezes raises questions regarding possible mixing of warmer water and cooler ground water near the surface.

Daubney (1839) reported another slightly thermal spring at Canaan, Vermont but it was not listed again by others.

Saratoga Springs, New York, is situated in the Taconic Range and is the site of approximately 18 natural springs; one of which is a spouting spring. These springs, although rich in carbon dioxide content, are not considered thermal. The apparent geyserlike quality of the spouting spring is caused by the release of pressure within the CO_2-rich spring. The resultant depressurized gas behaves in a manner not unlike a can of beer or tonic when shaken and opened.

TABLE: 5-11

ANALYSES OF THE WATERS OF THE SARATOGA SPA IONS AND RADICALS AS PRESENT IN SOLUTION, PARTS PER MILLION

Element or Radical:	Hathorn #3	Hayes	Orenda	Karista	Lincoln	Polaris	Ferndell
Sodium	3820.	3025.	2420.	1760.	1150.	560.	10.
Potassium	340.	333.	266.	170.	219.	80.	3.
Lithium	10.	12.	8.	9.	6.3	5.	------
Calcium	872.	724.	672.	414.	348.	370.	55.
Magnesium	353.	277.	224.	178.	171.	95.	4.
Barium	25.	12.	15.6	12.6	8.1	2.1	0.04
Strontium	12.	10.5	10.	18.3	9.9	------	0.1
Ammonium	14.	13.	13.	15.	6.	1.2	0.02
Iron	2.2	1.8	1.7	6.	8.2	1.1	0.4
Aluminum	4.0	9.	8.	11.	3.	6.	.03
Manganese	0.4	0.3	0.3	0.13	------	------	------
Bicarbonate	4850.	4550.	3600.	3890.	2610.	2130.	79.
Chloride	6030.	4500.	3800.	2000.	1540.	1000.	13.
Bromide	53.	51.	46.	8.	34.	5.	------
Iodide	2.9	2.1	2.0	0.9	1.3	------	------
Metaborate	7.0	7.0	7.5	5.1	4.1	0.9	0.008
Silica	12.	11.	11.	6.3	51.	17.	15.
Sulfate	0	0	0	0	0	0	34.
Total Solids (Dried at 110°C)	16407.	13539.	11105.	8540.	6166.	3260.	231.
Radium 226 (Pico Curies per liter)	430.	284.	232.	95.	48.	102.	1.3

All of the above waters, except Ferndell, are effervescent as they come from the ground and contain from 2 to 5 volumes of carbon dioxide.

(General information on the waters of the Saratoga Springs Reserv.)

CHAPTER VI: SHALLOW TEMPERATURE MEASUREMENTS

In making shallow-depth temperature measurements in thermally equilibrated drill holes, 65.6 ft (20 m) is the approximate depth at which the temperature variation due to the seasonal air temperature variation becomes negligible for typical values of thermal properties (Van den Bouwhuijsen, 1934; Kappelmeyer, 1957; Lovering et al., 1963). The amount of this variation differs, these differences having been attributed to structural features, with the local temperature differences due to thermal conductivity of the soil, the vegetation and the microclimate (Kappelmeyer, 1957). The diurnal periodic temperature variations can be detected down to a depth of approximately one meter (Kappelmeyer, 1957; Poley and van Steveninck, 1970).

The temperature measured at a given depth at a certain time depends on the thermal diffusivity of the soil, the amplitude and phase of the fundamental and component waves of the temperature variation curve and the mean annual temperature. Of course, the thermal conductivity of a sample of earth material depends upon its constituent materials. Vegetation contrasts can also affect thermal values. They can cause ground surface temperature variations of up to 2°C over a lateral distance of a few tens of meters (Poley and van Steveninck, 1970).

The most important temperature changes at the surface, which are propagated through the ground, are the regular diurnal and annual variations. At depths greater than 1m, the annual variation has a very long period (365 days), making day-to-day changes very small. A grid of regional temperature differences at about

1.5 m depth (well outside the reach of diurnal variations), made in a reasonably short time can be considered to be undisturbed by solar effects (Poley and Van Steveninck, 1970). Van den Bouwhuijsen (1934) offered the reasoning in using such measurements to denote possible structural differences:

> The flow of heat from the earth's center towards a fixed point close to its surface depends upon the heat conductivity of the rock formations between the center and the point and on the thickness of the different layers. One may therefore expect that a shift in the location and a variation in the thickness of the layers, as may be noted in various geological structures, would result in differences of temperature, when measured across the structure at the same depth. The horizontal gradient of the temperature in a layer close to the surface, therefore, should supply some evidence as to the structure of the underlying formations. The differences in temperature must of course be of a magnitude higher than the differences caused by the inevitable errors in measurement.

The application of shallow-depth measurement has been made towards the description of subsurface geology in areas of special importance. Heald (1929), in a progress report, concludes that in central Oklahoma, for instance, the isotherms definitely reflect the regional geologic structure, while Van Orstrand (1943), summarizing the survey's results, states, "...evidence shows that temperature variations have been found to be associated with salt domes, sand lenses, faults and structures with both large and small closure."

Taking into account that the geology of the New England area is beset by a series of deep-seated fault zones (see chapter IV), the application of such shallow-depth temperature measurements in conjunction with finding fault traces would enhance the possibilities of finding near-surface expressions of deep-seated faults and/

or fault traces which may be conduits of ground water with elevated temperature. The Sand Spring in Williamstown, Massachusetts and Lebanon Warm Spring in Lebanon Springs, New York, are well-known expressions of ground water being warmed at depth and percolating along fracture traces to the surface (chapter V).

Poley and van Steveninck, in a study of the delineation of shallow salt domes and surface faults by temperature measurements at a depth of approximately 2 m, concluded that in several cases strong thermal anomalies coincided with known surface faults and that it was their opinion that the method of 2 m depth thermal measurements is efficient in locating fault traces as well as shallow salt domes. Their qualitative reasoning makes the existence of a thermal anomaly of a given shape plausible over a surface fault zone:

> Consider a surface fault in either consolidated or unconsolidated material. Particularly in the case of consolidated materials, the heat conductivities of the formations on either side of the fault will not differ much and can effectively be taken as equal. This need by no means be the case, however, for the fault zone itself. Owing to the shearing action along the fault, a zone of the formations on each side may have been fractured and its original texture, porosity etc. may have been completely upset. It seems reasonable to assume that such a fault zone has a heat conductivity (λf) which differs from that of the surrounding formation (λs). Also, fault zone mineralization may lead to $\lambda f \neq \lambda s$.
>
> When, under stationary conditions, an equal heat flow (q) pervades the entire structure and dissipates to the (isothermal) surface, we get the following conditions at depths Δz with respect to the surface in the undisturbed zone (A) and in the fault zone (B).
>
> $$\text{At (A): } q = -\lambda s \frac{\Delta T_A}{\Delta z} \qquad \text{At (B): } q = -\lambda f \frac{\Delta T_B}{\Delta z}$$
>
> Between the fault zone and its surrounding formations a temperature difference θ will be observed:

> $$\theta = \Delta T_B - \Delta T_A = -\frac{q \cdot \Delta z}{\lambda f} + \frac{q \cdot \Delta z}{\lambda s} = \frac{q \cdot \Delta z}{\lambda s}\left(1 - \frac{\lambda s}{\lambda f}\right)$$
>
> With $q = 1.3 \times 10^6$ cal/cm^{2}sec, $\Delta z = 200$ cm and λs (tentatively) = 2.6×10^{-3} cal/cm^{2}sec °C. In this case, $\theta = 0.10\ (1 - \lambda s/\lambda f)$ °C. It is obvious that whether the observed temperature difference will be positive or negative, larger or smaller, is dependent on the ratio of $\lambda s/\lambda f$. However, there is a complete lack of pertinent data on this ratio. (From Poley and van Steveninck, 1970)

In a Mesa, California, survey, geothermal temperature measurements made at depths of 61, 122 and 183 m indicate that the temperature patterns change with depth, suggesting that ground water flow affects the results at shallow depths (Douze and Sorrells, 1972). The Mesa survey was not intended to study shallow depths in detail nor was the study on fault traces intended. The suggestions about ground water flow and its effects was, however, augmented by the possibility that the water as it cools will deposit some of the minerals heretofore in solution, thus decreasing the permeability. The Mesa area is a prime study area for geothermal water deposits due to tectonic activity. However, in a study on the central and southern Appalachians, Diment and Werre (1960) noted that irregular and low heat flow values at less than 200 m depths are probably the result of ground water movement.

To drill holes to a depth below the level of the annual temperature variation, approximately a 20 m depth, involves heavy costs for machinery and wages and increases the time necessary for survey. Since the possibilities of delineating faults in the New England area could well be linked to the discovery of thermal groundwater, such a study was carried out in the semi-rural area of Newbury, Massachusetts. The location was Scotland Road in Newbury.

SCOTLAND ROAD FAULT

The Scotland Road Fault was inferred by A. Shride of the U.S. Geological Survey (Shride, 1971) to have an easterly trend through the towns of West Newbury, Newbury and Newburyport, Massachusetts. Shride has interpreted the Scotland Road Fault to represent the eastern portion or continuation of the Clinton-Newbury Fault, which trends northeasterly for a distance of about 60 miles, from the area of Worcester, Massachusetts, to project offshore at Plum Island in Newbury, Massachusetts.

A detailed study of the fault zone in an open field owned by the Marion H. Marshall Estate was carried out in June, 1974 to locate and examine the fault and its overlying Pleistocene deposits. The study done by the Public Service Company of New Hampshire and Weston Geophysical Engineers, Inc. of Weston, Massachusetts. Information pertaining to location, makeup, localized geology and seismic data has been graciously provided and is appropriately referenced herein.

Geologically, the fault is very old (Early to Middle Permian) and the altered and deformed bedrock materials in the fault zone are annealed and compact. Nine core borings define the fault zone as being about 300 ft thick and dipping at about 44° to the north adjacent to Scotland Road in Newbury, Massachusetts (Rand, 1974). All the evidence compiled by and observed in the investigations indicates that Pleistocene deposits overlying the Scotland Road Fault have not been subjected to disruption by faulting. It is the intention of the following data to provide an additional set of references for the area.

SHALLOW THERMAL MEASUREMENT TECHNIQUE

In exploration for shallow thermal sources, measurements of temperature are sufficient. Practical experiments of such measurements using standard thermometers have often been carried out with some success, but the field procedures were tedious (Krcmar and Masin, 1970) described a thermal measurement technique using a thermistor and an electrical bridge. It seemed to meet requirements of easy, inexpensive and fast field operations with a high degree of accuracy and reproducibility.

In the shallow temperature measurement technique being reported on, a Fenwall thermistor was used as the sensing element, weighted down with a ½lb (.226 kg) weight of low thermal conductivity. This thermistor was mounted on a cable which was wound around a portable winch. The total weight of the cable and winch is 68 lb (30.87 kg). A Wheatstone bridge (Biddle-Gray model, cat. # 603108 - ser. # 40091) was used with a Keithley-type null detector. The total weight of the bridge and the nullmeter is about 5 lb (2.3 kg).

The actual method of measuring was to record the time at which measurements were begun and finished at each hole. The ground surface temperature was determined and measurements were made at every 5 ft down the hole and every 10 ft uphole. In all eight holes the water table was relatively high (less than 15 ft deep). At all of the holes at Scotland Road the water table was flush with the ground surface. The measurements were carried out between the dates of October 28, 1974 and November 26, 1974, between the hours of 11:45

and 3:30 P.M. During the period of the investigations, the sun shone every day and the weather was moderately mild fall New England weather with maximum temperatures in the 40-50°F range.

There are four holes in the Scotland Road area reported on herein, one at Weston Observatory, Weston, Massachusetts and three at Seabrook, New Hampshire. Since geologic sections were provided at Scotland Road by Weston Geophysical Engineers, Inc., a more detailed study was done in that area.

Ground cover ranged from no vegetation at Scotland Road to dense vegetation at the Weston and Seabrook sites. The holes at the Seabrook and Weston sites were kept open by metal pipes along their entire depth, while those at Scotland Road were kept open with PVC plastic piping.

There are two graphs of temperature vs. depth for every hole except for S-1, a hole at Seabrook only 35 ft deep which was too shallow to yield a reliable gradient trend. As previously stated, gradients are not considered reliable when taken at bottom-hole depths. Bottom-hole temperatures were therefore discarded in the enlarged graphs due to their inconsistency. There are cases where the bottom two or three values were also discarded in these graphs for the same reason. The enlarged graphout of these gradients indicates the number of values taken and shows the calculation of the particular "reliable" gradient.

In the Scotland Road graphs, the materials found by Rand (1974) are labelled at the appropriate depths.

TABLE: 6-1
RESISTANCE VALUES AT SCOTLAND ROAD

HOLE #	SR-1		SR-2		SR-3		SR-4	
DATE	10/28/74		10/28/74		11/26/74		10/29/74	
TIME	12:30 PM		2:15 PM		1:00 PM		1:15 PM	
DEPTH (ft)	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP
0	1900		1975		2141	1923	1700	1920
5	1862	1906	1816	1823	1955	1931	1795	1810
10	1815		1790		1922	1911	1810	
15	1798	1927	1848	1953	1919	1912	1824	1840
20	1828		1931		1937	1935	1903	
25	1953	1962	1956	1957	1948	1950	1937	1931
30	1984		1964		1953		1941	
35	1989	1989	1964	1964	1954	1954	1939	1939
40	1988		1964		1954		1937	
45	1985	1984	1963	1963	1953	1953	1935	1935
50	1982		1963		1953		1935	
55	1979	1978			1952	1952	1934	1934
60	1977				1952		1934	
65	1976	1975			1951	1951	1934	1934
70	1974				1951		1933	
75	1972	1971			1950	1950	1933	1933
80	1970						1932	
85	1968	1967					1931	1931
90	1966						1931	
95	1965	1966					1930	1929
100							1929	
105							1928	1928
110							1927	
115							1927	1926
120							1925	
125							1924	1924
130							1923	
135							1922	1922
140							1921	
145							1919	1919
150							1918	
155							1918	1917
160							1916	
165							1914	1915
170							1914	
175							1914	1913

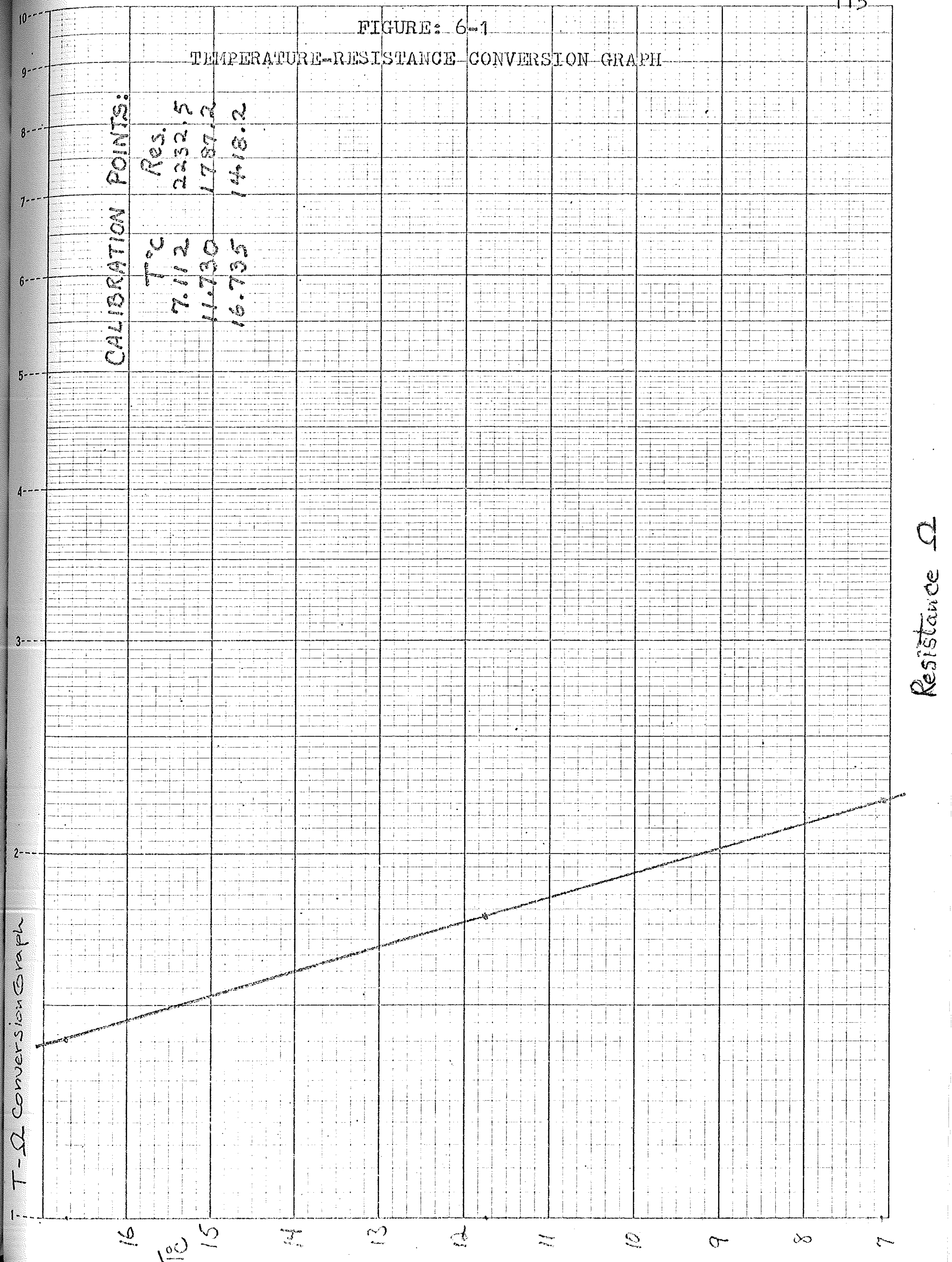
TABLE: 6-2

RESISTANCE VALUES AT WESTON AND SEABROOK

HOLE #	W-1		S-1		S-2		S-3	
DATE	11/13/74		11/5/74		11/7/74		11/12/74	
TIME	11:45 A.M.		12:00 NOON		2:00 P.M.		2:30 P.M.	
DEPTH (ft)	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP
0	1950	2013	1833	1906	2037	2041	1650	2059
5	1927	1892	1628	1910	2020	1898	1912	1941
10	1880	1884	1848	1860	1887		1904	1890
15	1913	1918	1860	1858	1877	1879	1866	1866
20	1964		1890	1994	1917		1909	1912
25	2005	2008	1937	1939	1989	1972	1987	1986
30	2030		1979		2020		2022	2021
35	2040	2039	1979	1979	2046	2047	2037	2038
40	2040				2045		2044	
45	2039	2038			2064	2054	2048	2049
50	2035				2066		2048	
55	2031	2031			2052	2052	2048	2048
60	2027				2050		2047	
65	2023	2023			2048	2048	2044	2044
70	2023				2045		2039	
75					2043	2043	2036	2037
80					2041		2033	
85					2038	2038	2031	2031
90					2035	2035	2028	
95					2033	2033	2025	2025
100					2030	2030	2022	
105					2027	2027	2019	2019
110					2025		2016	
115					2022	2022	2013	2013
120					2019		2010	
125					2017	2016	2007	2007
130					2014		2003	
135					2010	2010	2000	2000
140					2009		1997	
145					2007	2007	1994	1994
150					2006		1991	
155							1989	1989
160							1986	
165							1985	1985
170							1983	

FIGURE: 6-1

TEMPERATURE-RESISTANCE CONVERSION GRAPH



CALIBRATION POINTS:

T°C	Res.
7.112	2232.5
11.730	1787.2
16.735	1418.2

TABLE: 6-3

TEMPERATURES (^{o}C) AT SCOTLAND ROAD

HOLE #	SR-1		SR-2		SR-3		SR-4	
DEPTH(ft)	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP
0	10.20		9.45		8.79	9.97	12.20	10.00
5	10.58	10.14	11.04	10.97	9.65	9.89	11.25	11.10
10	11.05		11.30		9.98	10.09	11.10	
15	11.22	9.93	10.72	9.67	10.01	10.08	10.96	10.80
20	10.92		9.89		9.83	9.85	10.17	
25	9.67	9.58	9.64	9.63	9.72	9.70	9.83	9.89
30	9.36		9.56		9.65		9.79	
35	9.31	9.31	9.56	9.56	9.66	9.66	9.81	9.81
40	9.32		9.56		9.66		9.83	
45	9.35	9.36	9.57	9.57	9.67	9.67	9.85	9.85
50	9.38		9.57		9.67		9.85	
55	9.41	9.42			9.68	9.68	9.86	9.86
60	9.43				9.68		9.86	
65	9.44	9.45			9.69	9.69	9.86	9.86
70	9.46				9.70	9.70	9.87	
75	9.48	9.49					9.87	9.87
80	9.50						9.88	
85	9.52	9.53					9.89	9.89
90	9.54						9.89	
95	9.55	9.54					9.90	9.91
100							9.91	
105							9.92	9.92
110							9.93	
115							9.93	9.94
120							9.95	
125							9.96	9.96
130							9.97	
135							9.98	9.98
140							9.99	
145							10.01	10.01
150							10.02	
155							10.02	10.03
160							10.04	
165							10.06	10.05
170							10.06	
175							10.06	10.07

TABLE: 6-4

TEMPERATURES (°C) AT WESTON AND SEABROOK

HOLE #	W-1		S-1		S-2		S-3	
DEPTH(ft)	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP
0	9.70	9.07	10.87	10.40	8.83	8.79	12.70	8.61
5	9.93	10.28	12.92	10.10	9.00	10.22	10.08	9.79
10	10.40	10.36	10.72	10.60	10.33		10.16	10.30
15	10.07	10.02	10.60	10.62	10.43	10.41	10.54	10.54
20	9.56		10.30	9.26	10.03		10.11	10.08
25	9.15	9.12	9.83	9.81	9.31	9.48	9.33	9.34
30	8.90		9.41		9.00		8.98	8.99
35	8.80	8.81	9.41	9.41	8.74	8.73	8.83	8.82
40	8.80				8.75		8.76	
45	8.81	8.82			8.56	8.66	8.72	8.71
50	8.85				8.54		8.72	
55	8.89	8.89			8.68	8.68	8.72	8.72
60	8.93				8.70		8.73	
65	8.97	8.97			8.72	8.72	8.76	8.76
70	8.97				8.75		8.81	
75					8.77	8.77	8.84	8.83
80					8.79		8.87	
85					8.82	8.82	8.89	8.89
90					8.85	8.85	8.92	
95					8.87	8.87	8.95	8.95
100					8.90	8.90	8.98	
105					8.93	8.93	9.01	9.01
110					8.95		9.04	
115					8.98	8.98	9.07	9.07
120					9.01		9.10	
125					9.03	9.04	9.13	9.13
130					9.06		9.17	
135					9.10	9.10	9.20	9.20
140					9.11		9.23	
145					9.20	9.20	9.26	9.26
150					9.14		9.29	
155							9.31	9.31
160							9.34	
165							9.35	9.35
170							9.37	

TABLE: 6-5

AVERAGE VALUES OF "RELIABLE" GEOTHERMAL GRADIENTS AT SCOTLAND ROAD, WESTON AND SEABROOK SITES

HOLE #	"RELIABLE" GRADIENT DEPTH (ft)	NUMBER OF MEASUREMENTS	ARITHMETIC MEAN TEMP. (°C)	VARIANCE (σ^2) x10^{-4}	STANDARD DEVIATION (σ) x10^{-4}
SR-1	65 - 90	6	9.490	14	374.17
SR-2	30 - 45	4	9.563	.25	50
SR-3	45 - 70	6	9.680	.8	89.44
SR-4	90 - 150	13	9.951	17.41	417.25
W-1	45 - 65	5	8.890	40	632.46
S-1	(none)	0	---	---	---
S-2	65 - 130	14	8.888	120.02	1095.57
S-3	85 - 150	14	9.089	168.13	1296.67

Gradients were considered reliable within intervals of stabilization at depths below diurnal and seasonal fluctuation and excluding bottom-hole readouts.

PUBLIC SERVICE CO. of NEW HAMPSHIRE
SEABROOK STATION
LOCATION MAP - SCOTLAND ROAD FAULT INVESTIGATIONS

on property of
ESTATE of MARION H. MARSHALL
SCOTLAND ROAD, NEWBURY, MASSACHUSETTS
J. R. Rand Consulting Geologist

FIGURE: 6-2

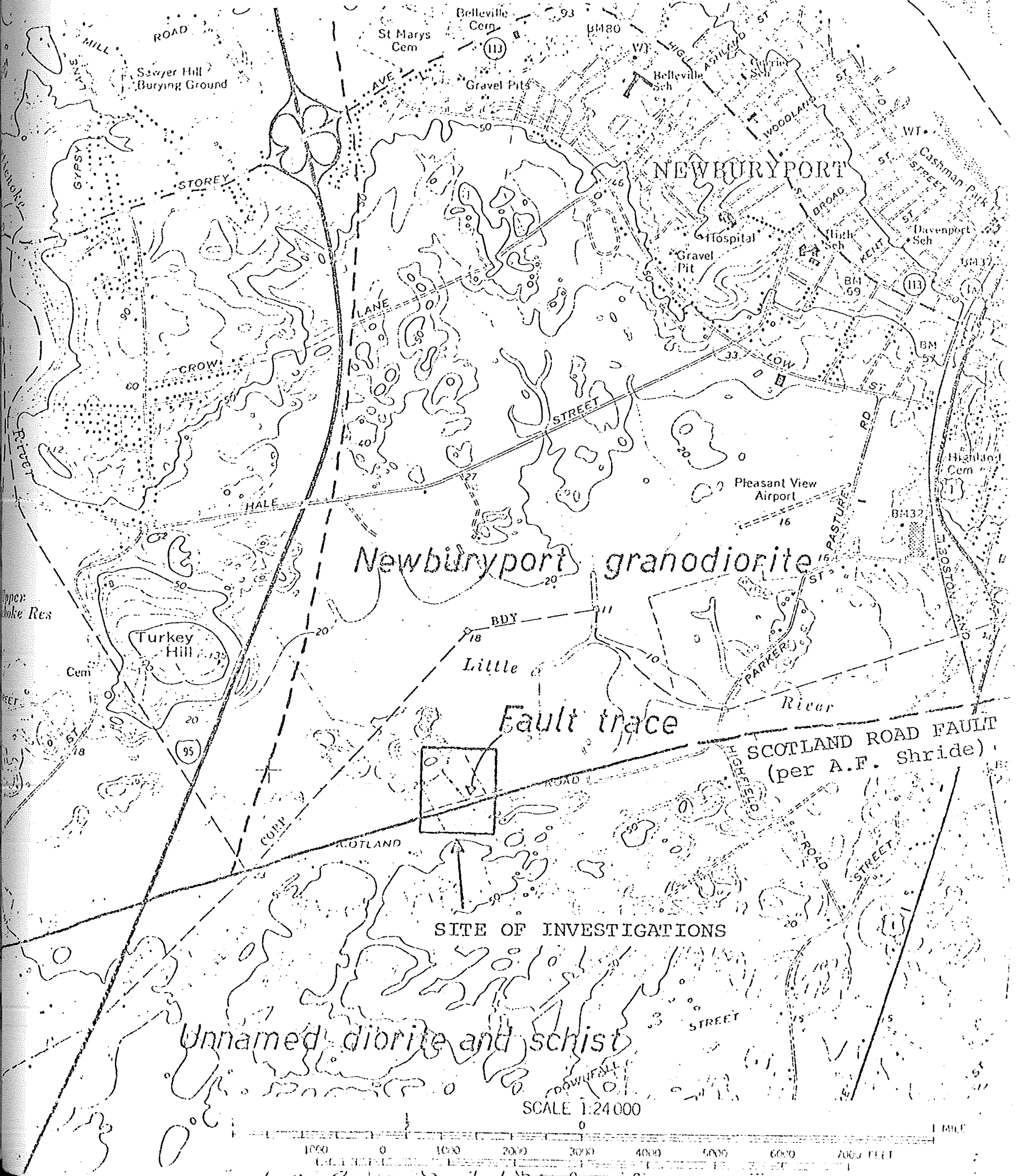
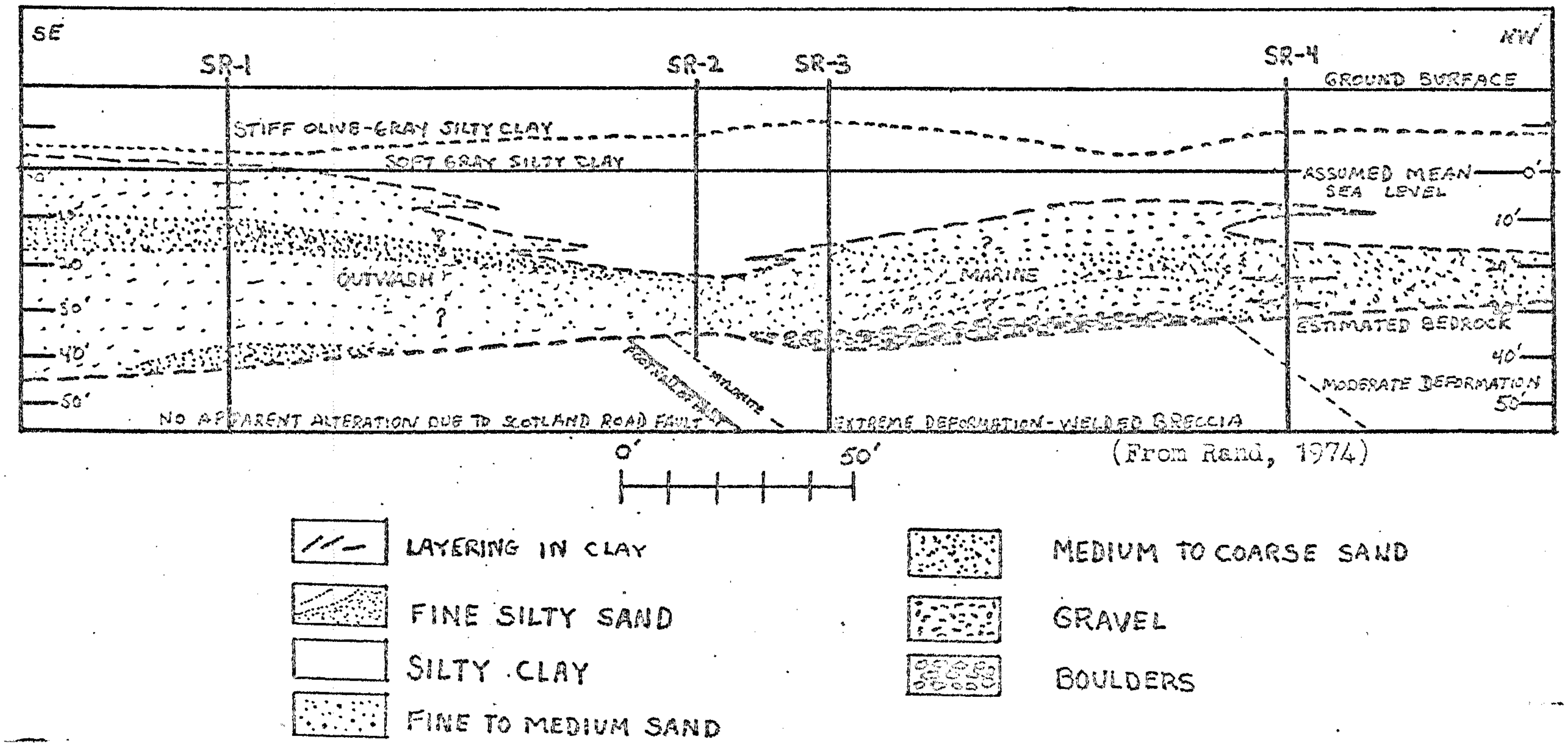
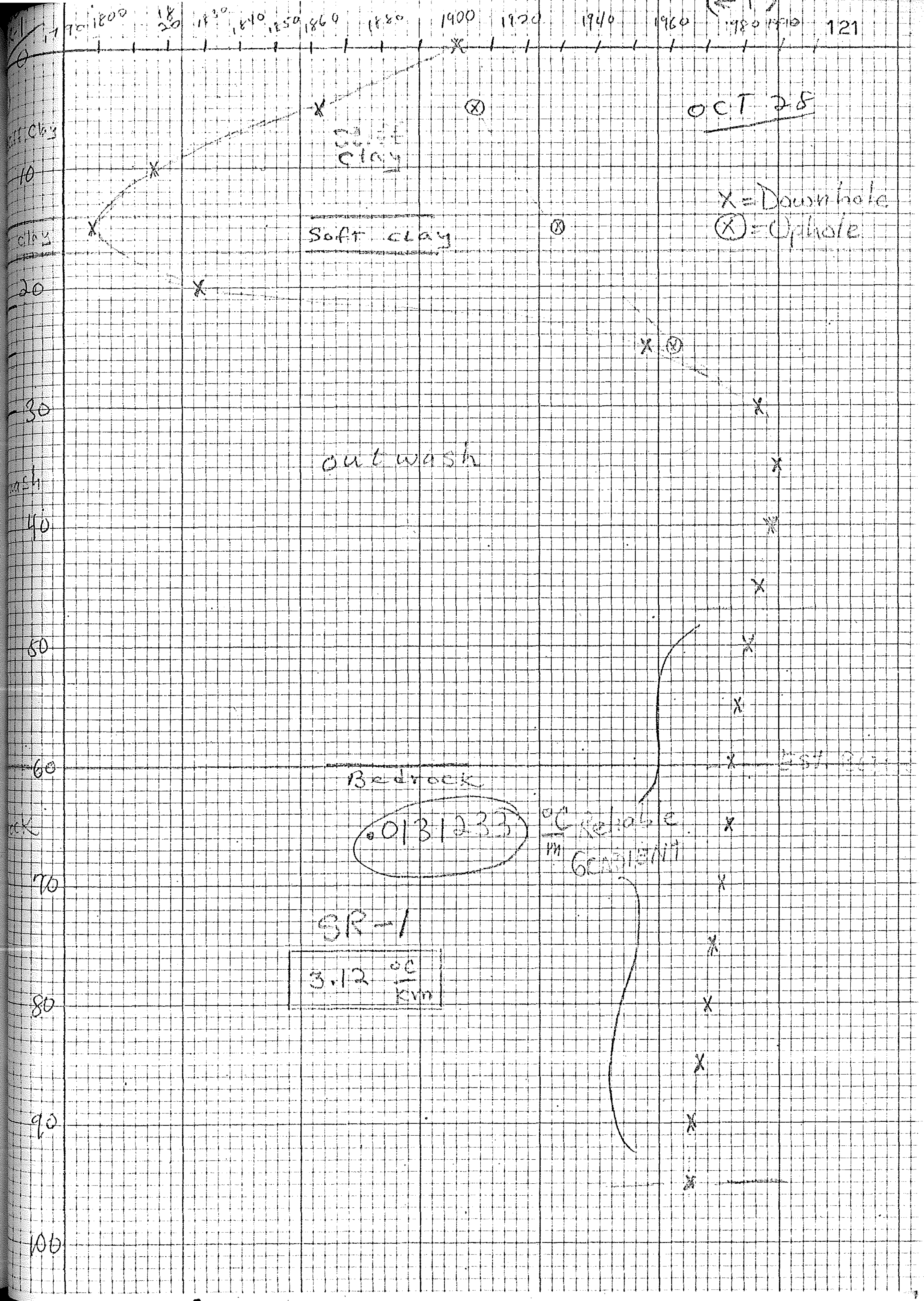


FIGURE: 6-3
SURFICIAL DEPOSITS AND DRILLHOLE LOCATIONS AT THE
SCOTLAND ROAD FAULT ZONE
(on property of Marion H. Marshall Estate: Newbury, Massachusetts
for the Public Service Company of New Hampshire by John R. Rand)



(From Rand, 1974)

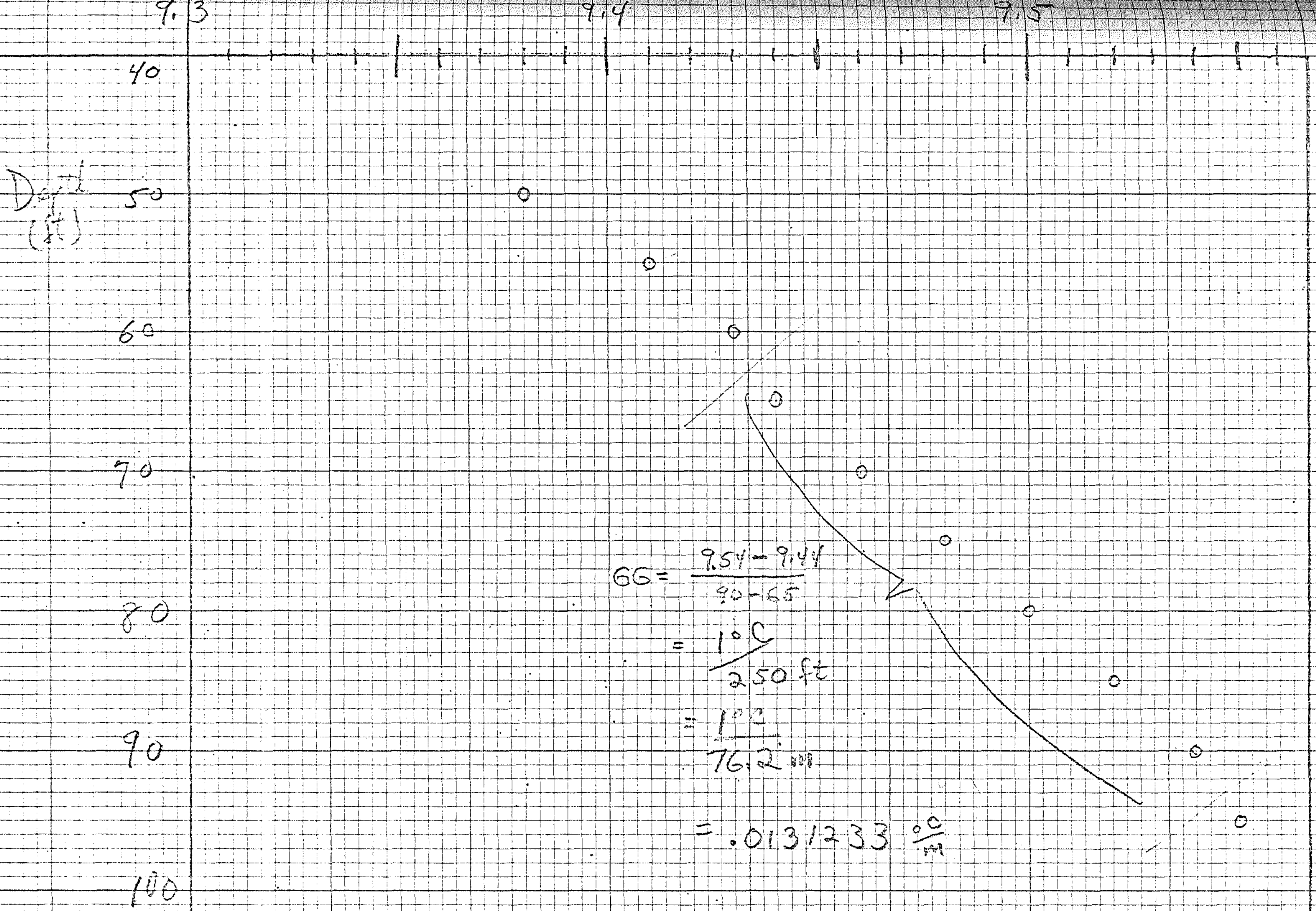


.0131233 $\frac{°C}{m}$ Reliable GRADIENT

SR-1

$\boxed{3.12 \frac{°C}{Km}}$

SR-1



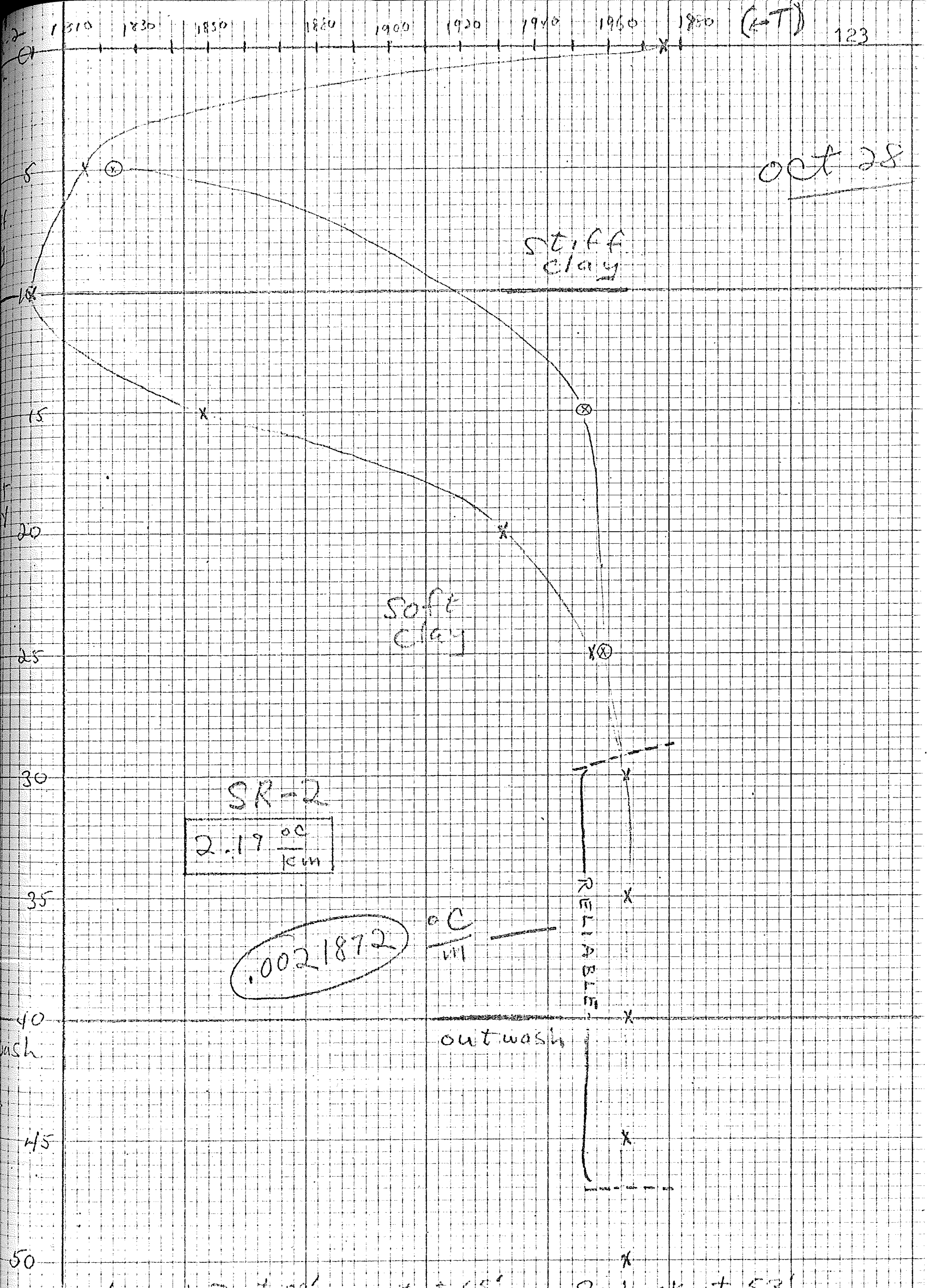
$$GG = \frac{9.54 - 9.44}{90 - 65}$$

$$= \frac{1°C}{250\ ft}$$

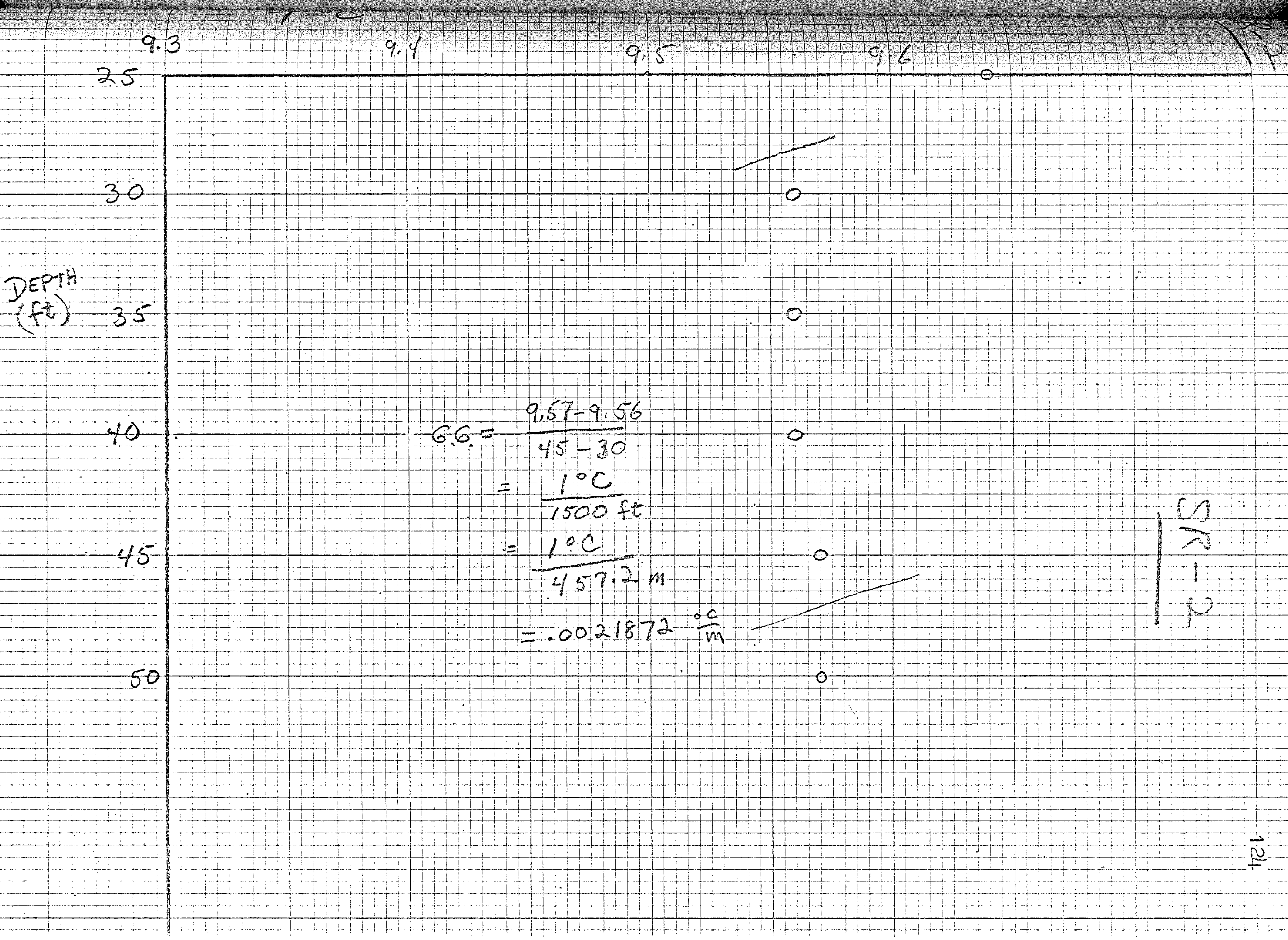
$$= \frac{1°C}{76.2\ m}$$

$$= .0131233\ \frac{°C}{m}$$

Oct 28



at 53' Mylonite at 58' Fault at 65' Bedrock at 53'



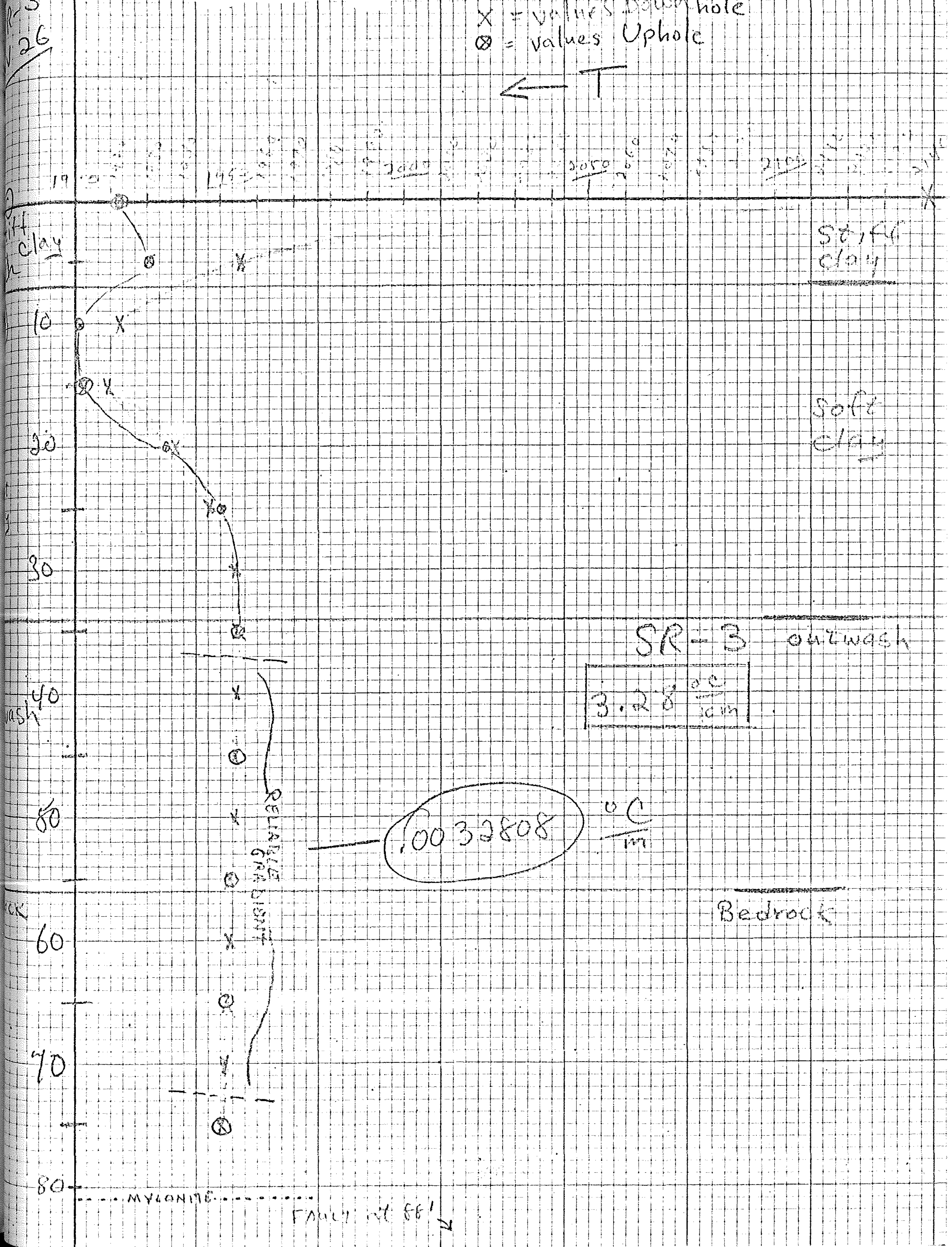
$$G.G. = \frac{9.57 - 9.56}{45 - 30}$$

$$= \frac{1°C}{1500 \text{ ft}}$$

$$= \frac{1°C}{457.2 \text{ m}}$$

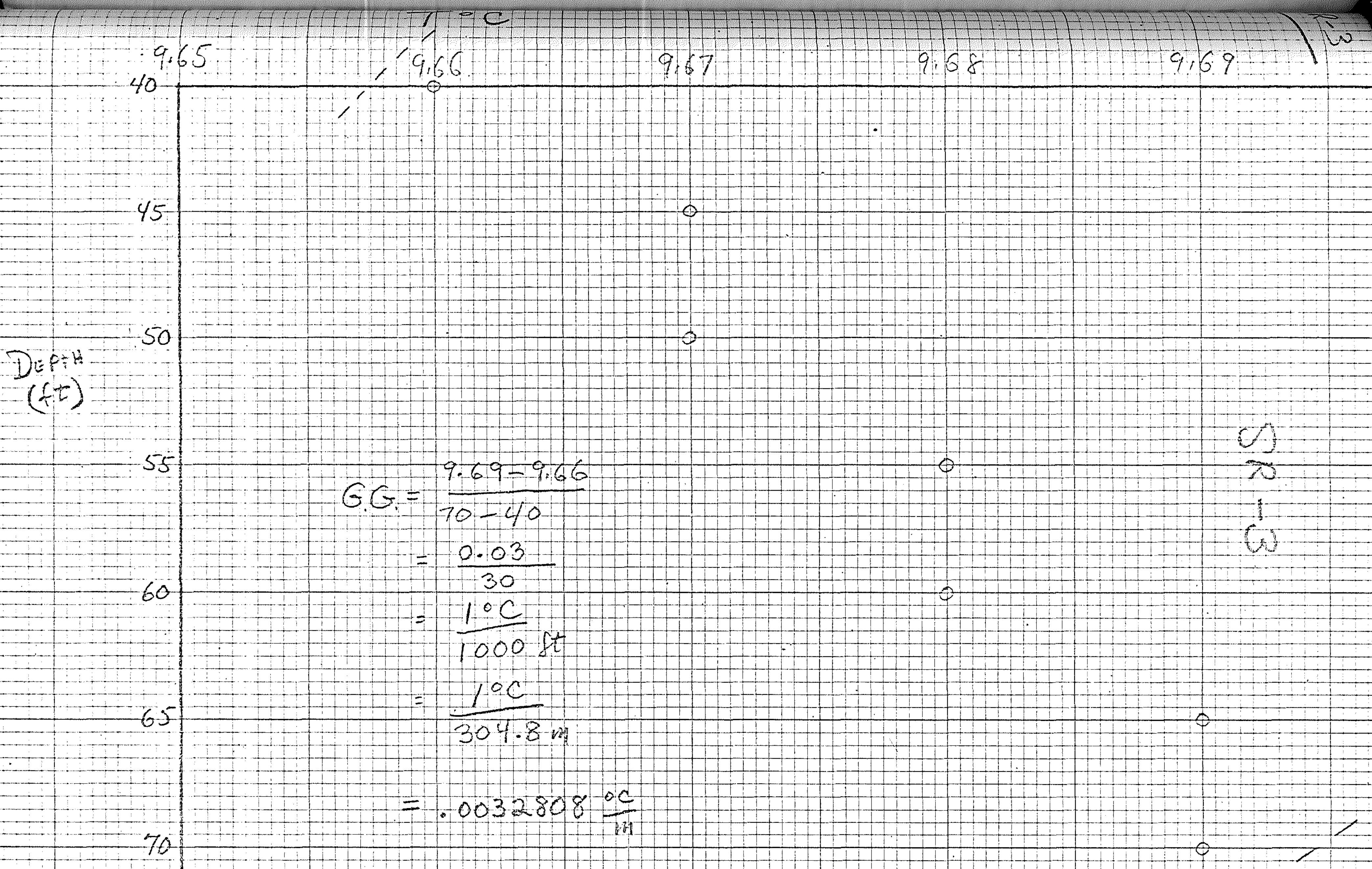
$$= .0021872 \ \frac{°C}{m}$$

SR-3


X = values Downhole
⊗ = values Uphole
← T
19
1950
2000
2050
2100
0
10
20
30
40
50
60
70
80
Stiff clay
Soft clay
SR-3 outwash
3.28 °C/100m
RELIABLE GRADIENT
.0032808 °C/m
Bedrock
MYLONITE
FAULT AT 88'

R-3

SR-3



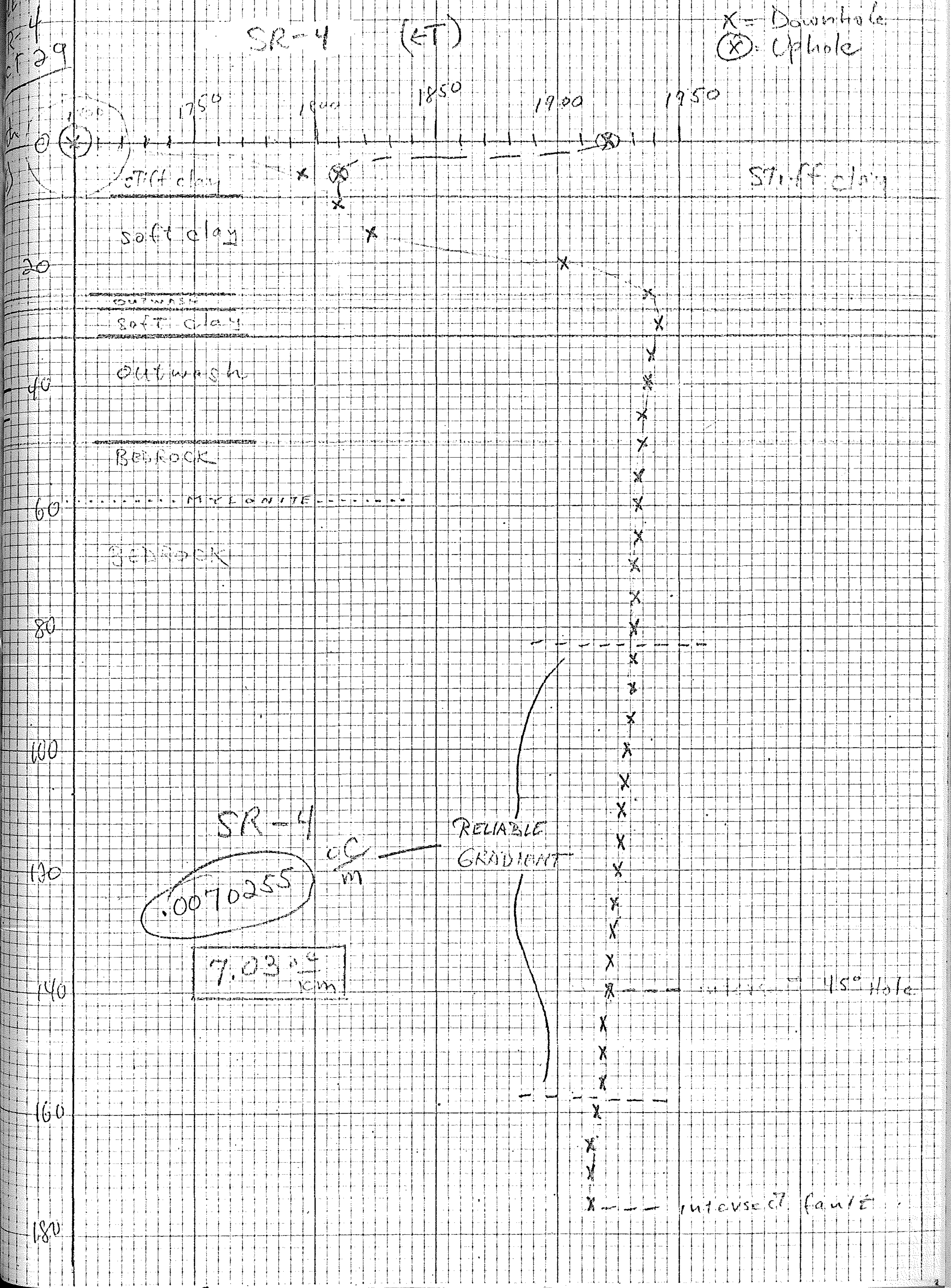
$$G.G. = \frac{9.69-9.66}{70-40}$$

$$= \frac{0.03}{30}$$

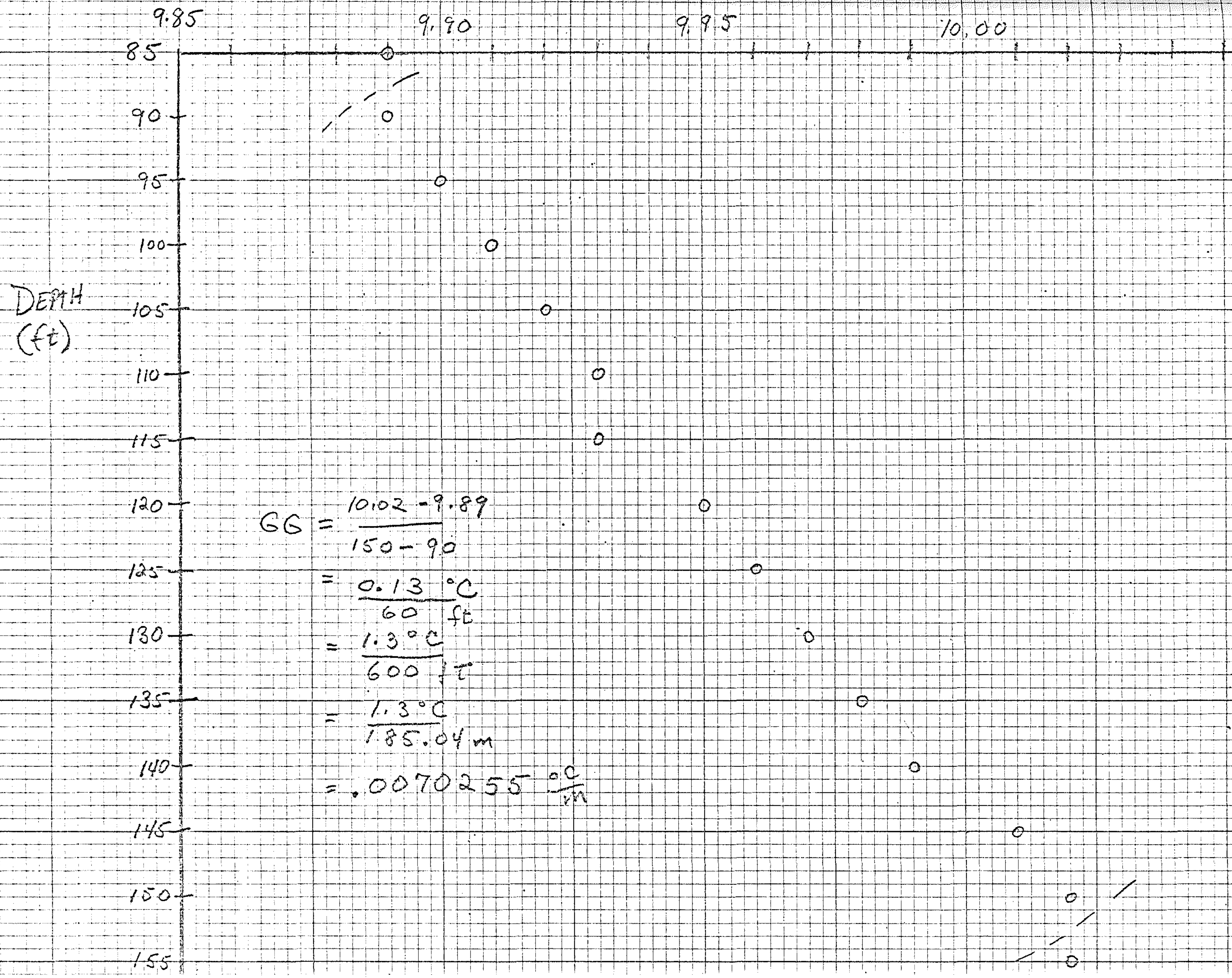
$$= \frac{1°C}{1000\ ft}$$

$$= \frac{1°C}{304.8\ m}$$

$$= .0032808\ \frac{°C}{m}$$


SR-4 (ET)
X = Downhole
⊗ = Uphole
1700
1750
1800
1850
1900
1950
0
20
40
60
80
100
120
140
160
180
stiff clay
Stiff clay
soft clay
OUTWASH
soft clay
outwash
BEDROCK
MYLONITE
BEDROCK
SR-4
.0070255 °C/m
RELIABLE GRADIENT
7.03 °C/km
45° Hole
intersect fault

SR-4



$$GG = \frac{10.02 - 9.89}{150 - 90}$$

$$= \frac{0.13\ °C}{60\ ft}$$

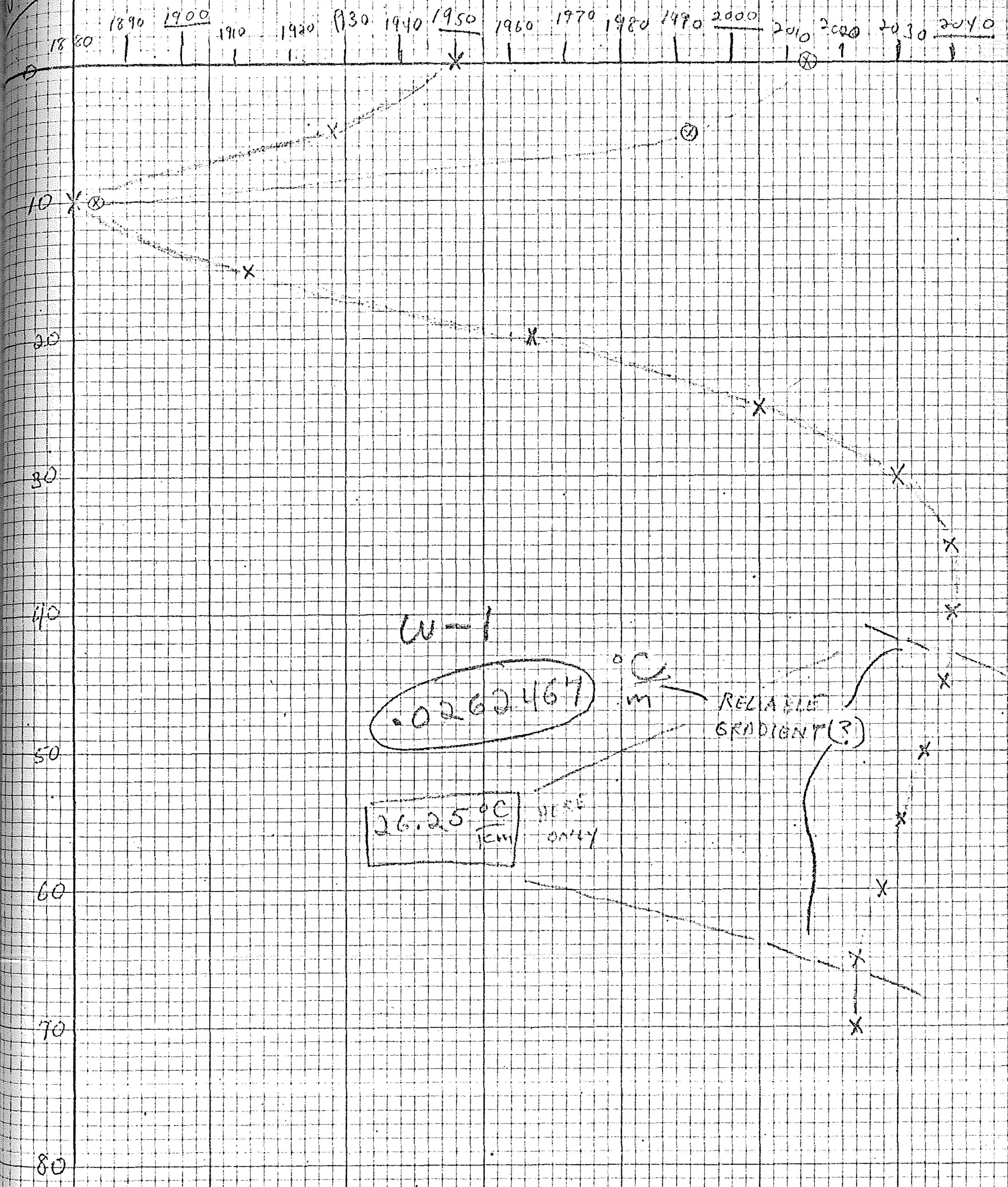
$$= \frac{1.3\ °C}{600\ ft}$$

$$= \frac{1.3\ °C}{185.04\ m}$$

$$= .0070255\ \frac{°C}{m}$$

HOLE W-1

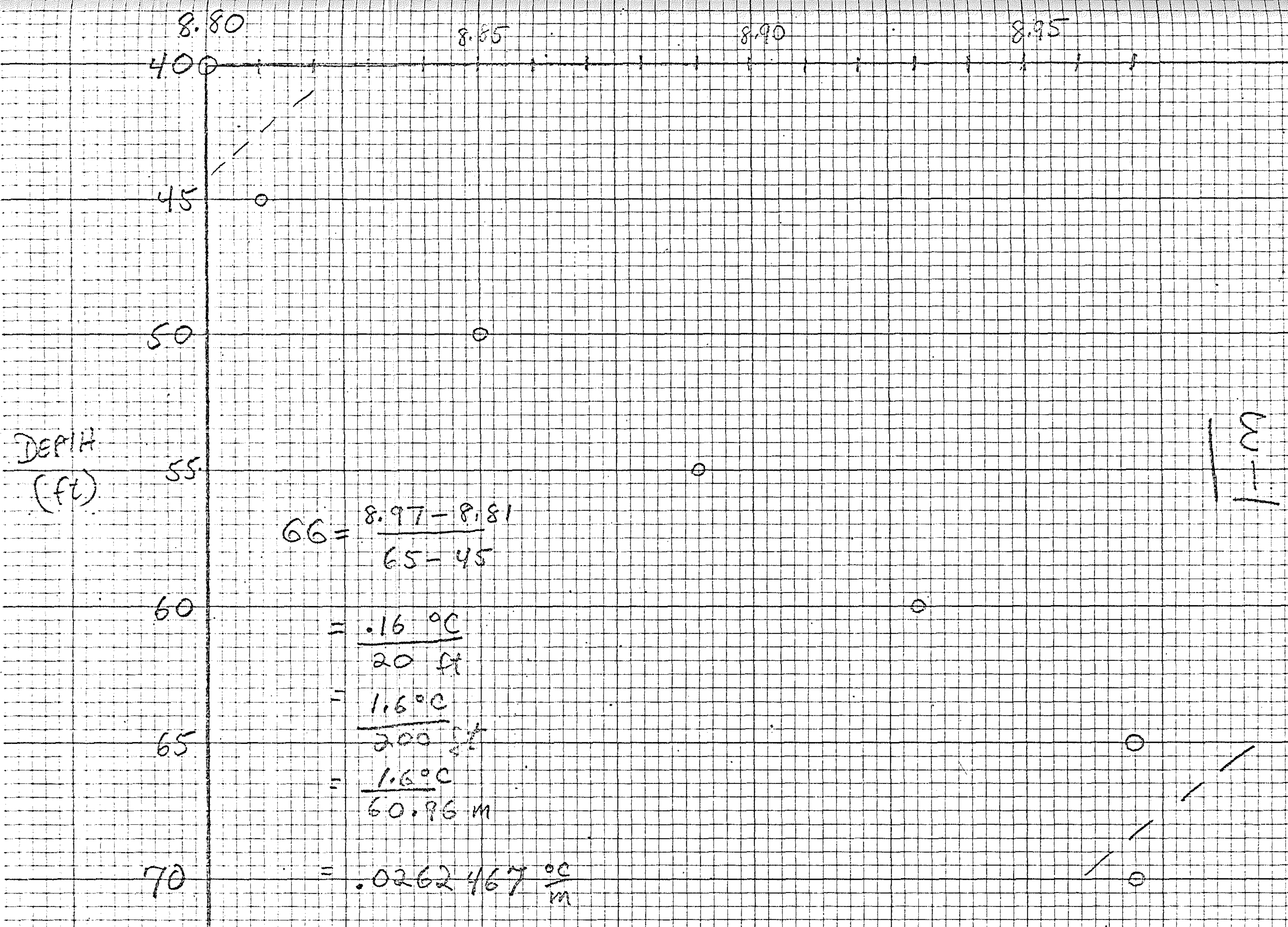
X = Downhole
ⓧ = Uphole



W-1

.0262467 °C/m — RELIABLE GRADIENT(?)

26.25 °C/Km HERE ONLY



$$GG = \frac{8.97 - 8.81}{65 - 45}$$

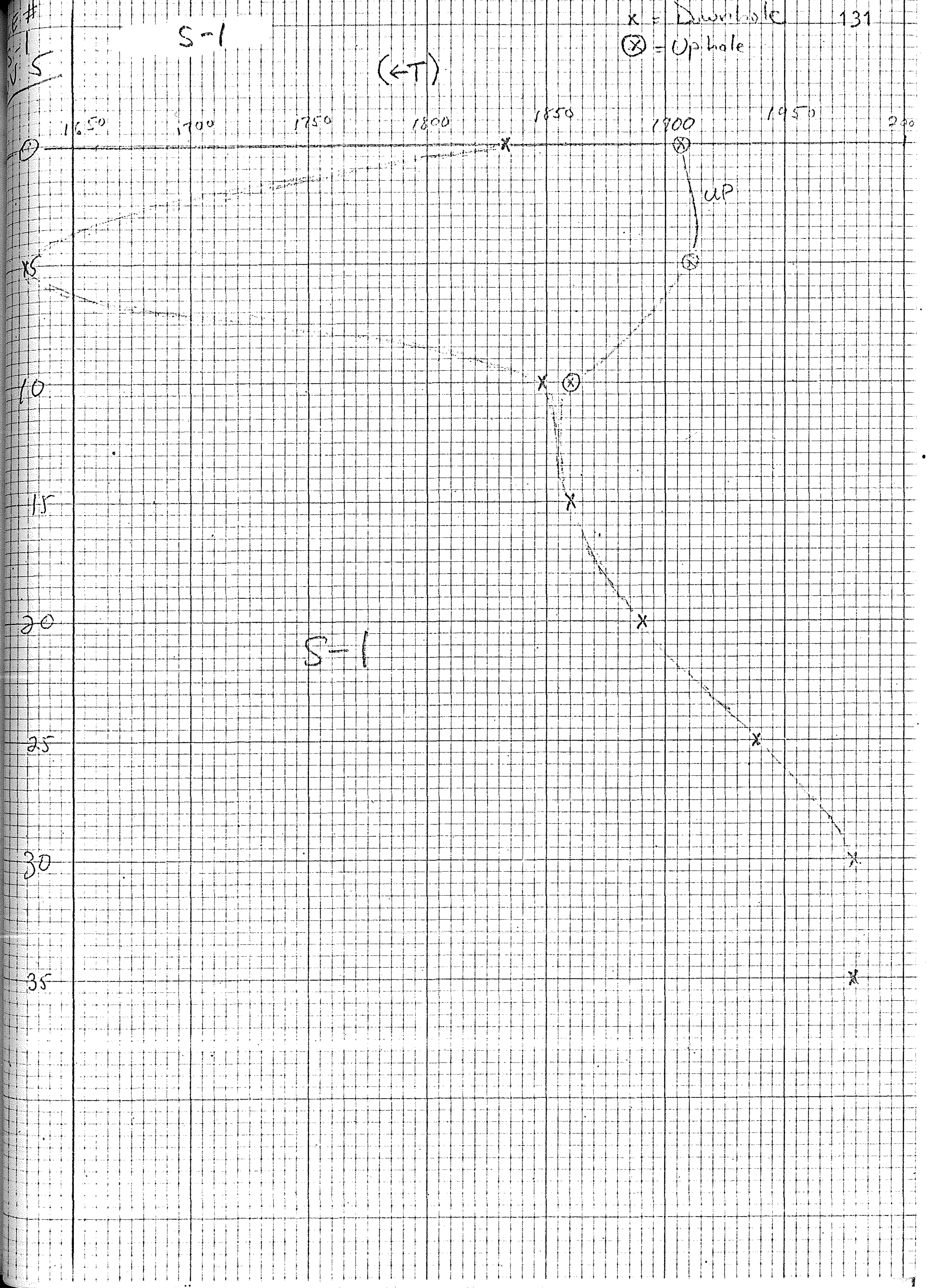
$$= \frac{.16\ °C}{20\ ft}$$

$$= \frac{1.6\,°C}{200\ ft}$$

$$= \frac{1.6\,°C}{60.96\ m}$$

$$= .0262467\ \frac{°C}{m}$$

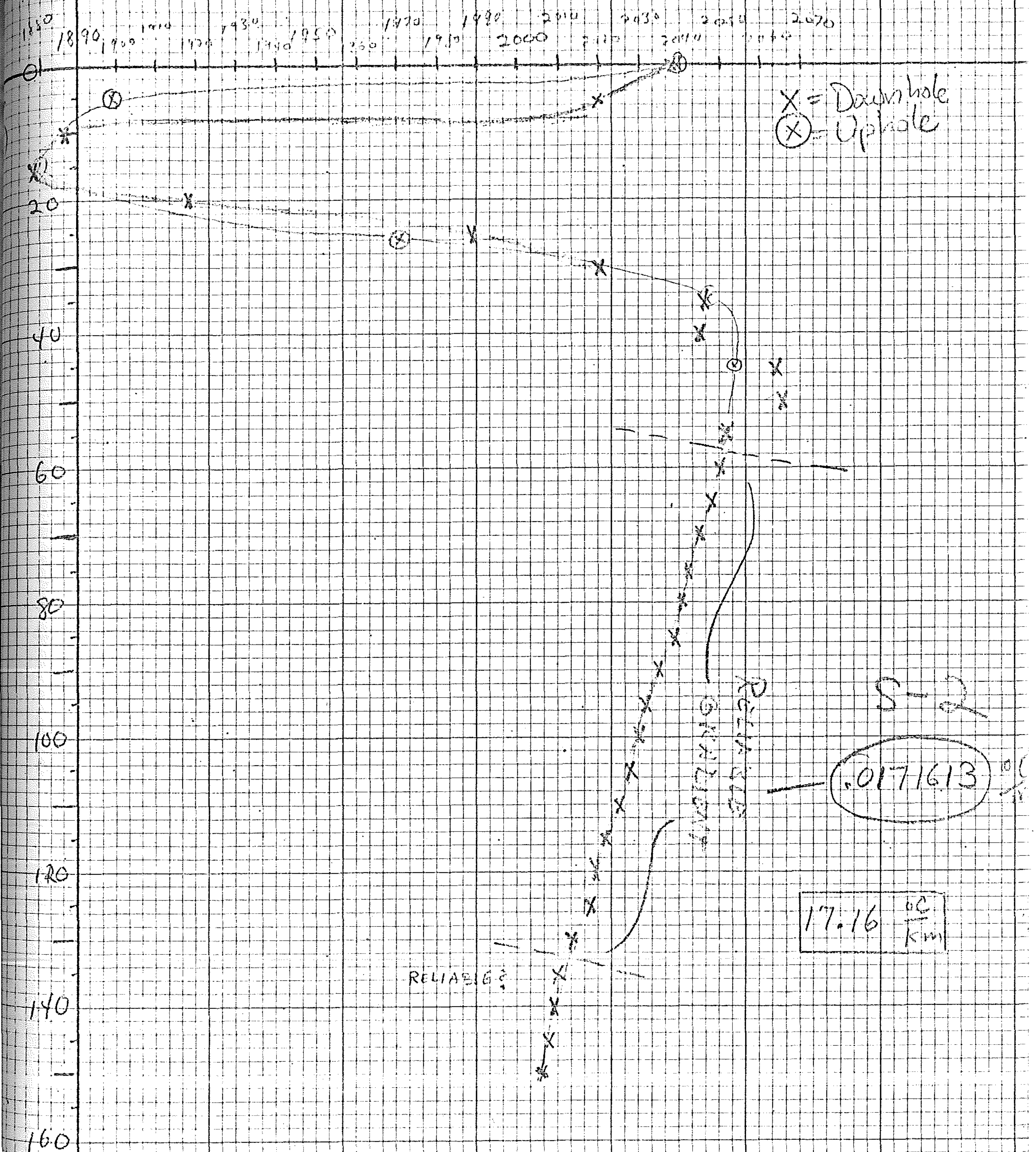
S-1


x = Downhole
⊗ = Uphole
(←T)
1650
1700
1750
1800
1850
1900
1950
2000
0
5
10
15
20
25
30
35
UP
S-1

S-2

(LT)

NOV '7


1880
1890
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1910
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1990
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2030
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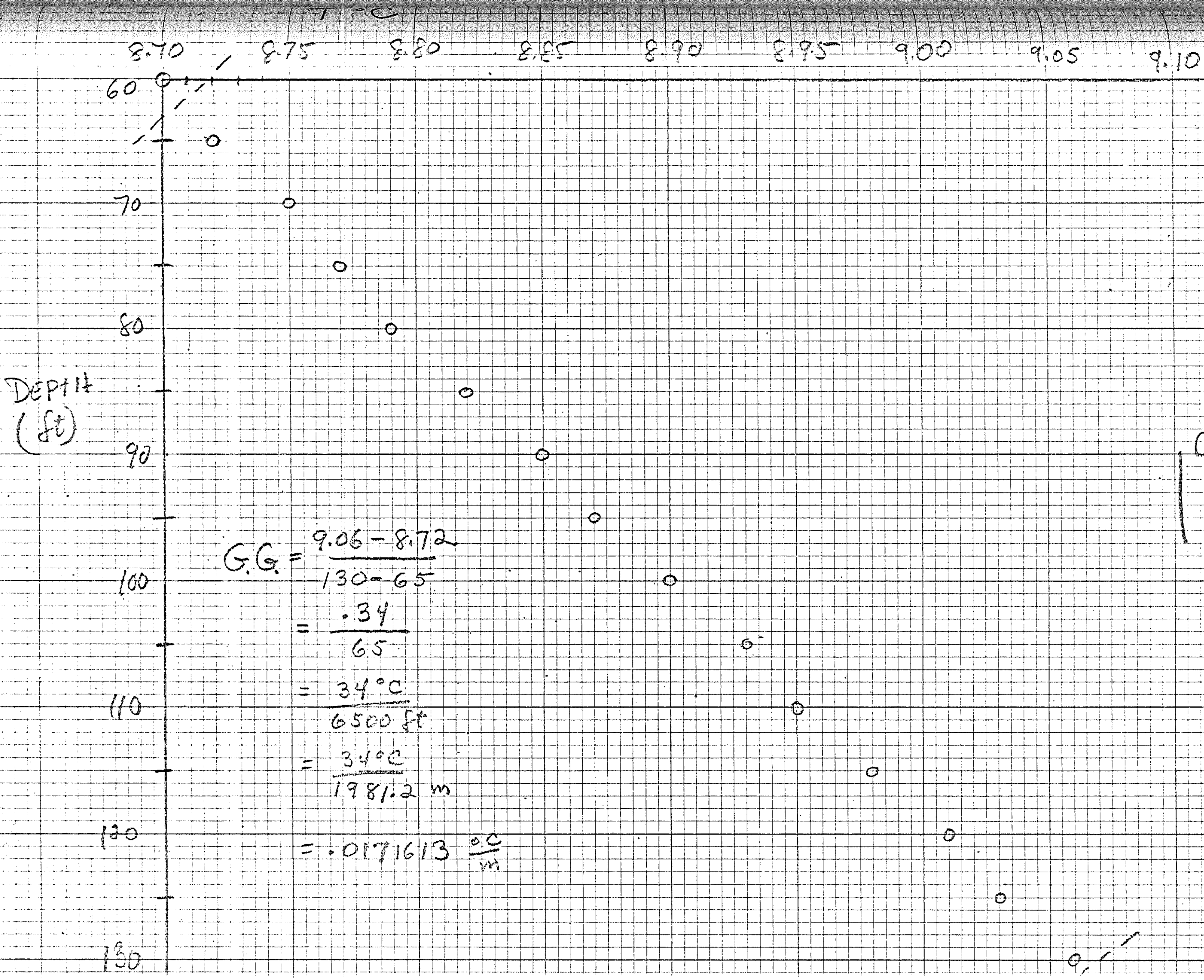
2060
2070
0
20
40
60
80
100
120
140
160
X = Downhole
(X) = Uphole
Retained
Gradient
RELIABLE?
S-2
.0171613
17.16 °C/Km

S-2



$$G.G. = \frac{9.06 - 8.72}{130 - 65}$$

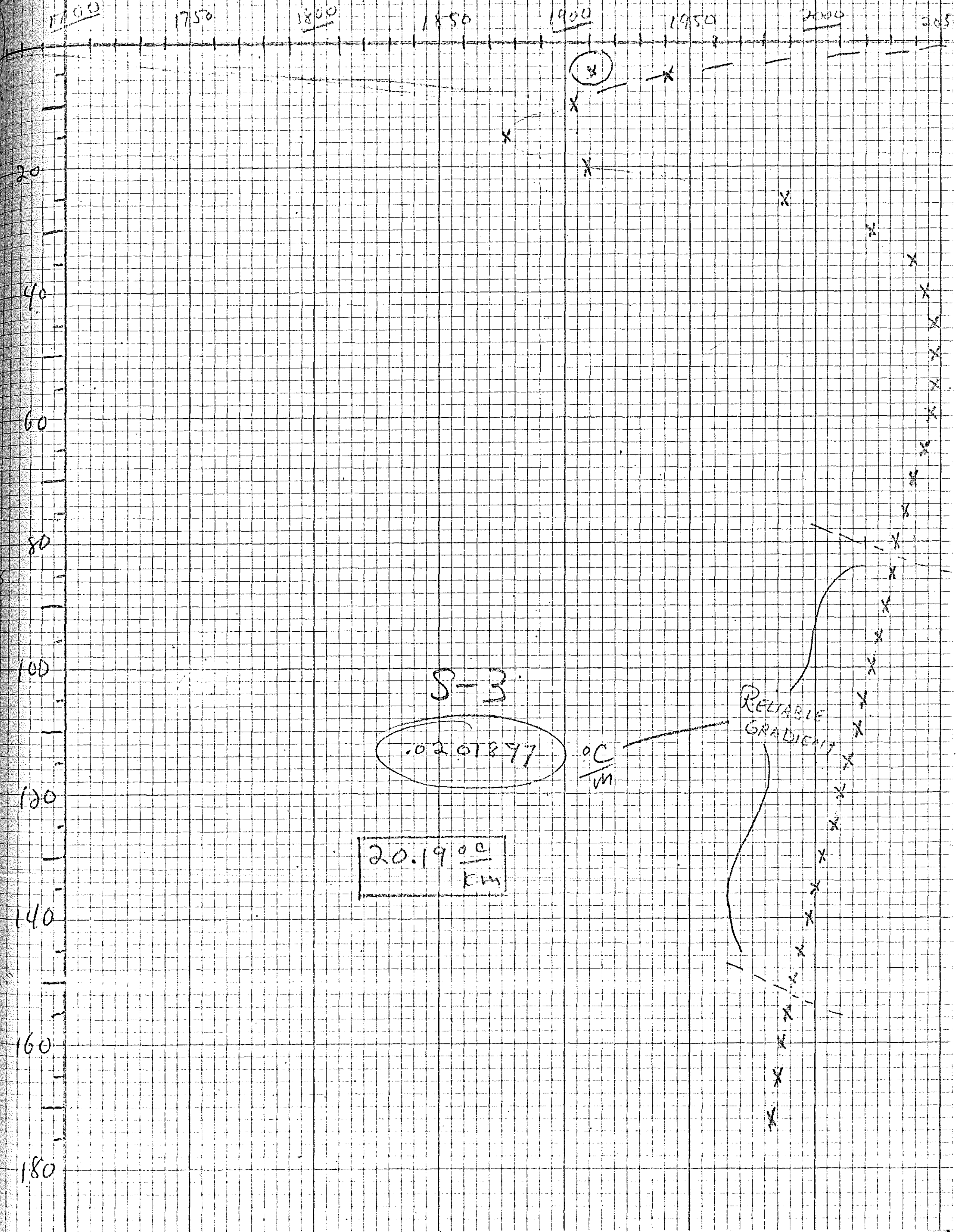
$$= \frac{.34}{65}$$

$$= \frac{34\,°C}{6500\ ft}$$

$$= \frac{34\,°C}{1981.2\ m}$$

$$= .0171613\ \frac{°C}{m}$$

S-3 (←T) NOV 12



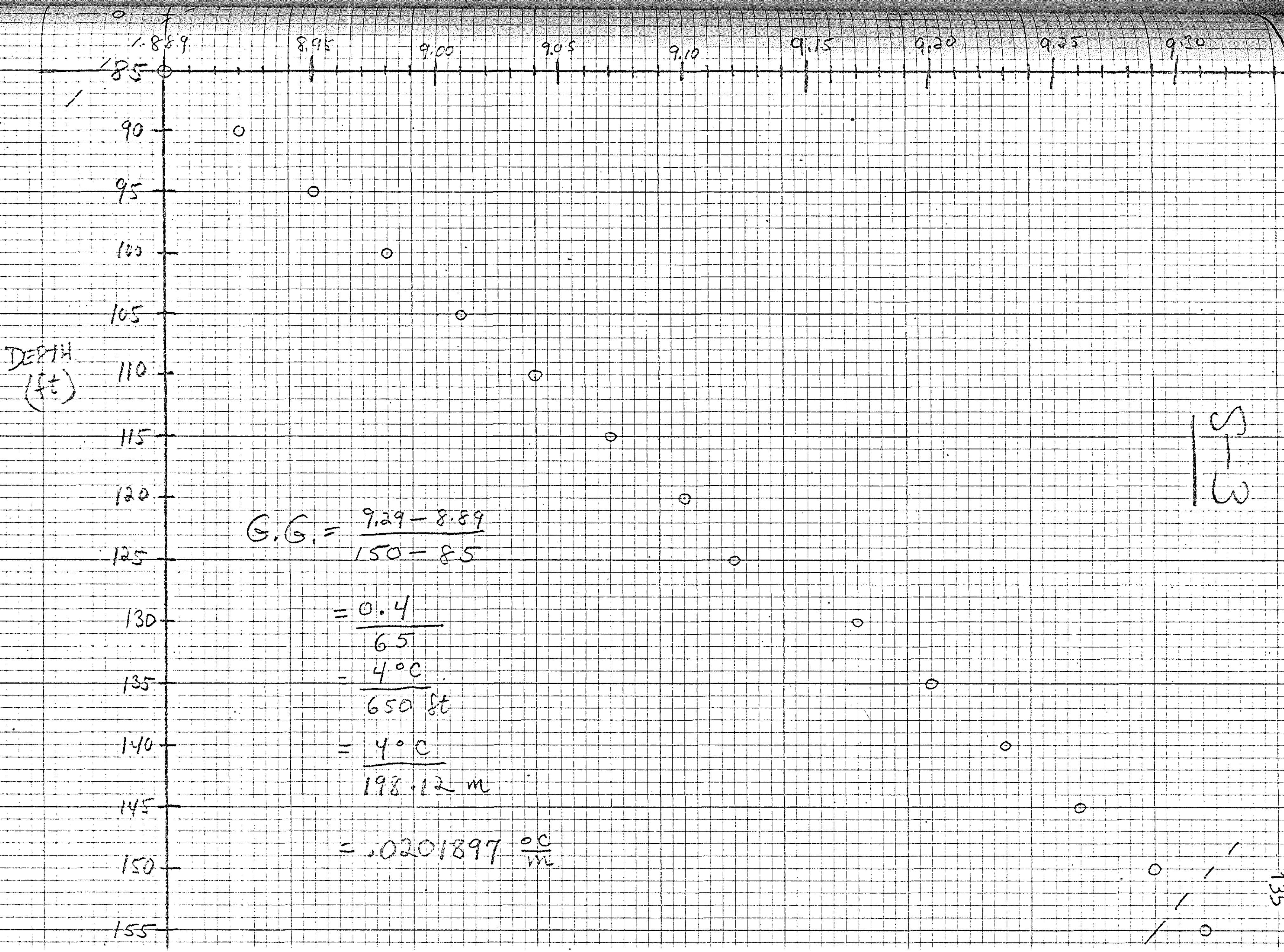
S-3

.0201877 °C/m

RELIABLE GRADIENT

20.19 °C/km

S-3



$$G.G. = \frac{9.29 - 8.89}{150 - 85}$$

$$= \frac{0.4}{65}$$

$$= \frac{4\,°C}{650\ ft}$$

$$= \frac{4\,°C}{198.12\ m}$$

$$= .0201897\ \frac{°C}{m}$$

CHAPTER VII. CONCLUSIONS AND ACKNOWLEDGEMENTS

CONCLUSIONS

Much of geothermal technology in the United States is still underdeveloped simply because Americans have not yet had to rely greatly upon geothermal energy for for domestic usage of heat or energy. The depletion of fossil fuels and the resulting steady drain on related industries underscores the need for increased research and development.

Legally, geothermal energy occupies an untenable position. Judicial action will be necessary to classify geothermal energy. Presently it has not been legally determined whether geothermal energy sources should be classified as water, gas or a mineral. Definite decisions in this area are needed to determine tax and ownership status along with economic considerations associated with utilization. Different types of geothermal resources have unique problems concerned with localized geology, environmental impact, regional geography, projected power output and other associated questions.

In the greater New England area more data are needed concerning heat flow in intensely faulted zones and geological and geophysical analyses of natural and thermal spring systems. No such concentrated research has been done. There have been no heat flow studies made in vital faulted zones of the Taconic, Green Mountain and Berkshire systems, nor along the Clinton-Newbury, Bloody Bluff, Mystic or other fault zones of southeastern New England. The thermal springs of the region have not been analyzed for geothermal potential at depth by such methods as silica and gas percent or by Ca-Na-K ratios, which are considered standard investigations of thermal spring waters the world over. Indeed, a reliable geologic and tectonic map of these areas does not presently exist. The area has not been geologically mapped since Dale's work in 1923.

Despite this lack of information the author concludes that the two thermal spring systems of the New England area display definite geothermal potential, as does the Conway Granite. The thermal springs, Sand Spring in Williamstown, Massachusetts and Lebanon Warm Spring in Lebanon Springs, New York, have potential for domestic heating purposes. The exact extent of their heating capabilities is subject to some amount of debate but theirs is the range of temperature which has been successfully utilized for the heating of swimming pools, biodegredation, fermentation processes, warming water for year-round mining in cold climates, de-icing, hatching and farming of fish and shrimp and soil warming for agricultural and horticultural purposes. There is also the possibility that there is mixing of the thermal water with cooler ground water near to the surface, thereby diluting the heat concentrations to those observed. The author has identified what may be an extensive thermal spring system which appears to exist along a contact of Stockbridge Limestone with both the Berkshire Schist and the Cheshire Quartzite formations.

The high heat flow observed in some areas of the Conway Granite in New Hampshire is an indication that geothermically useful heat will be reached by drilling to a depth far less than in areas of normal heat flow. One estimate of the amount of heat in the Conway Granite is that the heat at a depth of 10 km was about 400°C before the intrusion of the White Mountain Volcanic-Plutonic Series approximately 185 m.y. ago (Birch et al., 1968). In the same study the assumption was made that a layer of Conway Granite 10 km thick would generate all the heat now coming to the surface in north-central New Hampshire (See figure 5-1). The estimates are said to be in reasonable agreement with those of Joyner (1963) for the thickness of the Conway Granite required to explain the White Mountain gravity low.

The radioactivity responsible for the high heat flow in the Conway Granite is also responsible for interest in its mineral potential. In January of 1975, New Hampshire Governor Meldrim Thompson Jr. asked the United States Interior Department to fund a study of the mineral potential of the Conway Granite. Uranium and thorium, along with columbium, fluorite, berylium, tin, iron, feldspar, quartz and scrap mica are to be studied for possible extraction (Jarvis, 1975).

Hopefully these geothermal possibilities in the New England area will be further investigated for addition to the area's supply of energy sources. Investigations of this sort will not only be important scientifically but will benefit the community and will have important economic benefits. As an alternate source of energy, the demand for such can only become greater.

ACKNOWLEDGEMENTS

I acknowledge with thanks the assistance of James W. Skehan, S.J. and John Devane, S.J. in the formation and development of the project as my thesis advisors; the advice, loan of equipment and assistance in data analysis of Gene Simmons of M.I.T.; Mary Chessman for the assistance in preparing and using equipment and data; Marc Eccles, Jack Rand, consulting geologist, and Richard Holt of the Weston Geophysical Engineers, Inc. and John Herrin and Richard Staples of the Public Service Co. of New Hampshire for access to data from their survey of the Scotland Rd. Fault area; Donald F.X. Finn for providing endless assistance and encouragement in the field of geothermal energy; James J. Centorino and John Kroen of Salem State College for assistance in making field measurements; Donald Goodell, Joseph Sinnott, Bruce Hansen, Mr. and Mrs. Robert Carlin and Michael Meehan for information concerning Sand Spring; Donald Fisher, Joseph Salls, Mr. and Mrs. Stephen Stouter, Mrs. Emma Poore, Mr. and Mrs. Warren Wiegand and Lillian Cummings for information concerning Lebanon Warm Spring; Michael Chinnery and John MacFadyen for information on geology and seismicity of western Massachusetts; Carl Edwards, H.G. Savage, Robert Olsen, Daniel Linehan, S.J. for information concerning natural springs in the New England area; Pablo Huidobro for assistance in statistical data analysis; Brian Koch and Marylin Grant for extended loans of texts and Ms. Kathleen E. Kroen for manuscript review, typing and unrelenting support throughout the project.

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