The ORE BIN
Volume 28, No. 7
July, 1966

ENERGY AND POWER OF GEOTHERMAL RESOURCES

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Introduction

Geothermal resources are now being utilized for power generation and building heating in a number of locations in the world (see companion article by Groh). This industry is of a rather recent origin and has not yet been developed to its full capacity. A great number of undeveloped geothermal areas are found in various locations, mainly in the Circum-Pacific Belt. The State of Oregon obviously has a number of geothermal prospects.

The geothermal industry has many procedures and principles in common with the petroleum industry, although there are, as a matter of course, a number of peculiarities resulting from the special thermal processes involved. A considerable amount of descriptive literature is available on the various phases of the geothermal industry, but relatively few papers discuss the underlying physical principles.

The present paper has been written for the purpose of giving a brief review of the main physical concepts that have to be taken into consideration in geothermal exploration and exploitation. The material presented is largely an outgrowth of the writer's own experience in this field, both in Iceland and in other parts of the world.

For further information on this field, the reader is referred to the many important papers presented at the United Nations Conference on New Sources of Energy in Rome, 1961.

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Heat Flow in Nature

It is well known that the temperature of the earth increases with depth, but the rate of increase varies considerably. In general, the values obtained for areas which are undisturbed by volcanism and thermal activity fall between 10° and 50° C/km. Hence, the normal temperature at the depth of one kilometer should be a few tens of degrees C. The temperature gradient indicates that the earth is losing heat by conduction at an average rate of about 1.5 microcal/cm^2 or about 60 kW/km^2. The major part of this heat flow is the result of a generation of heat by radioactive materials at depth. A minor part may possibly represent a very slow cooling of the earth.

Convection, that is, mass transport of heat by subsurface fluids such as magma, waters, and gases, is a much more efficient mode of transport than conduction; but its influence is restricted to certain areas where the transporting fluids are available, and, moreover, where they can move through the rock formations. The places where the convective transport dominates are the areas of volcanism and thermal activity, which are generally located along certain definite global structural features such as the Circum-Pacific Belt and Mid-Atlantic Ridge. It is believed that the deep large-scale fractures in these belts provide the necessary channels for magmatic fluids to rise from depths of more than 100 km to the surface or to near-surface layers.

The temperature of the magma at depth is of the order of 1,200° to 1,500°C and it follows that the sensible heat (above 0°C) carried by this magma is of the order of 400 to 500 calories/gram, or about 500 kWhr/ton. A considerable amount of heat is therefore carried by each unit mass of magma. The rising magma is partially poured out at the surface in the form of lava by volcanoes, and partially trapped in near-surface layers where it forms intrusives of various types and shapes such as stocks, dikes, and sills. There are indications that the amount of magma forming intrusives is considerably greater than the amount of lava which has been poured out at the surface. The size and distribution of intrusives varies greatly.

A body of magma which has been injected into the upper parts of the crust will be cooled because of both conductive and convective heat losses to the surrounding rock. The process of cooling is rather slow, even on the geological time scale. For example, the time required for a purely conductive cooling of a sill having a thickness of one km is of the order of a hundred thousand years. It is obvious that large intrusives supply a very great amount of heat to the surrounding country rock.

Magma has in many locations been intruded into, or close to, porous and permeable water-bearing horizons relatively near to the surface. The heat escaping from the cooling magma raises the temperature of the country rock and this may result in the setting up of convective ground-water currents involving high-temperature waters. The convecting fluids carry great amounts of heat to the surface where thermal water, steam, and gases are issued by springs. Moreover, the convective currents greatly contribute to the distribution of the magmatic heat to the surrounding country rock.

These conditions exist in the well-known thermal areas which are found in most of the volcanic belts of the world. The thermal areas vary considerably in size and subsurface temperature. In the largest, surface thermal activity may be scattered over surface areas of tens of square kilometers and the total flow of sensible energy escaping from these areas in the form of hot water, steam, and surface conduction cooling may be of the order of one million kW of heat flow. Measurements of the energy escaping from thermal areas in Iceland and New Zealand indicate that in each country these areas dissipate a total of about 5 million kW of heat flow.

Although the magmatic origin of thermal areas has been stressed above there are good reasons to mention that a number of well-known, relatively low-temperature, thermal areas may be of non-magmatic origin. They may represent the outlets for circulation systems which reach considerable depths, for example, 3 km where the normal temperature would be of the order of 100°C.

The Geothermal Reservoir

In the previous paragraphs we have drawn a crude picture of thermal areas in general and stressed the volcanic, that is, magmatic origin. On this basis we can conclude that the major high-temperature thermal zones consist essentially of two parts, first, the primary magmatic heat source, and second, the permeable water-bearing formation heated by the primary source. This second part forms the geothermal reservoir or heat mine, which in many cases can be exploited profitably.

It is only fair to stress the uncertainty of some of the concepts applied. In fact, although a considerable amount of research has already been carried out in some geothermal areas, very little concrete information is available as to the source-reservoir relation. This is still one of the major problems of geothermal research.

Sufficient information is available, however, to draw the sketch in Figure 1. This sketch shows a primary heat source, which may consist of a single large intrusive, or of a great number of dikes, emplaced directly below a horizontally layered reservoir rock located near the surface. Heat is being conducted and convected into the reservoir, which has been heated to a temperature considerably above the normal for its depth. The reservoir is assumed to have a relatively large horizontal permeability along the contact of individual layers. Hence, the encroaching ground water can flow into the reservoir rock.

Reservoirs of this type are encountered in some of the large thermal areas in Iceland, where the reservoir rock consists of a series of flood basalts 2 to 4km thick. The horizontal permeability along the contacts of

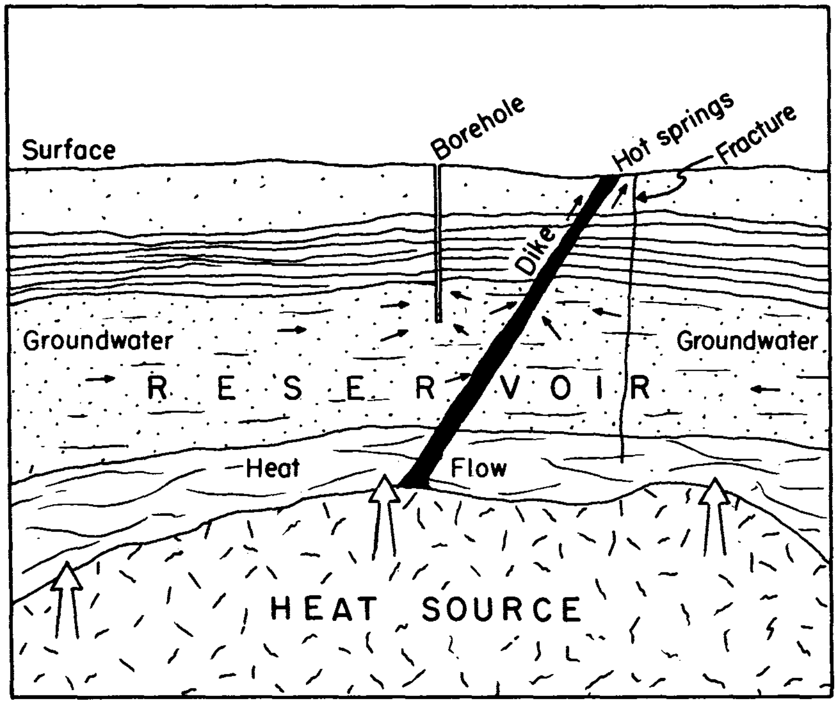

Figure 1. Sketch showing relationship of heat source to reservoir.

some of the lava flows is very great. A somewhat similar situation is encountered in the well-known thermal areas in Tuscany, Italy, where the reservoir consists of essentially a sedimentary series containing thick layers of limestones with solution openings. The thermal areas of New Zealand are also rather similar, since the reservoir there consists of a thick layer of highly permeable sediments. The horizontal extent of the reservoirs in these countries amounts to tens or hundreds of square kilometers.

With the help of this simple sketch, we are in the position to discuss a few important concepts which, to a certain degree, provide the foundation of geothermal reservoir mechanics. Within this context, it is helpful to realize that there is a rather close similarity between some of the processes encountered in petroleum and geothermal reservoirs.

Temperature measurements in boreholes in the major geothermal regions of the world have shown that the reservoir temperature is rather uniform below a certain depth, which may amount to a few hundred meters. This situation is indicative of a high permeability, since convection currents in the reservoir tend to equalize the temperature in the rock. The reservoir temperature at depth is perhaps the most important single reservoir concept and it has been called the base temperature of the thermal area. It is remarkable that the base temperature of the most of the major thermal areas of the world now under exploitation appears to be around 250° C.

The depth to the bottom of the reservoir is another concept of importance. This depth, which is sometimes called the base depth, is a vaguer idea than the base temperature. It depends on the permeability - that is, the reservoir terminates at the depth where the rocks become impermeable. There is little doubt that the reservoir depth is generally not less than 2 or 3 kilometers.

Two physico-chemical facts are of importance. First, the density of water at temperatures between 200° C and 300°C is considerably lower than the density below 100°C. For example, the density at 250°C is only 0.8 gm/cm^3, whereas the density at 50°C is 0.99 gm/cm^3. The high-temperature water within the reservoir, therefore, has a considerably lower density than the surrounding colder ground water. The surrounding water will exert a hydrostatic pressure on the reservoir and the density difference will then provide a strong gravity drive, if we borrow this concept from petroleum reservoir mechanics. Second, the solubility of many minerals in water increases substantially with the temperature; in this respect, silica is of particular importance. Moreover, the solubility of calcite is dominated by the amount of dissolved carbon dioxide. Since both temperature and pressure increase with the depth, we can expect the solubility of minerals to be much higher in the lower parts of the reservoir than in the near-surface layers. The reservoir fluids will, therefore, have a tendency to dissolve materials at depth and precipitate them near the surface. In many cases this leads to the formation of a rather impermeable cap rock above the main reservoir. Large thermal reservoirs may, for this reason, show very little surface display.

In geothermal reservoirs, heat is the principal commodity of economic value. It is, therefore, of utmost importance to be able to derive a measure of the heat content of a given reservoir. The above considerations show that this quantity will be proportional to the product of the reservoir volume and the sensible base temperature - that is, the excess reservoir temperature. In reservoirs with a base temperature of 250° C the excess temperature is of the order of 150° C, and it is easy to derive that the sensible heat energy content is then about 90 cal/cm^3 or about 100 kWhr/m^3. In the present context a more convenient unit is the MWyear, which is equal to 8.7 million kWhr. Expressed in this unit, the heat energy content would be roughly 10,000 MWyears/km^3. Hence, the total sensible heat energy content of a reservoir having a base temperature of 250° C, a thickness of 2 km and a horizontal extent of 50 km^2 would be about one million MWyears.

The available power, or rate at which this energy can be tapped, is another concept of great economic interest. Since water is the heat carrier, and the energy has to be "washed out" of the reservoir by the water flowing through it, the available power will depend completely on the magnitude and the geometry of the permeability of the reservoir - that is, on the rate at which water can be driven through it. It is independent of the energy content. A large reservoir with a negligible permeability may contain lots of energy, but its power is zero.

Exploitation

As already indicated, the exploitation of geothermal reservoirs is effected by a "washing out" of the sensible heat content of the rock. Wells are drilled into the reservoir in order to cut available fissures and permeable contacts. Because of the gravity drive of the encroaching colder ground water surrounding the reservoir, the high-temperature water in the fissures will be under artesian pressure and, in general, the wells will flow when a fissure has been cut. On the way to the surface, a part of the thermal water flashes to steam. Wells of this type will, in general, produce a steam-water mixture. Under certain circumstances, where there is a large exchange of heat between the water and the rock, the wells may even produce dry saturated or slightly superheated steam. The water produced by the wells is partially or wholly replaced by the inflowing ground water encroaching on the reservoir. Upon contact with the reservoir rock, this water is heated to the reservoir temperature and new thermal water is produced.

The heat-recovering process described above can theoretically be carried out as long as there is heat and water available. Moreover, under ideal circumstances, most or all of the sensible reservoir heat could be recovered. But actual situations are far from being ideal. In general, the permeability of the reservoir rock is unevenly distributed and the efficiency of the heat recovery is greatly reduced. This important matter will not be discussed further, but it is the opinion of the writer that under reasonably good circumstances the recovering of roughly 10 percent of the total sensible heat content should be possible.

If we base our considerations on a 10 percent recovery, we find that the geothermal reservoir discussed above, containing a total of one million MWyears of sensible heat, could produce about 100,000 MWyears of heat energy. Since a MWyear of heat energy corresponds to the heat content of about 5,000 bbls of petroleum, the reservoir would thus be roughly equivalent to an oil field containing about $\frac{1}{2}$ billion bbls of petroleum. This is an oil field of a substantial magnitude. The heat produced by such a reservoir is available in the form of a steam-water mixture produced by the wells and it can be utilized directly for building heating and chemical-process heating.

It is well known that the conversion of heat to electrical energy is a process of a limited efficiency. Thus, the conversion of the heat content of the steam-mixture produced by the wells to electrical energy has an efficiency of only about 10 percent. Hence, the over-all efficiency of the conversion of reservoir heat to electrical energy has an estimated efficiency of about one percent. In terms of electrical energy, the reservoir discussed above will be able to produce a total of 10,000 MWyears of electrical energy, that is, operate a power plant of 100,000 kW for a period of 100 years.

Exploration

In the initial exploration phase of a geothermal situation, we would be mainly interested in obtaining data on the following important characteristics: (1) the base temperature; (2) the horizontal extent and thickness of the reservoir; and (3) the permeability and the hydrological conditions.

The technique of exploring geothermal resources by the means of geological, geophysical, and geochemical methods falls into two classes: (1) the so-called direct or temperature-sensing methods, which have the aim of obtaining data on the subsurface temperature field, particularly the base temperature and the reservoir dimensions; and (2) the indirect or conventional structural methods, which have the principal purpose of uncovering the geological structure and providing information on the permeability situation. Since the second class of methods is largely identical with the conventional geological and geophysical methods in petroleum exploration and hydrology, our attention will be directed toward the direct methods which are of special importance in geothermal exploration. Three types of temperature sensing methods are available.

First is shallow temperature probing by the means of boreholes with depths ranging from 10 to 100 feet. An array of such boreholes is laid out in the area to be studied, and the temperature profile is measured accurately. Geothermal areas, even those with no surface display, will exhibit abnormally high temperatures in these boreholes. As of now, shallow probing is the most important direct exploration method in geothermal areas. This method yields important data on the magnitude and horizontal extent of geothermal anomalies. It has been used with success in many areas around the world. The relatively high cost is the main drawback of this method.

Second, the chemistry of water and gases issued by surface springs is indicative of temperatures at depth. As already pointed out, the solubility of many minerals in water is highly temperature dependent. Silica is mainly interesting because of its very slow precipitation from supersaturated solutions. The silica content of thermal waters issued at the surface will, in many cases, be almost equal to the silica content of the reservoir fluids. Since there is a relation between the solubility and the temperature, the silica content of the surface water will be indicative of the reservoir temperature and hence of the base temperature. This method has to be used with some care, since the nature of the reservoir rock has a dominant influence on the solubility of silica. But it has been of rather great value in Iceland, where conditions are quite favorable.

The third group consists of the D.C. conduction and the electromagnetic methods which measure the electrical conductivity of the subsurface. Due to high temperatures and relatively high concentrations of minerals in solution in thermal waters, the typical geothermal reservoir has a much higher electrical conductivity than ordinary rock formations. There may be a factor of 100 or even 1,000 involved. It is, therefore, possible to study geothermal reservoirs on the basis of electrical prospecting methods. But the D.C. conduction method has a rather limited depth penetration and the electromagnetic methods are still in an early stage of development.

Economics of Geothermal Heat Production

Under favorable conditions geothermal areas can provide a very inexpensive source of heat. Unfortunately, few reliable data have been made available on the production economics, but the following figures obtained from sources in Iceland should give a reasonable basis for areas where conditions are not too unfavorable.

Boreholes for natural steam in high-temperature thermal areas may have to be 2,000 to 5,000 feet deep and the main casing should have an inner diameter of not less than 8 inches. A borehole of this type can produce as much as 100 tons/hour of steam. The distance between individual boreholes may be several hundred feet. Including well-head facilities and piping of the steam to a collection center in the area, the total investment in boreholes and equipment has, in Iceland, been on the order of $5,000 per ton per hour of steam flow. On the basis of an interest rate of 6 percent, the production cost per unit mass steam delivered can be on the order of $0.15 to $0.20 per ton of steam delivered. These figures apply to relatively small installations. As a matter of course, the cost figures may vary considerably between areas.

In terms of cost per unit electric energy generated by natural steam, the above figures would indicate a steam cost of 1.5 to 2.0 mills per kWhr of electric energy. In the case of large installations under favorable conditions, a figure of 1.5 mills/kWhr should be easily obtainable.

Reference

United Nations, 1964, New sources of energy: Proceedings of the Conference, Rome, Aug. 21-31, 1961, vol. 2, Geothermal Energy I, viii and 420 p., and vol. 3, Geothermal Energy II, ix and 516 p.

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PLEASE STAY OUT OF OLD MINES!

Once again, please, if you are out in the hills just looking around, stay out of any old mines you come upon. The rock that was in the mine, along with any pretty minerals, is now on the dump. Look for them there.

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GEOTHERMAL ENERGY POTENTIAL IN OREGON

By Edward A. Groh*

An enormous source of heat exists within the depths of the earth. Throughout most of the world's surface this heat is too deep and too diffuse to be utilized as energy, but along the volcanic belts a concentration of it lies near the surface. Within these belts, displays of surface heat such as geysers, steam vents, and hot springs have captivated man's interest for centuries. Now, at several "hot spots" about the world, thermal energy has been put to work developing a total capacity of 1 million kw of electric power as of this date.

World Geothermal Development

The first harnessing of natural steam for electric power was accomplished at Larderello, Italy, a little more than 60 years ago. Production has now risen to 370,000 kw, and other thermal areas in Italy are being explored. At its Wairakei Hot Springs area on North Island, New Zealand has developed more than 150,000 kw capacity and expects to reach 250,000 kw in the near future. Other thermal areas of the North Island are also being explored. Some 50,000 people in the vicinity of Reykjavik, Iceland, are provided residential and building heat by natural hot water. Since Iceland has sufficient stream flow for economic hydroelectric power generation, there is no immediate need for geothermal power development; however, studies in this field have been made. Besides these three examples in foreign lands, exploration and development is going on also in Japan, Mexico, USSR, Central America, Kenya, Java, New Britain, and the Fiji Islands, and a number of other countries are beginning to look at their geothermal potential.

It has been only within the past 10 years that geothermal power has received serious attention in the United States. Increasing demands for energy have prompted the utilization of natural steam at The Geysers, Calif. This locality, which has long been known for its natural steam vents, is now operating at a capacity of 27,000 kw. A similar capacity has been produced recently from wells drilled about a mile to the west and an additional generating installation is planned. Exploration at Casa Diablo, Calif., and at Beowawe and Brady Hot Springs in Nevada indicate a power capacity

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which may be exploited in the near future. Unusual are the wells which have been drilled in the Niland, Calif., vicinity. Here a concentrated brine and steam mixture is produced which is very hot (450°F or more), and bottom-hole temperatures as high as 800°F have been measured. The brine alone may be valuable for recovery of its contained potash, lithium, copper, and silver.

Geologic Environment of Geothermal Areas

Most geothermal areas known today are associated with structural features which show both uplift and subsidence in the belts of recent volcanism. The movement of magma within the crust and to the surface is believed to be the major factor producing these structures. Several of the geothermal areas are located on primary rift zones of the world, where heat presumably is flowing up from greater depths within the earth. Many of these features have their counterparts in Oregon, as will be discussed later.

Although surface display of steam or hot water is a great aid in the location of geothermal reservoirs, it is not necessarily present in all reservoirs. Without surface indications, reliance must be placed first on finding geologically similar structures and then on measuring the geothermal gradient by the use of shallow drill holes. Much more needs to be learned about the relationship of geothermal sources and geologic structures to aid in the application of geothermal gradient surveys for these hidden reservoirs. As the science and technology improves, hidden sources of heat will provide an ever-larger part in the supply of geothermal energy.

Role of Geothermal Energy in Oregon

Recently the Bonneville Power Administrator stated that planning must go forward on steam plants for the generation of electric power, which will be needed in the Pacific Northwest after 1975. By that time, all the economic hydropower sites of the region will be under construction or in operation. These future thermal plants will require fuel, either fossil or nuclear. Except for some coal fields in central Washington which may prove economic, the fuel resources of the Northwest are scant. At present, oil and gas are transported into the region from outside sources and are costly for power production. Even discoveries of these hydrocarbons on land or off shore in the Pacific Northwest would not necessarily make them more economic. Under the current trend of capital and fuel costs for thermal power plants, nuclear power will in all probability be the preferred type for installation in the Northwest from 1975 on.

Largely ignored in this future power picture is the role which geothermal energy could play, especially in Oregon. Of all the western states, Oregon has been favored with the greatest amount of volcanism throughout the Tertiary and Quaternary periods. Therefore Oregon should have an excellent geothermal-energy potential. It is not unreasonable to expect that 20 years from now a share of the thermal power capacity will be supplied from geothermal sources. Coupled with this expectation is the evidence that geothermal electric power can be as low in cost or lower on the average than power generated by any other method. As the technology of finding and exploiting natural steam fields improves, costs should go down, which in turn will spur greater effort in producing this natural resource. Therefore, its potential should not be discounted at this time, since development of this energy is in the state of earliest infancy.

Conversion of the heat in natural steam to electric power is the most convenient method of utilizing the energy, because electricity may be transmitted considerable distances economically. Under some conditions, though, the steam could be more valuable when used in industrial heating. Large consumers of process steam, such as the pulp and paper industry or some types of chemical plants, might find it desirable to locate near a geothermal steam field, provided that other factors were favorable. Costs per unit of heat can be very low when geothermal steam is used in this manner.

Exploration for Geothermal Sources in Oregon

Initially, the groundwork for exploration of geothermal sources in Oregon will probably fall on the public agencies concerned with geology and minerals. Field studies, mapping where necessary, temperature measurements, well logging, photogeologic studies, limited geophysical surveys, and compilation of the data will need to be accomplished in order to provide fundamental information for private industry interested in Oregon's geothermal future. Some of this preliminary work is already in progress. For example, gravity data gathered from private and public sources is being plotted at the Oceanography Department of Oregon State University, and a gravity map of Oregon will soon be published. This map should be of considerable help in interpreting a number of structures that may be related to geothermal sources. Research in the use of electromagnetic methods for outlining higher temperature zones in the earth's crust is another example of geothermal studies now in progress. There is a paucity of basic heat-flow data concerning the western states and none at all for Oregon. Information of this sort can aid greatly in delineating the hyperthermal regions of the state on which the major development efforts should be brought to bear. It is hoped that research groups now engaged in this work elsewhere can be encouraged to do some of it in Oregon.

Private enterprise has been seriously hindered so far in geothermal exploration on public lands in the United States. Exploration and development work which has been done on federal lands proceeded either under the general mining laws or mineral leasing acts. Neither provides any clear-cut legal rights of ownership regarding geothermal steam or fluids. In 1964 the Eighty-eighth Congress sought to remedy this situation by instituting a geothermal steam-leasing act. It was passed by the Senate, but failed to make the floor of the House. An improved version of this leasing act has been again passed by the Senate in the present Congress and now awaits approval in the House. It is hoped that passage will be accomplished shortly. Upon establishing the statutes governing the production of natural steam from public lands, private developers should begin to take an ever greater interest in this form of energy. Passage of this legislation is particularly important to Oregon, since within the area favorable to geothermal exploration at least two-thirds of the land area is federally controlled.

Prospective Geothermal Areas in Oregon

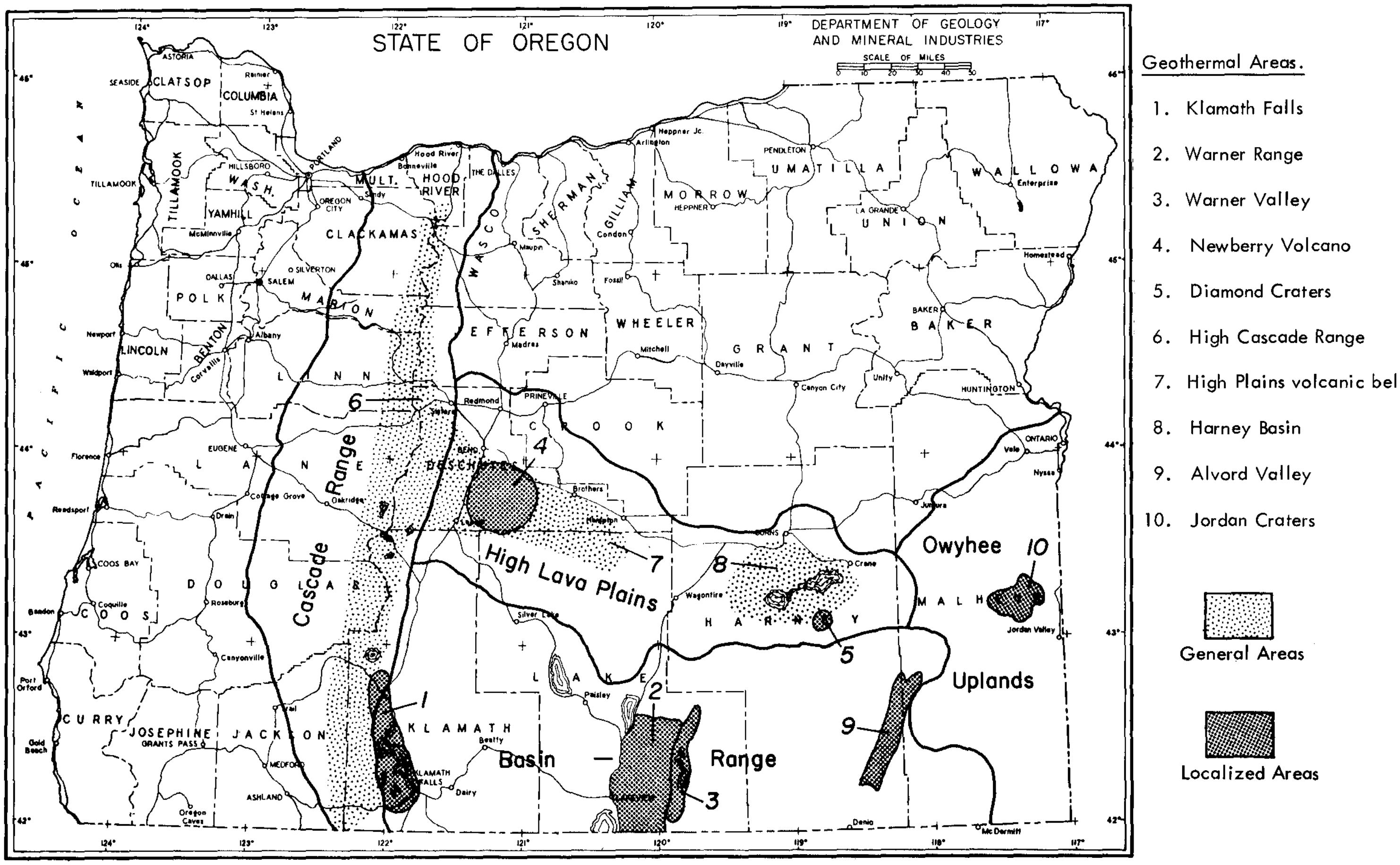
The possible geothermal areas of Oregon are, in general, within four contiguous physiographic divisions (see accompanying map): the Cascade Range, the High Lava Plains, the Basin-Range, and the Owyhee Upland. Together they form a region comprising more than 40 percent of the state's total area. Practically all of the late Cenozoic volcanic activity has occurred within this region. About 80 of the 100 thermal springs known in Oregon are found within its borders.

Some of the structural and volcanic features which appear attractive as possible geothermal sources are briefly described below.

Klamath Falls area

Within the city of Klamath Falls is Oregon's major geothermal display. The hot springs and wells drilled in the thermal area have been utilized for the space heating of many residences and other buildings since 1900. The thermal zone is located along one of the many northwest-trending faults prevalent in the Klamath Basin. To the north, a graben has formed and this major structural feature extends on towards Crater Lake. No thermal springs are present along the bounding faults of the graben; nevertheless, a geothermal potential is strongly indicated by this depression, which is believed to be associated with the volcanism in the Cascade Range to the west. Many of the faults in the Klamath Falls area have exposed slickensides indicating very recent movement. In these respects, the area resembles the Wairakei geothermal region of New Zealand, but smaller in area. The thermal fluid being discharged at Klamath Falls has a high sulphate - low chloride content which strongly suggests a volcanic origin for its heat. One is tempted to theorize on the possibility of a deeper thermal reservoir which may be leaking only a small portion of its heat upward along a fault. Mixing of this thermal fluid from depth with cool ground water may set up a near-surface convective circulation which provides the hot springs at Klamath Falls.

The large heat flow manifested in this area makes it the prime prospect in Oregon for eventual geothermal-power development. With large



PHYSIOGRAPHIC DIVISIONS AND PROSPECTIVE GEOTHERMAL AREAS IN OREGON.

power-transmission lines crossing the area already and an intertie line being built, there is no problem of a market for energy. Immediate work suggested for this prospect would be a detailed geologic field and photogeologic study, coupled with measurement of surface-heat flow. Gravity, and perhaps some seismic and electromagnetic, surveying would be the next step. Results from these investigations would determine if the risks of a full geothermal exploration program were warranted.

Warner Range

Standing as a horst bounded on the east and west by faults, this structure is of geothermal interest for the numerous hot springs along its margins. A thermal zone along the east side about 4 miles north of Adel was drilled by Magma Power Co. in 1959. Although the results were not satisfactory, the well did erupt as a continuous geyser for more than a year. Wells have been drilled and some steam produced on the eastern, or Surprise Valley, side of the extension of the Warner Range into California. On the western margin, an oil test well was drilled by Humble Oil Co. in 1961. Bottom-hole temperature at total depth of 9,564 feet was 295°F as recorded on the electric log. Since equilibrium conditions were not reached prior to the temperature measurement, true temperature is undoubtedly greater and signifies a high geothermal gradient. Near the Oregon border, late Tertiary silicic volcanic intrusions are exposed which are part of a group continuing into California. The Warner Range horst bears certain similarities to the geologic structure at The Geysers steam field. The structure at The Geysers has been attributed to upthrusting by a probable bathylithic intrusion, which may also be conjectured as a cause of the Warner Range feature.

Here, again, detailed geologic studies will be needed to appraise the potential of the area. Follow-up by geophysical surveys and, if favorable, ultimately by drilling must be done to give the answers on the geothermal potential this structure holds.

Warner Valley

This structural trough or graben lies on the east side of the Warner Range. The high scarps of Hart Mountain and Poker Jim Ridge border the graben to the east. It has a width of 5 to 6 miles and is more than 40 miles in length. A number of hot springs are present along the bounding fault zones. The close association of this feature of subsidence with its complement, the Warner Range horst, may indicate large-scale movement of magma at depth. Although much of the subsidence is Recent, the graben probably has been active since Pliocene time. This offers an opportunity for an accumulation of sediments in which the pervious beds may act as reservoirs for thermal fluids rising from depth. Again exploration of this structure will require the geological and geophysical studies mentioned for the

Warner Range. Part of the data gathered will be common to both features.

Newberry Volcano

During late Cenozoic time this immense shield cone, some 20 miles in diameter, was formed from innumerable eruptions of lava. In the latest Pleistocene a collapse of the summit began, probably from many flank eruptions which withdrew magma from the reservoir and, therefore, support from the roof. Collapse proceeded, along with some infilling by later volcanic action, to produce the caldera now called Newberry Crater. From the size of the caldera, about 4 miles wide by 5 miles long, it has been estimated that the magma chamber may lie at shallow depth, perhaps as little as 2 miles. Since the magma chamber was only partly emptied in the recent collapse, in all probability a very large body of hot magma underlies this feature. A great amount of heat must flow outward from the remaining magma and, if aided by thermal convection currents to higher levels, could offer a tremendous geothermal source. Several surface thermal indications are present within the caldera, and the caldera block would be most attractive for exploration. Because of its value for recreational purposes, the caldera is closed to any mineral exploration. Nevertheless, the great flanks of the shield are available. Although no surface thermal displays are known to exist on the flanks, this does not preclude the finding of vast quantities of heat at economic depths around the flanks.

Geothermal exploration of Newberry Volcano will require a heavy reliance on geophysical methods to seek out the hidden heat zones. There will probably be a great need for borehole surveys to determine geothermal gradients. Yet efforts may eventually prove a vast heat source.

Diamond Craters

This area is exceptionally inte esting, since preliminary study indicates that a laccolithic intrusion ha. taken place at shallow depth. After the extrusion of a lava field about 25 square miles in extent, intrusion of basaltic magma domed part of the area. An age of around 5,000 years is estimated for the intrusion. Except for the eruptive phenomena accompanying the volcanism and intrusion, no surface displays of thermal waters occurred or are evident now in the immediate vicinity. The only heat flow to the surface is by conduction alone and the intrusion should be still quite hot. The domed structure is probably a closed system. While nothing is known concerning the permeability of the laccolith, it is reasonable to expect that an influx of ground water through fractures could take place, generating a flow of steam when tapped by wells. If a natural flow did not take place or was insufficient, injection methods might be tried experimentally. Estimated thermal conditions of the Diamond Craters area do not appear to offer an immense heat source. Nevertheless, it remains as an intriguing area where high temperatures probably can be reached at a depth of around 1,000 feet. Exploration is needed to determine if an economic steam field can be developed.

High Cascade Range

Extending the length of Oregon from north to south, this volcanic pile represents part of the largest and latest extent of volcanism in the conterminous United States. The High Cascades division formed, from Pliocene time onward to the present, on an older Tertiary volcanic basement. The tens upon tens of thousands of separate eruptions required to build this volcanic chain must have resulted from a fundamental but as yet unknown process at work in the earth's interior. Obviously a great amount of heat has been brought near the surface by virtue of this activity.

Numerous hot springs are present in and about the High Cascades, although no unusual indications of heat are displayed. Yet it is difficult to believe that there are not innumerable bodies of hot rock and magma at shallow depths. The segment of the Cascades running from Mount Jefferson to Crater Lake is particularly impressive, since so much late Quaternary and Recent activity centered here. Many of the large cones very likely are underlain by large magma chambers at no great depth. Before some of this heat can be utilized, further progress in geothermal exploration and development will be needed. The area remains one of great potential for the future.

High Plains volcanic belt

A zone of intense Quaternary volcanism extends some 75 miles southeast from the Three Sisters in the Cascade Range. Within this belt is Newberry Volcano, previously described as an individual geothermal prospect. A dominant fault zone beginning in the neighborhood of Mount Jefferson curves off to the southeast towards the Harney Basin. The fault zone generally separates the older Cenozoic rocks to the north from the late Cenozoic rocks to the south. The High Plains volcanic belt seems to be strongly associated with the fault zone. Volcanism is confined to the south and parallels it. Because of the great amount of late Quaternary eruptive activity in this belt, it should be of future interest in geothermal exploration.

Harney Basin

A number of hot springs which occur in this area are no doubt a result of the volcanism of late Cenozoic time. Vast sheets of ignimbrites and tuffs surround much of the basin. In this respect, the basin may have a volcano-tectonic origin and be similar to some other localities of this type throughout the world where geothermal investigations are proceeding. Again, this is an area open to future study and possible exploration.

Alvord Valley

This graben is bordered on the west by the great Steens Mountain fault scarp and on the east by low fault scarps. The graben valley is from 6 to 9 miles wide and about 30 miles long. Several hot springs occur along the margins and also within the valley south of Alvord Lake. Although the amount of subsidence is unknown, the fault activity probably began in the Pliocene and has continued to Recent time. The valley may contain an accumulation of sediments in which thermal fluids could be trapped.

This structure resembles the previously described Warner Valley in many respects; studies suggested for that feature would also apply to Alvord Valley.

Jordan Craters

Northwest of the town of Jordan Valley, basaltic lavas of late Pleistocene to very Recent age have been extruded over an area of several hundred square miles. A few thermal springs occur within the general area. Below the lavas, older lacustrine and tuffaceous sediments are predominant. Laccolithic intrusions similar to those at Diamond Craters may penetrate these incompetent strata, making this area a geothermal prospect. Initially, photogeologic studies will be of greatest benefit with a follow-up by geophysical work on any suspected dome-like structure.

Summary and Conclusions

Earth heat energy has been harnessed at several places in the world to make electricity; the installations are economically successful, and this is spurring further exploration and development, such as at The Geysers, Calif. Geothermal regions appear to be intimately connected with certain structures in zones of late Cenozoic volcanism, and since Oregon has received as much late Cenozoic volcanic activity as practically any part of the world, it would seem to be in a most promising position for exploration and development. Those concerned with future power requirements of the Pacific Northwest have stated that after about 1975, new supplies of electric power in the Pacific Northwest will need to be generated from thermal plants, since all the satisfactory hydro sites will have been developed. Most of this new power capacity will be nuclear, because fossil fuels are scarce in the region. Economic studies of currently operating geothermal power plants show that they can produce power at a cost competitive with contemplated nuclear plants. In this light, it would seem that effort should be directed now towards finding geothermal resources in Oregon.

About 40 percent of the land area of Oregon has been subjected to late Cenozoic volcanism, and within this area a number of tectonic structures having uplift and subsidence exist. Of these, the Klamath Falls area, Warner Range, Warner Valley, Harney Basin, Alvord Valley, and Diamond Craters appear to be logical geothermal prospects. Other possible areas are the High Cascades Range, the High Plains volcanic belt with Newberry Volcano, and the Jordan Craters volcanic area.

Much of the preliminary work in geothermal exploration of these structures will consist of mapping, photogeologic studies, geophysical studies, and field observations. Most of this work will probably need to be done by public agencies in order to provide a foundation for exploration and development. From this point it is up to private industry to become interested and to take the risks inherent in the future development of this form of energy.

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MOUNT JEFFERSON PRIMITIVE AREA DESCRIBED

The U.S. Geological Survey has issued Bulletin 1230-D, "Mineral Resources of the Mount Jefferson Primitive Area, Oregon," by George W. Walker and Robert C. Greene of the U.S. Geological Survey and Eldon C. Pattee of the U.S. Bureau of Mines. The bulletin is one of a series of mineral surveys being made of primitive areas to determine their suitability for incorporation into the Wilderness System.

The Mount Jefferson primitive area, encompassing more than 150 square miles, extends for about 25 miles along the crest of the Cascade Range in Jefferson, Marion, and Linn Counties. The area is underlain by predominantly volcanic rocks which range in age from middle Tertiary to Recent and correlate with the older Western Cascades and younger High Cascades volcanic units. The only mineral deposits found in the area were small amounts of alunite and native sulfur near volcanic vents and scattered deposits of pumice and cinders, none of which were considered by the authors to be of commercial value.

The 32-page bulletin with geologic map may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. The price is 55 cents.

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SUPPLEMENT TO THESES BIBLIOGRAPHY PUBLISHED

The Department has issued "Bibliography of Theses and Dissertations on Oregon Geology, from January 1, 1959 to December 31, 1965," compiled by Miriam Roberts. This new publication is a supplement to the Department's Miscellaneous Paper 7, which lists theses on Oregon geology from the earliest known through 1958. The supplement lists 94 theses and includes an index map of the State showing location of theses that cover specific areas. Supplement to Misc. Paper 7 can be purchased from the Department's offices in Portland, Baker, and Grants Pass for 50 cents. Copies of the earlier report are still available, also at a price of 50 cents.

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LUNAR CONFERENCE BULLETIN REISSUED

The popular Lunar Geological Field Conference Guide Book, first issued last year, has been reprinted. The new issue contains the same material that appeared in the original printing, with additional photographs. Four Ranger Nine photographs of close-up views of the lunar surface have been added to show the close resemblance of the moon's surface to that of parts of the Bend area of Central Oregon. There are 18 colored geologic and index maps which accompany the detailed geologic descriptions of the five field trips to the unique volcanic features in the area. Copies are available from the Department's office in Portland at $3.50 per copy, postpaid.

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GEOLOGIC HISTORY OF FOSSIL LAKE PUBLISHED

"Fossil Lake, Oregon -- Its Geology and Fossil Faunas," by Ira S. Allison, has been published as Oregon State Monograph, Studies in Geology No. 9. The 48-page booklet is illustrated with sketch maps, diagrams, and numerous photographs. It contains an index and an extensive bibliography. The publication can be obtained from Oregon State University Press, Corvallis, Oregon, for $2.00.

Dr. Allison has studied the geology of the Fossil Lake area over a period of many years. In this monograph he has gathered together his own findings, along with those of other workers, and has come up with a comprehensive report on the Pleistocene lake beds and their relation to the abundant fossil fish, mollusks, birds, and mammals. In addition to their paleontological significance, the lake beds reveal a sequence of regional events dating back 100,000 years to include development and waning of large pluvial lakes and the final eruption of Mount Mazama.

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