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UNDERSEA GEOTHERMAL DEPOSITS—THEIR SELECTION AND POTENTIAL USE

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ABSTRACT. Geothermal deposits beneath the ocean floor appear to be the principal indigenous energy source available to installations in the deep-sea environment and are the only apparent alternative indigenous power source to fossil fuels in the continental shelf and slope environment. This study presents a review of geothermal deposits from four points of view: (1) locating potential geothermal deposits at or near which undersea installations might be established; (2) waste disposal considerations; (3) the estimation of deposit structure, chemistry, and size prior to development; and (4) the use of geothermal deposits in the undersea environment including their relative merits as opposed to fossil fuels and reactors.

U.S. NAVAL ORDNANCE TEST STATION
China Lake, California
July 1966

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

This report summarizes concepts developed through extensive literature and field studies as a part of the continuing investigation of geothermal phenomena and of the Coso thermal area.

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INTRODUCTION

Thermal waters in the form of hot springs have long held a source of healing and of mystic power, and mankind has no doubt pondered upon the origin of thermal waters since the first intelligent being found hot water running out of the ground. Despite this long-term interest in thermal waters, our factual knowledge about the origin and occurrence of thermal waters on the land surface has remained scanty, and our knowledge of suboceanic thermal occurrences is essentially nonexistent except for an occasional report of hot waters adjacent to island volcanoes. Throughout the span of industrial history there has been little commercial drive to conduct the deep exploration that would provide an accurate third dimension to the abundant published observations on the hot springs and mineral springs of the land surface. With the inaccessibility to date of the deeper continental shelves, slopes, and oceanic regions, there has been essentially no interest in defining the suboceanic potential for geothermal deposits.

This general disinterest in geothermal concepts has begun to change within the last few years and the concept of geothermal deposit exploitation on land has come into some degree of acceptance within the United States. This acceptance has been the result of several stimulants, but two have played especially prominent roles: these are the initial operating success of the generating installations at The Big Geysers in northern California and the discovery of the dense metal bearing and depositing brines at the Salton Sea in southern California. Because of the abundance of other power sources in the United States, notably fossil fuels, the continued success of the Italians, New Zealanders, and Icelanders in their efforts at utilizing geothermal deposits for power and for process heat has had relatively little influence on the stimulation of geothermal development in the United States.

In an era of increasing awareness and concern with air pollution, three potential large-scale power sources can be considered "off-the-shelf" concepts. These are hydroelectric (i.e., an open system based on gravity), nuclear, and geothermal. In the confined space of an undersea installation, gravity systems at present appear of a dubious value although large convective loops using gravity appear to offer a future promise as a means of using diffuse geothermal energy. At the present time, except for near surface air breathing power based on the use of fossil fuels, the only two off-the-shelf concepts for large-scale undersea power installations are nuclear reactors and geothermal steam systems, for these two systems are in themselves compact and they do not yield large volumes of air pollutants per se.

As a matter of general concept, geothermal power systems will probably never be considered as initial power sources for establishing undersea installations but rather as long-term power sources for consideration at already established undersea bases and colonies, even when geothermal development may be the over-all aim of some particular undersea venture. The preceding statement is based upon the simple fact that nuclear reactors are "sure-thing" power sources as well as portable power sources. Thus they will, under reasonable conditions, produce power in exactly the quantities predicted for a given assembled design regardless of the geographic location. This is not true of a geologic raw material such as geothermal steam. No matter how favorable the geology appears to be and no matter how badly the steam is needed, the power potential of a geothermal field can only be guessed at until the steam production is actually in hand. Thus nuclear power sources should prove highly attractive for initial undersea site establishment and for modest-sized permanent installations while vast permanent installations can be envisioned that will rely on geothermal exploitation for their continuing large-scale power needs.

Mineral exploration groups in the United States who seek to enter the geothermal field will find a voluminous literature on the surface appearance of thermal and mineral springs found on land and an abundance of scientific speculation upon the origin of specific springs that occur on land. Data on undersea springs and practical exploration guides for any type of geothermal locale are virtually nonexistent. When known geothermal areas are presently developed on land by private companies, the information developed tends to remain proprietary.

In the literature there is the recurring suggestion that steam wells should be drilled where steam is leaking out of the ground, but even on dry land this is a suggestion that should not be taken too literally for reasons of safety, engineering, and structural geology, and in the case of undersea installations for the added reason of ease of access to the well head area in general.

Most projects whose goal is the location of geologic raw materials are based on the fundamental hope that previous geologic experience will repeat itself. In the field of geothermal deposit location and evaluation, even when taken on a world-wide basis, the total experience is still too scanty for reliable predictions. The investigation of geothermal deposits, with the present state of knowledge, must be approached as an applied research problem, drawing chiefly on the fundamental knowledge developed by studies of petrogenesis, theoretical geochemistry, the genesis and migration of ore fluids, and upon the general concepts of ground water origin and circulation.

The knowledge developed and available within these disciplines when combined with surface observations of thermal-spring chemistry and structural environments will yield useful working concepts for the exploration man who must make the recommendation regarding the advisability of spending funds on the acquisition and development of any given prospect, be it on land or undersea.

The literature on thermal and mineral spring phenomena of necessity merges into the literature of volcanic emissions and fumarolic gases. Furthermore, the pertinent genetic concepts have been widely discussed, quoted, and requoted by many authors. To avoid long lists of references within the body of this report, there has been no attempt to single out the papers that have presented some individual factual or interpretive bit of data. Because this is an interpretive presentation and not a recounting of data, the person desiring more information on specific thermal and mineral water occurrences and more information on published theories is referred to both the bibliographic list at the end of this report and to the many published texts in each of the supporting geologic fields of study that have been mentioned previously. The bibliographic list that is given includes the published data which the author has used in addition to his own experience in preparing the interpretations that follow.

Papers on contemporary vulcanism, on the role of water in silicate melts, on ore fluid genesis and chemistry, on hydrothermal alteration, and the multitude of papers on the radioactivity of thermal and mineral springs have generally been omitted.

Specific mention of a few authors is warranted, for their papers and interpretations are of great value to anyone working in the geothermal field. These authors include D. E. White of the U. S. Geological Survey, V. V. Ivanov of Russia, and C. J. Banwell of New Zealand. Work by E. T. Allen and A. L. Day warrants their inclusion in this select list, in particular the paper of Day's entitled "The Hot Spring Problem," because the problems have not changed. The vast reference compilations by Gerald A. Waring of the U. S. Geological Survey are also worthy of note, and papers by George C. Kennedy on the role of water in silicate melts, by T. S. Lovering, et al., on hydrothermal alteration, and by W. H. Newhouse and by Edwin Roedder on fluid inclusions also warrant specific mention as major contributions to the interpretations presented in this report.

This report is intended to provide a practical, somewhat conservative approach to the immediate problem of selecting geothermal prospects for acquisition and exploration along the continental margins. To the extent that the scanty data at hand warrants, speculations, mostly theoretical, are also included which pertain to the less accessible and very poorly known deep-sea areas.

From a broad practical operating point of view, the problem of undersea geothermal prospect selection and evaluation is at least threefold.

To arrive at a useful understanding of the development potential of a geothermal deposit, all three pertinent aspects must be considered, whether the deposit is on land or under the sea. To ignore any aspect will lead to the expenditure of funds upon deposits that have little chance of economic or commercial success. These three broad aspects are:

1. The politico-legal environment

2. The size, chemistry, temperature, and pressure of the deposit

3. The availability of a market or the establishment of a need for the products anticipated

To these three problem areas should be added perhaps an initial problem; "Does the area under consideration as an undersea site have any geothermal potential that warrants a first look?" All of these aspects are closely interrelated. Any organization going into the geothermal field on land today or into the undersea geothermal field in even the near future is unquestionably in the position of being a pioneer in a new field, and will find more hopes and theories than useful solid facts when studying the three principal aspects that have been enumerated. The situation is summarized by a recent statement of the present author in a publication on geothermal deposits:

> "Since the geologic evidence is scanty and geothermal deposits are poorly understood at best, the concepts presented...must be considered to be of a tentative nature only."

On the other hand, those organizations that are aggressive in developing an understanding of all of the aspects of geothermal prospect evaluation as they pertain to each individual prospect whatever the undersea location will have a much better chance of success in the field of geothermal exploitation. The author hopes that this report will help in the achievement of this understanding.

The sections that follow in this report discuss each of the various steps in prospect selection in the undersea environment of the continental shelves and margins, and also pertain to areas of known or probable geology in the vicinity of existing islands, sea mounts, and ridges. Speculations regarding the deep-sea environment as classically envisioned by contemporary geologists are presented, but only as geologic possibilities for further study. For all cases, examples of the problems and concepts are presented, and to the extent practical in a report of moderate length, the theories and principles involved are indicated.

DELINEATION OF POSSIBLE GEOTHERMAL SITES WITHIN A GIVEN GEOGRAPHIC REGION

The selection of a broad geographic region in which more detailed prospecting is to be conducted is based on several considerations. The area selected should make maximum usage of the geologic talent within the organization. The past experiences of the company management with the political subdivision involved must always be considered in the case of private concerns operating in territorial waters, and the general attitude of company or organizational management with regard to the advisability of working in certain geographic or political areas must always be taken into account. In particular, any broad region chosen for further geologic study as a potential geothermal site, should, in advance of detailed work, show some degree of geologic favorability, sufficient political stability to warrant the expenditure of funds in developing any promising sites located, and sufficient market or use potential to indicate a chance for economical exploitation. The area may be dictated by the availability of concessions, by the available submergence systems, or as far as the field geologist is concerned, by the field area for which the individual is responsible. In this portion of the presentation, the assumption is made that the broad region for geothermal site selection has been established by company management or by governmental agreement and that the delineation of possible individual geothermal prospects is the immediate concern.

In the undersea environment as on land, geothermal prospects are areas of steam emission, hot-water emission, fumarolic- and volcanic-type gas emissions (other than directly from active volcanoes or contemporary lava flows), mineral springs of any temperature, mineral deposition indicating young-to-recent liquid and gas leakage of the preceding types, and young intrusions at modest depths, with emphasis on domes and caldera structures.

Specific geothermal prospects in any given area are located by any or all of the following four general processes:

1. Literature study

2. Geologic interpretations including those based on bottom topography, bottom heat-flow studies, and upon projections of the results of adjacent map and aerial photographic studies on land

3. Verbal communications

4. Accidental discovery

Once a region is selected for prospect delineation, all four methods of prospect location come into immediate play. The possibility of additions to the list of potential prospects in any area under study will always remain open. Obscure prospects can be overlooked and then located at a later date, and new original discoveries can be made on the basis of geologic studies, or accidentally. All of the methods that can be used within the framework of company or governmental requirements for secrecy should be vigorously pursued at this initial step in the selection process.

Literature surveys are usually the most rewarding for the effort and money expended with regard to dry-land geothermal sites and the same will hold true for the establishment of geothermally favorable areas by projection into nearshore undersea areas. Literature studies will establish the major structural framework that has been defined, the known mineralogic or ore trends; present and former hot springs and mineral springs, and areas of young calderas and doming. An example of the place to begin such a study would be the many published tabulations of thermal springs and mineral springs that are available for the coastal areas of individual states or countries.

Geologic interpretations will become of increasing significance as the general setting of the over-all prospect areas becomes more familiar. A simple example would be the decision to include certain types of ore deposits as indicative of recent thermal fluid activity, with common on-land examples being manganiferous breccia zones or cinnabar-sulfate-sulfur deposits. For undersea areas, a simple, well-known example would be a structural trend such as a major fault zone that on land has associated geophysical anomalies as well as thermal sites that when pursued offshore shows additional geophysical anomalies.

Broader geologic interpretations can prove very valuable in denoting areas of probable geothermal prospect location on continental shelf and slope areas. Although geologists are perennially accused of drawing lines, a plot of many of the known thermal spring regions of the world shows that they occur along a series of well-defined linear trends. As a specific dry-land example, a plot of the known thermal springs in the state of Nevada shows that the thermal springs of this entire region occur along a very limited series of linear trends. Certainly anyone conducting exploration for thermal deposits on the basis of either sea-floor or dry-land alteration as a guide to thermal deposits or on the basis of structural interpretation should examine these linear trends quite closely. Some possible linear trends of interest within Nevada are the margins of the Antler orogenic belt, the Nevada epithermal belt, the margin of the volcanic field of northwestern Nevada, and the eastern Sierra front, or if preferred, the area between the Walker Lane and the Sierra front.

Verbal communications should never be overlooked as useful sources of information concerning prospects. As an example, the author has lead a number of field trips for a local museum to the Coso thermal area located within the confines of the Naval Ordnance Test Station. When this became well known through newspaper publicity, many people brought in information on unrecorded gas flows along fault zones, on hot ground in old mines, and on hot water and steam encountered in old wells and tunnels. With regard to undersea prospecting, those organizations that became known for their efforts in the undersea geothermal field can expect to be the recipients of information regarding unusual concentrations or the lack thereof of bottom life (hot springs and mineral springs), of information on gas bubbles and local upwellings (hot springs and fumaroles), on unusual salinity, density, and temperature readings taken by submarine or anti-submarine warfare groups (all indicative of possible geothermal emissions), and on reports of more violent submarine geologic phenomena indicative of contemporary vulcanism. Unintentional disclosures, such as a leak in a competitors security in the case of commercial ventures are obviously interesting. As an example of the latter, an illustrated lecture on Chilean mineral deposits at a recent technical meeting revealed an area of excellent doming and caldera formation with attendant thermal springs, indicating a geothermal area in Chile that warranted immediate investigation.

Accidental discoveries always play a part in raw material exploration and they are best illustrated by the occasional water well that finds steam or hot brine instead of water. The old original steam well at Red Mountain in California is a good example. Mines of the Red Mountain area have had problems with hot ground for years, and about a half century ago, an attempt at drilling for water encountered steam in this area at a shallow depth. Only after a long period of commercial disinterest is the Red Mountain area seeing even minor commercial consideration, though the knowledge of steam in the area has been available for decades. As off-shore drilling for hydrocarbon fuels expands to cover larger areas, the chances that a number of wells will accidentally penetrate geothermal deposits is excellent. It is probable that industry's entry into the undersea geothermal field across the next several years will result almost exclusively from accidental discoveries.

The prospect delineation phase of study for continental shelf and slope areas should result in a base map of the region under study plus a series of overlays. These overlays should include one of each known thermal and mineral spring plus additional features interpreted as prospects on the adjacent dry-land areas, and all suspected thermal and mineral springs on the sea floor itself. In addition, overlays of the structural trends of the region under study and of the available pertinent geophysical data should be prepared. If the base map is not a geologic map, a geologic overlay should be prepared with the emphasis on young-to-recent volcanic centers, larger calderas, and doming that may be related to relatively shallow intrusion. At this point, the next phase of the selection process is warranted, presuming some possible prospects have been located. However, as a point of both commercial and international competitive practicality, all of the selective procedures will be used simultaneously when competing organizations are actively acquiring prospects on developmental sites in the same general area.

POLITICO-LEGAL REQUIREMENTS

The politico-legal problems that will be discussed in this report pertain to the control and disposal of well discharge products and in particular to the disposal of well effluents. There are other pressing politico-legal problems, chiefly how to acquire and legally retain geothermal deposits wherever their location Thus on dry land in the United States, at the present time, there is a serious problem in the establishment of land acquisition methods valid for geothermal steam and brine deposits on the public domain. In like manner there are the increasing important questions of territorial limits, who owns the continental shelves and slopes and who owns the deeper ocean basins, ridges, and trenches. Since these problems are outside of the scope of geology and hence of this report, there will be no attempt to discuss them at this time though their solution is certainly fundamental to any undersea geothermal development program.

On the other hand, the well discharge problem is a permanent problem that falls within the province of geology. Failure to solve the problems of waste disposal on dry land has stymied the development of the Salton Sea geothermal field in southern California, and has halted the attempts at the exploitation of the Casa Diablo goethermal field in northeastern California.

To illustrate the waste dumping problem, let us consider the troubles resulting from these two projects alone, for they are typical of the problems that must be dealt with and solved if an economical or otherwise justifiably useful geothermal deposit is to result.

At the Salton Sea, the casual observer would probably suggest the dumping of the well effluents into the Salton Sea, using the philosophy of "out of sight, out of mind." Unfortunately for the geothermal operators of the area, the Salton Sea is a sport fishing and recreation area for the major population centers of southern California. As a drying lake, the Salton Sea has a limited biologic lifespan, and any addition of salts to the lake would shorten this lifespan. Thus sportsmen and conservation groups, the local Department of Fish and Game, and the local Water Pollution Board all vigorously oppose the dumping of any waste saline waters into the Salton Sea. The land adjacent to the Salton Sea geothermal field happens to be excellent agricultural land, so that ponding would be very expensive and even ponding would probably not be acceptable unless adequate bottom sealing to prevent ground water contamination could be demonstrated. Thus the Salton Sea geothermal area will be of little commercial value, though of great scientific interest until a workable waste disposal method is established. At present, these efforts are concentrated in the area of recovering the chemical wastes as economic by-products, although waste reinjection into the ground has also been proposed for the area. Whether or not the Salton Sea area would warrant selection and drilling using the author's present selective scheme would depend on the selecting person's degree of optimism concerning the development of cheap, high-volume well-effluent disposal methods.

Casa Diablo, California, as a geothermal prospect, has good surface shows and an excellent structural environment. Casa Diablo also has a rather typical problem regarding effluent disposal. Aside from the problems of well control and blowouts and the problems of condensate icing on an adjacent highway in winter (all of which merely illustrate the hazards of shallow geothermal drilling near public facilities) Casa Diablo has no place to put its waste fluids. The well effluents are too mineralized (arsenic and boron) to be acceptable in useful quantities in the local drainage system (Mammoth Creek) or in any stream that drains into the Los Angeles aqueduct system. The climate is not suitable for evaporation ponding. Deep reinjection might work, but must be proven to the satisfaction of a number of state and federal agencies before being legally acceptable. Under the presently enumerated criteria, Casa Diablo, which is an excellent steam deposit per se, would be rejected for development on the grounds that there is no immediately forseeable method of economically disposing of well effluents. No doubt, the companies operating in the Casa Diablo area have taken a more optimistic point of view, but to date they have not met with success. As a point of fact, the only operating geothermal deposit of any size in the entire United States is one whose wells produce only steam, free of saline brines.

With respect to the undersea environment, one is once again faced with the casual observers approach of "out of sight, out of mind" and indeed the oceans of the world have been used as vast junk and waste receptacles on the assumption that a little pollution in a vast ocean can be ignored. This is a dubious argument at best and the cumulative effects of a little pollution over a long time are becoming increasingly alarming in some local areas along inhabited bays and coastlines. Without doubt, the simplest approach and at present the most practical approach to well effluent disposal for the undersea geothermal operation is to dump all undesirable materials into the ocean. This cannot, however, be done with complete abandon but must be accomplished as a problem in dilution with due regard for biologic conditions, water temperatures, and salinities. The small volume of undersea installations is expected to preclude completely the ability to pond or to store geothermal fluids within the working space of an undersea installation whether it be on the surface of the sea floor or as is more likely, be constructed as a fully enclosed excavation in the rock beneath the sea floor. Since some geothermal fluids may contain raw materials of no immediate value but of potential later value, some undersea installations may not wish to lose their effluent through dilution. In this event reinjection into nearby rock strata is a proven fluid storage concept. Recent discoveries of dense brines that can persist in the subaqueous environment as high density accumulations in topographic lows on the bottom (the Red Sea plus data on various Pleistocene saline lakes) show that ponding for storage on the sea bottom itself is feasible on the basis of density segregations alone.

A brief mention of the problems of blowouts should be made at this time. The Big Geysers steam field operators in California were extremely fortunate in that the blowout that has been out of control there for several years has involved only steam. If, for example, the blowout had emitted large quantities of brines in addition to steam, the resulting legal problem with downstream ranchers and water users would have been catastrophic to the operating company. Anyone drilling a geothermal well, be the drill site on dry land or under the sea, would do well to ponder the problems of blowouts, especially from a brine-rich deposit. In the undersea environment, blowouts besides contaminating the surrounding waters can break through into the working areas of in-the-rock undersea installations, causing considerable difficulty in the recovery of the blowout area.

Well products can be disposed of. The problem is one of both cost and of convincing regulatory agencies, pertinent special interest groups, and downstream or down current water users of the reliability and harmlessness of the method chosen for disposal. Common possibilities for well product disposal include:

1. Avoidance--the development of deposits with only dry steam.

2. Reinjection into the producing horizon--this method has been widely discussed but full-scale successful reinjection has yet to be convincingly demonstrated on a commercial basis for geothermal fluids. The recent experience of apparent earthquake-triggering by the deep reinjection well of the Rocky Mountain Arsenal near Denver has furthermore cast a serious note of caution over all new attempts at deep fluid injection into areas other than the general area of fluid production.

3. Reinjection into contaminated horizons other than the producing zone (for discussion see item 2 preceding).

4. Dilution--this is a cheap and practical method on land where surface waters are abundant and the amount of effluent is not large, but in the western United States this is seldom if ever possible in useful amounts. Most western and particularly southwestern stream systems are already facing salinity problems such as those experienced by the lower Colorado River at present. The Mexican government, on the other hand, is the last downstream user of the Colorado River and is reportedly dumping large quantities of geothermal brines into this river and hence into the Gulf of California. Whether or not the near future will see a serious upset in the biologic community of the upper Gulf of California is a serious unanswered question. As for direct sea water dilution, sufficient currents and density gradients are required to ensure mixing and removal of diluted materials. Sea water dilution will require careful study and presentation to sportsmen, to conservationists, and to fish and game agencies, and industries, especially when operating within national territorial waters. The problems of dilution-pollution are not voided by

going beyond all territorial limits, for geothermal fields may often develop as multi-company-multi-nation complexes, and even if unitized for production by a single company, can run into multiple-use problems over fishing and bottom harvesting of sea foods by nations with no interest whatsoever in the problems of the geothermal installations below save as they affect sea-food harvesting.

5. Ponding--onshore geothermal fluids can be ponded for evaporation, or for indefinite storage and certainly in the case of nearshore operations, valuable brines from undersea operations can be piped ashore, too. Ponding for evaporation is a cheap method of handling waste brines and is practical for areas where the climate favors evaporation and the land surface is inexpensive. Desert regions meet both requirements and nearshore geothermal deposits, especially where the shore areas have large lagoons or playas, look especially attractive for solar evaporation as an initial brine-processing step.

Ponding for intermittent evaporation is an obvious possibility and ponding for permanent storage is feasible both on land and under the sea. On land the requirement is an unused closed basin, a common feature of much of the basin and range province of the southwestern United States. Under the sea, closed sea-floor basins also exist as topographic lows, and these can serve to pond vast quantities of dense geothermal brines, either for semi-permanent storage or for later or co-temporal small-scale dilution in the event the local biologic scene cannot withstand large-scale dilution methods at certain seasons of the year.

Prospects that appear to be of interest are those that will produce steam, or steam and nontoxic brackish or saline waters or those deposits for whose saline brines there appears to be an immediately practicable method of brine disposal. Prospects for which a brine disposal system is not presently available should be looked upon as long-term ventures or research projects. These deposits may warrant some immediate sea-bottom aquisition by either private companies or by governments, depending on the deposit location, as a hedge against ultimate disposal method development for the field under consideration by some competing organization, but normally a lack of disposal methods should be equated with a lack of immediate exploitative interest.

PROPERTIES OF DEPOSITS

Regardless of the surface show for dry-land prospects or of the sea-bottom show for undersea geothermal prospects, the question at hand, once a prospect is selected for evaluation is "What, if anything, is within a drillable distance?" To provide an answer to this question requires a geologic evaluation and a rational estimation of each of the following:

1. Heat source
2. Fluid source
3. Fluid composition with depth
4. Reservoir or conduit configuration with depth
5. Temperature and pressure with depth
6. Probable extent of the deposit

To ask for answers to these questions is a simple matter. To provide the answers in advance of any detailed drilling programs will require some shrewd scientific guesswork based on careful geologic observations and interpretations. The information that can normally be used as the basis for the needed interpretations is obtainable from the following:

1. Analyses of the emitted liquids and gases and any deposits formed at the point of emission

2. Local and regional geology

3. Amount of young-to-recent vulcanism in the area

4. Type of rock involved in the vulcanism, if any has occurred

5. The climatic history and associated ground water potential, including the duration of submergence for continental shelf areas

6. Extent of alteration including evidence based on biologic distribution patterns on the sea bottom (which are affected by heat flow and salinity variations, both of which are closely tied to fluid leakage rates)

7. Local gravity and magnetic patterns established for the area under study

SOURCES OF HEAT AND FLUIDS

Heat and fluid sources are so closely interrelated that they should be considered together. Of a certainty, one can talk blandly about heat flows in the crust as the source of geothermal deposits, but this is too broad a generalization to be an aid to exploration. More specifically, the mechanism for large-scale anomalous heat flows in much of the undersea portions of the world appears to be the direct intrusion of magma with its associated contact metamorphic effects and volatile emissions, or else the collection and transportation to the sea floor of deep metamorphic fluids or circulating sea-floor fluids along major fractures.

Waters at or near the sea floor have four fundamental sources, as do their contained gases. These sources are:

1. Volatiles expelled from intrusives

2. Volatiles expelled from rock masses undergoing metamorphism and in particular recrystallization to more anhydrous silicates

3. Expelled formation fluids including connate waters or other intergranular fluids older than the active geothermal fluids traversing the formations of interest

4. Circulating ground water which can be of compositions ranging from uncontaminated fresh waters derived from the land surface (in the case of nearshore or formerly exposed continental shelf and ridge area to essentially uncontaminated sea water

The waters arriving at the sea floor can vary from any one of these water types in quite pure form to a complete mixture. A scattering of published isotopic studies have appeared that indicate that the magmatic or juvenile water content of surface spring waters found on land is negligible. This may ultimately be proven to be the universal rule as has been suggested by some investigators, but a very careful distinction must then be made between juvenile water and water that has been through a magmatic cycle, since the concepts and evidences of granitization and of the intense metamorphism of deeply buried young sediments indicate that large volumes of otherwise normal ground water can take part in the formation and emplacement of magmas.

As is seen in dry-land thermal shows, whether the waters emitted on the sea bottom are hot, cold, concentrated, or dilute will depend on the distance to the heat source, the degree of dilution and quenching by added ground water or entrapped waters, and by the amount of flow in the conduit system versus the amount of heat loss through the conduit walls.

Within continental shelf and slope areas, those waters and gases whose origin can be traced to intrusive and metamorphic sources are of major interest as geothermal energy sources. Waters whose origin is believed to be that of descending shore-derived ground water or sea water and whose heat is due solely to passage through rocks exhibiting a normal geothermal gradient are of minor interest for heating or greenhousing. They may ultimately prove of value in large-scale gravity-based energy systems, especially when artificially constructed, but such waters are not considered to be of interest for large-scale steam-power development or for the development of brines with potential recoverable metallic or unusual nonmetallic compounds. Descending sea water that uses a structure-convection system of fluid heating and flow, can be expected in areas of the sea floor where there is both fracturing and considerable topographic relief, a feature that may well flush out and mask most other near-bottom evidences for undersea geothermal fluid leakages. The increasing evidence for a moderate to rugged relief across much of the deeper sea floor will add to the probability of widespread undersea convective systems. One argument that may be advanced by some is that the abundance of sea water within the ocean and its floor plus the long spans of geologic time will have destroyed the anomalous heat flow potential of all but the very youngest fractures and intrusions. This is a fallacious argument for, geologically, not all or even very much of any given fluid transporting fracture is apparently an active conduit at any given time. Hence, a locally cooled area will reheat through self-heating or through slow deep fluid percolation during those intervals when large volumes of sea water may be denied due to local movements and permeability shifts along the fracture or other conduit.

Thermal springs whose waters lack strong indications of magmatic volatiles and whose regional geologic setting is not indicative of young intrusives or of deep active metamorphism should be interpreted as belonging to a structure-convection system of fluid flow. This type of flow involving sea water has been observed along coastal areas, and not to anticipate the same phenomenon in abundance in the undersea environment would be shortsighted at best. The structure-convection interpretation can be valid not only with normal sea water as the emitted fluid but with many other compositions as well, with the possibility of even extinct thermal fluids being involved in the flushing process. This is not to say that such sequential fluid compositions will be common, or even recognizable when found, but does point out that many confusing possibilities will be encountered in the interpretation of submarine as well as normal dry-land geothermal prospects.

The heat potential of a structure-convective geothermal system can be estimated from the amount of recharge water available and from the probable depth to which the water descends. The chemical potential of the fluids involved is negligible and can be accurately estimated from the composition of the emitted waters, something that can not be done accurately or at times even speculatively with magmatic or metamorphic geothermal systems.

This is perhaps a good place to point out that the gravity-based structure-convection geothermal deposit is the one type of deposit that can with present technology be made on an artificial basis. This is done by using nuclear bursts at a depth to create both hot zones and large areas of caved and broken naturally hot rock that can be used as a heat source, be it for a modest scale of steam formation or for fluid operation of displacement engines, using the density differences between the incoming cold and outgoing hot fluids, which can be sea water that is discharged directly back into the ocean.

On the sea floor as on dry land, areas of widespread basaltic flows derived from scattered fractures or volcanic centers at fracture intersections are of little or no exploitive interest in themselves. Until the number of feeding dikes becomes very large per unit of surface area involved, the stored heat in the subsurface rock will be very limited.

Furthermore, the generally anhydrous nature of basaltic vulcanism, as observed on the land surface, means a much poorer heat-transfer mechanism can be expected between basalts and their surrounding host rocks. The possibility of hydrothermal fluid formation in basalts with attendant brine formation is quite low, even when large basaltic magma chambers are involved. The concept of using heat from a large molten mass of essentially dry rock, such as a major gabroic intrusion, by means of sea-water injection within the deep-sea floor was mentioned above in the use of nuclear cavity formation as a means of achieving a large heat transfer area in gravity based artificial systems. The problem of entirely basaltic (gabroic) systems will probably be one of the principal considerations in regard to potential deep-sea systems.

It is the granitic "acid to intermediate" intrusive, so common throughout the world, that generally appears to be a sufficient fluid emitter to yield large quantities of hydrothermal waters within the areas of the continental shelves and slopes, whether the granitic rock be granite in composition or one of the less siliceous and potassic rocks such as a diorite.

Summing this entire section, the fluid and heat sources that appear to be of value are those that can be ascribed to young-to-recent intrusions or to active metamorphic horizons. The instrusive (or volcanic) areas of greatest interest are the acid to intermediate rocks of the type normally associated with hydrothermal ore deposition. The deep-sea environment apparently, with our present state of knowledge, will rely primarily upon gabroic convective systems for its geothermal heat sources, but the presence of granitic-type rocks on some oceanic islands strongly suggest at least localized granitic igneous processes may occur in the oceanic basins as well.

FLUID COMPOSITIONS

The estimation of the fluid compositions expected with deep development within the continental shelf and slope areas and at any deep-sea-floor—deep-sea-ridge areas with dioritic to granitic intrusive activity is presented in the section that follows. For dry land deposits the estimation of fluid compositions will be based (1) upon the evidence that can be obtained from surface water and gas emissions which can, on dry land, be easily collected in abundance and analyzed; (2) upon an estimate of the most probable type of intrusive rock active at depth; and (3) upon local observations of the type of deposits associated with the same or similar rock types. Since projections will be made from land areas into adjacent submarine areas, a brief review is given first of the complex problems of interpreting dry-land chemical data, many of which are non-existent upon the sea floor.

Dry-land-surface chemical analyses must be used with great caution. Spring waters are almost invariably contaminated by accumulations of scrap metal and garbage. Tin cans contribute tin and lead from solder and tin from tinplate. Iron comes from pipe and other scrap, and zinc is common from galvanized pipe, sheet metal, tubs, and buckets. Because of superstition, people toss surprising quantities of coins into hot springs and wells, with the result that the analyses of the waters emitted almost invariably show some nickel and copper plus silver. Livestock around springs contribute nitrogen that will concentrate in some types of springs as retained ammonia, and bones of all sorts can contribute phosphate. Analyses of dry-land thermal springs are particularly difficult to use if the spring is an acid sulfate system on the land surface. Acid sulfate springs are invariably loaded with soluble salts and trace elements derived from the surface rocks that have been decomposed and altered by the sulfuric acid formed by interactions between atmospheric oxygen and the emitted hydrogen sulfide.

In the undersea environment, contamination should be far less of a problem in the event a thermal fluid vent is found and sampled. Other than sea water per se and the possibility of random junk and local biologic accumulations, the ions in a sample should have all arrived via the geothermal emissions. Large amounts of atmospheric oxygen are lacking, H_2S should persist to some extent, and there should be no acid sulfate springs in the undersea environment. Hydrogen sulfide does appear to oxidize readily to sulfate in the sea water environment, as is observed above organic accumulations as in fiords, but the sulfate formation does not appear to occur at a rate sufficient to overcome the normal high pH of sea water. This statement does not mean there will be no acid geothermal systems, only that the typical atmospheric oxygen-acid sulfate system commonly seen on land will be lacking.

Analyses of emitted fluids are of great value and certainly should be among the first data gathered from a potential geothermal prospect. If an area of geothermal fluid leakage is high in the elements indicative of magmatic or metamorphic origins or contains elements considered typical of ore-depositing fluids, the system is of definite interest. Geothermal fluid leakage that is rich in boron, chloride (especially calcium chloride), potassium, and silica appears to be of this general type of fluid as do fluid emissions depositing or carrying anomalous quantities of base metals, precious metals, manganese, tungsten, and the like. The general criteria for waters of various origins as outlined by White are of great value, but must be applied to any given geothermal fluid emission with caution because of the problem of the subsurface mixing of waters of various origins below the point of emission or collection.

Geothermal emissions from the sea floor that indicate subsurface boiling are of great interest and indicate areas where dry-steam development can be possibly achieved. Subsurface boiling is indicated by a persistent emission of hot gases and volatiles, the type of occurrence that on dry land is apparently typified by acid-sulfate exposures accompanied usually by a scattered deposition of mercury minerals. In the undersea environment a bottom emission or collection of H_2S and CO_2 that is not attributable to oceanic chemical or sedimentary/biologic processes would be an example. Is the periodic upwelling of H_2S laden water from Walvis Bay off the coast of Africa a sedimentary/biologic feature as is seen in some fiords or a geothermal feature? It is not known. As people begin to look harder at underwater areas, predictions and theories are steadily being proven and improved just as the recent discovery of hot metal-rich brines at Niland, California, and the new discovery of hot rich brines emerging into the floor of the Dead Sea and apparently into the floor of the Red Sea have added useful corroboration to the speculations of many geothermal geologists.

Spring systems that have deposited minerals typical of epithermal ore deposits warrant immediate investigation, whether the deposition is still continuing or is very recent but presently inactive. Consider the common occurrence of manganese in the upper portions of many base metal and precious metal deposits. As a dry land example, a spring system such as that north of Delta, Utah, with its abundant manganese deposition in an area of rather recent vulcanism, looks especially attractive for further investigation. Of a more speculative nature are breccia zone deposits which appear very young such as the manganese bearing breccia zones of the Louis Lopez district of New Mexico. This area is one of locally anamolous heat flows and of scattered spring terraces and hot springs. Furthermore, there is a considerable content of lead in some of these manganese deposits. Although such former spring areas are of less interest than presently active ones, they are certainly of theoretical interest, and studies on both dry land and peripheral to such deposits on the sea floor might show them to be of considerable value as geothermal indicators. The analogy between gangue mineral depositing springs and the fluids that must have deposited many of the epithermal ores is too well established to overlook, and springs with epithermal ore and gangue elements in solution now or recently are excellent geothermal prospects.

Many investigators have spent a considerable amount of effort establishing ionic ratios as the criteria for thermal fluid evaluations. Such ionic ratios can give useful data on the probable origins of many waters. Thus if a spring in a continental shelf area adjacent to a low lying coastal area appeared to be sea water diluted by ground water, the interpretation of a convection system using local structures as the means of transporting and heating of the waters emitted would be reasonable. Such a spring would normally be of no further geothermal interest unless the structure, for example, indicated independently the probability of a good heat source in the same area. On the other hand, geothermal fluid leakages tend to contain extractable elements from the transportation conduits and conduit host rocks through which they have passed. As an example, suppose a geothermal emission upon analysis was found to have the ionic ratios typical of connate fluids or an oil-field brine. At this point ionic ratios would indicate little of value was present, but suppose these connate brines were being heated by a boiling subsurface heat source.

That this is not a farfetched series of suppositions is shown by the springs associated with some of the epithermal mercury deposits of Colusa County, California, which are hot but typical in composition of oil-field brines. Based on the author's interpretations, the geothermal deposits of this general area should produce heated formational brines, then steam, and, finally at considerable depth, they should produce hydrothermal fluid-type brines with a potential for both metals and nonmetals production in addition to steam. The use of ionic ratios to interpret geothermal fluids must be tempered not only by the elements available from the overlying rocks but by the natural radial and vertical zoning of geothermal deposits according to natural separations based on volatility (as demonstrated by some of the Russian studies in the Kamchatka area) and based on time and distance (as suggested by the present author based on the sequential alteration concepts demonstrated for many metalliferous districts).

Pursuing the hydrothermal fluid genesis further, for the granitic to dioritic intrusive in the continental shelf or at any other undersea location, leads to the following concepts. First of all, both radial and vertical zoning should be expected with geothermal fluids if the reservoir or conduit system is large. The earliest fluids in an active hydrothermal system appear on an average to be magnesic and basic, with the fluids becoming more acidic with the passage of time. The later fluids appear to become more siliceous with minor associated iron and sulfide ion, then increasingly potassic with a near neutral pH. Following these variations there is the active ore-depositing stage that is apparently acidic and rich in chlorides of calcium and potassium. To what extent these fluids result from their passage through a complex host and conduit system is a question far beyond the scope of this report and to some extent irrelevant, because the existence of these sequential fluids appears factual, whatever their mode of origin. Thus all geothermal deposits whose origins are of a hydrothermal ore fluid nature should show zoning with both time and distance from the source region. The geothermal brine at Niland, California, is a good example of an apparent ore-stage fluid as are the fluids recovered from fluid inclusions in various sulfide and gangue minerals. (Interestingly the fluids recently recovered from some intrusive minerals appear also to be high chloride brines.)

The most likely metallic elements in a geothermal system can be crudely estimated at present from the general statistical data available on elements deposited versus magmatic rock type and more precisely from a localized study based on local area associations between specific known deposits and apparent geothermal source rocks. The large amount of overlap indicated shows this portion of a geothermal prediction to be of real value only when considerable local association data can be demonstrated. The following are typical associations:

Granites: U, Fe, Mo, W, As, Sn, Bi, Au, Te, Cu, Zn, Pb, Ag, Hg, Sb, and minor Co, Ni

Quartz monzonite and granodiorite: Fe, As, Bi, Au, Te, Cu, Zn, Pb, Sb, Hg, W, Sn, Mo

Quartz diorite: Fe, As, Au, Cu, Zn, and minor Pb, Ag

Gabbro: minor Fe, Cu, Ti, and P

Syenite: Fe and minor Mo, P, Zn, Au, and Cu

Thus if the granites of an area are associated normally with lead-zinc-silver deposits, then the presumption of lead-zinc-silver-rich geothermal fluids of possible interest as underlying deep brines becomes quite reasonable. In this connotation, rich need not mean of a high percentage, but that the contained elements of interest are recoverable by decreases in pressure and temperature, as for example are the silver and copper contained in the Niland brines of the Salton Sea area of California.

A point worth noting is that geothermal fluids may not reach the sea bottom at all, and that only steam and other gases will quietly work their way to the actual sea floor. Here the steam will immediately quench while the other gases may either dissolve or diffuse upward and at least partially dissolve. After steam, CO_2 is probably the most abundant geothermal gas and it should certainly be anticipated in quantity.

If boiling is occurring at some depth below the sea floor, there is a good possibility that a zone of high metal concentration occurs in the fluids immediately below the brine-steam interface. Solubilities versus boiling point temperatures will determine the extent to which concentration will occur, but a good analogy is provided by the epithermal bonanza deposits, some of which appear to represent zones of boiling in a rising geothermal fluid system.

When geothermal prospecting is carried out on the continental shelves, on ridges, on guyots, and adjacent to islands, the potential effects of periods of emergence should be included in the deposit evaluation scheme. For at least the continental shelves, it can be fairly safely surmised that they were partially exposed to normal dry-land weathering processes during periods of major ice formation with attendant sea-level lowering. If this is indeed the case, geothermal deposits exposed during these intervals have the potential for fresh-water flushing of their surface portions and the probability of acid sulfate alteration occurring. How long before a deposit will return to normal after resubmergence into the sea water environment will depend on the circulation pattern of individual deposits but the possibilities for residual fresh-water dilution and for bleaching and alteration typical of dry-land environments should be recognized. The problem is very muc like that of the pluvial period flushing and dilution that has no doubt taken place in times past in the western United States, a phenomenon whose actual effects are not easy to specify for any single deposit, for the rate at which a flushed out geothermal system will recover its normal composition is entirely speculative.

Indeed, geothermal systems may not recover unless they are still actively growing or expanding in extent. As a result, the lack of chloride or emitted borate in many western thermal springs may be far less significant than assumed, especially in areas where young-to-recent intrusions can be demonstrated.

Summarizing this section, compositional interpretations regarding fluids at depth below the sea floor are based on the estimated fluid source and on the composition of any emitted fluids that can be collected and analyzed. The basis for compositional estimates in areas of young-to-recent intrusives are the concepts of hydrothermal alteration and the available theory on the composition and origin of ore fluids. When projecting from dry-land deposits to offshore areas, analyses of dry-land thermal springs can be very useful but must be employed with great caution because of the high probability of contamination. Undersea thermal waters should be essentially free of contamination and unlike dry-land deposits will not actively form acid sulfate alteration zones. Published ionic ratios are of value in indicating fluid sources and especially in estimating the degree of fresh-water and sea-water contamination of thermal fluids. Such interpretations, though, must take into consideration the probability of the intense metamorphic or magmatic heating or connate or other entrapped formation fluids that predate the passage of the present active geothermal liquids or gases that are providing the heat. Furthermore, the climatic and emergence history of the sea-floor area under study must be taken into account as a means of estimating the degree of fresh-water dilution and flushing that may have taken place during earlier periods of exposure to pluvial periods. Such flushing can contribute to the lack of observed chloride and boron in many dry-land deposits of the western United States and this depletion should be expected at least on most continental-shelf areas. Those geothermal emissions that deposit or that have recently deposited the elements typical of epithermal ore deposits are considered to be especially favorable for the development of steam and brine deposits. Deep brines overlain by a steam zone will probably be evidenced in the undersea environment by emissions of CO_2, H_2S, and by steam, although the latter will rapidly condense to yield only a slight temperature rise and minor dilution of the quenching sea water. On dry land these same deposits would be noted for their lack of chloride and their abundant acid-sulfate alteration. Such boiling deposits may well have zones of greatly enriched concentration at the gas-liquid interface but the concept of rich is a relative term, and may imply only increases in concentration of a few tens or hundreds of parts per million for some elements of interest. The chemical analyses of the discharge waters of acid sulfate or subsurface boiling systems will not normally provide data of value in assessing the probable detailed chemical nature of any fluids present at depth.

RESERVOIR AND CONDUIT CONFIGURATION WITH DEPTH

Given an apparently interesting geothermal prospect and hopefully a geothermal deposit below, some thought should be expended on the conduit and storage capabilities of the presumed subsurface environment. Most geothermal shows of fluids and gases that are of interest on dry land occur along fractures regardless of the local domal or cauldron subsidence structures that may be present. The reason for this fracture control is that fractures are good liquid and gas conduits. The same relationships will hold on the continental shelves, where fracture-controlled gas and fluid emissions should be the rule. In the undersea environment permeable beds can also serve as conduits, as can bedding planes, just as impermeable beds or horizons can serve as concentrating and limiting geologic features. Geothermal liquid and gas storage at depth can be in intergrain spaces, in cavernous structures, and most commonly in fractures. Fracturing as the source of storage volume is apt to be especially important in rocks that have been recrystallized or intensely altered.

Organizations planning a drilling program, especially one located within a limited volume such as an undersea drill site, should realize that to drill at the point of gas and liquid emergence is to court disaster if the rock in or immediately adjacent to the conduit is weak and permeable, and that collaring a hole in the conduit does not imply that the hole will stay in the conduit for any appreciable increase in depth. To collar a steam well in an area active thermal emissions is like the collaring of an oil well in an oil seep regardless of the dip of the bedding, as many a driller has found out to his sorrow. Even in vertical fractures, there is no reason to presume that the steam flow or fluid flow is vertical. On the other hand, the normal situation is one of tortuous flow paths that wander about laterally as well as up and down. Only repetitive and carefully spaced drilling will establish flow patterns in fracture zones or permeable horizons. In most domed or subsided (caldera) geothermal environments, the fracture patterns should be sufficiently well established from bottom studies to warrant predictions of subsurface conduit location to at least moderate depths. A sparker type of survey would be a typical approach. In collapsed caldera structures, a careful review of the geologic history of the area and of any adjacent exposed dry-land areas plus gravity studies should reveal some degree of prediction regarding the possibility of the presence of more or less permeable horizons with depth, with porous horizons such as pumice lapillae accumulations, and sands and gravels from pluvial periods being useful reservoir materials worth seeking. If the zone of anticipated production is in sediments, the local stratigraphy will provide some indication of the beds that are most apt to be brittle and hence highly fractured or that are most apt to remain reasonably porous and permeable upon some degree of metamorphism.

TEMPERATURES AND PRESSURES

Geothermal deposits can vary in pressure from that of the overlying liquid or gas column alone, in a shallow, near the bottom, very open breccia zone, to a pressure equal to the dead weight of the overlying water and saturated rock column plus an increment equal to the plugging or shearing resistance of the overlying rock mass. Geothermal systems, especially if carrying much in solution in either gas or liquid phases, tend to rapidly case-harden their conduits. This case-hardening or conduit-wall alteration sharply limits the lateral migration of liquids and gases, and cuts the permeability very markedly in the conduit host rock. This general phenomenon is very valuable and fortunate, for it permits the penetration of mine-type openings below the sea floor into the geothermal area itself. On the other hand a drill hole or manned working space ɿ be in a zone of potentially high pressure, but the pressure will not show significantly in an open or dynamic well or in a mine-type opening, because of the low flow rates into the opening, until an active conduit is cut. When the latter happens, the well or open space can flash to an operating pressure close to the hydrostatic pressure for the depth at which the mine opening or well is bottomed, even though the collecting space remains essentially open to the sea surface or at least to the floor of the undersea drill site. Since the high pressure in the geothermal system, especially in an open borehole, is not diminished by a dense fluid volume, the chance for a formation or hole failure near the hole collar is excellent and a major uncontrollable blowout could easily occur if the resulting geothermal bore is then shut in. Until a deposit is proven to be otherwise in behavior, the complete potential rock hydrostatic pressure at the drill-bit position should be the design pressure for both exploratory wells seeking deeper fluids and for horizontal pilot holes seeking adjacent fluids.

The temperatures encountered in a geothermal borehole will depend on the temperature of the initial source plus the heat loss and quenching history of the rising gas or fluid column. From the standpoint of geothermal deposit development, a "hyperthermal" prospect, i.e., one that is hot enough to boil at one atmosphere where it emerges at the sea floor is obviously of greater interest than a much cooler prospect, while prospects that emit truly boiling fluids at the sea floor will be thoroughly superheated in behavior once they are allowed to discharge into a one atmosphere or less environment through the use of condensing exhaust systems. The problem is the correct interpretation and evaluation of the warm-to-cold prospects that should be numerically more abundant on the sea floor, just as they are on dry land. Near-surface quenching in a dry-land environment can unquestionably convert a local flow of steam into a warm or hot spring. In the undersea environment, with its virtually unlimited source of quenching water and high bottom pressures, the flow of steam or other hot gases in any given conduit must be quite large to overcome the local quenching probabilities, and when steam or very hot water are found on the sea bottom, the geothermal potential at that location will be extremely encouraging.

The depth to steam at any given sea-bottom location will depend on the depth at which mixing is occurring between the rising gases and liquids and the descending ground water or sea water. Also, the probability of long-term quenching by convection in saturated sediments at depth, using older fluids or connate fluids as the principal heat transfer media, should be anticipated. In any event, a below-the-sea-floor location should in no case be considered a saturated or quenched area just because of the location. Experience with under-the-sea-floor mines has long proven that sediments in the continental shelf areas, at distance of up to several miles offshore, can persist as sea-water free areas for long spans of time, even in terms of modest spans of geologic time. There is no reason to suppose that conditions in other shelf areas will as a rule be any more susceptible (or less) to saturation by migrating sea water.

In general, if a geothermal fluid is found to be cool to warm and quite dilute, the best rationale is to presume that some form of cooling and dilution has occurred. The extent predicted, however, will depend on an estimation of the subsurface structure and ground water or migrating sea-water potential of the host rocks. Published estimates of mixing depths of 10,000 feet below the surface for dry-land deposits for mixing and dilution seem unduly pessimistic in some areas, but are undoubtedly highly optimistic in areas where overlying or surrounding formational fluids and convection provide the cooling system. These same statements are equally applicable to geothermal prospects located on the continental shelf areas of the world.

Warm to cold geothermal-type fluids with high salt or dissolved solids contents do not appear to be cooled by dilution. Such emissions are more apt to be cooled as a result of extensive travel through cold conduits, and are the result of either a dying system or of a new system that is still heating its host rock, with the latter the best interpretation for an area of host rock that is lacking in widespread alteration and other evidences of extensive past fluid flows. Another good explanation for cold but highly mineralized waters encountered in undersea drilling is the quenching of geothermal fluids, not by fresh ground water or normal sea water, but by concentrated formational brines. These brines can represent earlier fluids or connate fluids (or for that matter can represent salts extracted by either fresh- or sea-water passage through the sedimentary column, resulting in waters of salinities greater than normal sea water being emitted from stressed rocks in some undersea coal mines, as a specific example). Drilling into geothermal prospects that are cold but relatively concentrated chemically where exposed in undersea workings or on the sea bottom is unquestionably more risky than starting out in a surface show that is hot. However, if the base of the cooling system is penetrated or the depth of effective convective circulation exceeded, a useful geothermal can be the result. An estimation of the probable depth of convective or formational fluid cooling can be made on the basis of the geology of the host rocks believed present, their thickness, and their probable permeability.

One aspect of drilling into thermal shows on dry land that appears to have caused some confusion among investigators is the fact that temperatures can not only increase with depth, they can also decrease on a local basis. These same problems will exist just as much on the sea floor. As a drill approaches the active portion of a conduit for geothermal emissions, the temperature should rise. This rise will be due both to conduction and to some degree of fluid leakage from the active conduit into less active portions of the host. (Note that fluid leakage at any given site will occur even into saturated hosts through the establishment of local patterns of convectively driven flow.) After penetrating the conduit, the temperature will remain at about the same value for modest distances if the conduit is quite open (perhaps even hundreds of feet) and will then decrease as the drill hole passes out of the active conduit and into less active portions of the host beyond the conduit. The analogy between temperature as a variable and, e.g., trace elements as a variable is valid and both variables will give similar distribution patterns for their value about conduits or sources. With continuing depth, the same drill hole will see rising temperatures corresponding to the local geothermal gradient, but a temperature maximum will now have been passed until either the geothermal gradient-caused temperature value overtakes the temperature observed in the shallower active conduit or an additional deeper, hotter, active portion of the same or some other conduit system is cut.

The literature contains a number of suggestions that, due to mixing and dilution, a deposit will often show a short rise in temperature, and then follow only the local geothermal gradient. This has certainly been observed in some areas, but the assumption that this is a widespread phenomenon is not only geologically unwarranted, but, unfortunately, it is also a self-fulfilling prophecy, i.e., on encountering a thermal maximum a drilling concern at present is urged to quit drilling and hence to support the theory. Since there is no geologic reason at all to assume that hot fluids flow straight up, and a multitude of evidence to the effect that they do not, any thermal test hole that encounters a temperature maximum followed by locally decreasing temperatures is not, per se, a cause for alarm. If the drill logs show such a hole to still be within the geothermally active zone, the hold should be continued, seeking either other active portions of the same conduit or other active conduits at greater depths. In any deposit that utilizes fracture conduits or even formational permeability and porosity for the conduction of liquids and gases, there will have to be many carefully logged holes put down before the three-dimensional nature of the active portions of the conduit system can be accurately predicted.

DEPOSIT SITE

The size of a geothermal system located on the continental-shelf areas can be estimated on the basis of the observed heat flow from liquids and gases, which yields a pessimistically low but numerically verifiable value, or on the basis of the predicted heat source, its areal extent and hence the probable heat source volume. Using heat source as the basis for size estimates is a problem in structural geology. Two dry-land examples of this general approach would be to use the diameter of the structural depression as a measure of size, as is easily done with the Long Valley structural depression of California, which is both thermally and seismically active at present, or to use a caldera diameter in a volcanic complex as can be done with the Jemez Caldera of New Mexico, which is also thermally active. Gross caldera or subsidence measurements, however, should be modified by whatever evidence is at hand for localized stock formation or local magma reservoirs within the zone of doming or subsidence. In the case of the Long Valley structural depression, geophysical studies as well as structural relationships observable on the ground suggest that within the structural depression there are several localized areas worthy of greater immediate attention than the bulk of the collapse zone. These may well be apophyses of a larger stock or small younger intrusive masses that represent nearer surface or more accessible places of geothermal activity.

In the case of major fracture systems or other tabular permeable features that are leaking hot gases and liquids, the extent of accessible deposit will depend on the depth or lateral extent at which quenching is taking place and upon the degree to which the entire fracture is active as a conduit. Based on experience with ore deposits, the possibility that a geothermal fluid flow uses the entire volume of a conduit structure is negligible. Normally only a small percentage of any tabular conduit system appears to have actively transported fluids at any given instant in geologic time.

THERMAL POTENTIALS OF DEEP-SEA FLOOR AND TRENCH AREA

The knowledge of the detailed host-rock geology and structures of these areas is generally nil. On an over-all average, geologists still assume on the basis of exposed island areas that the bulk of the deep-sea floor is a basaltic region, and this is amply supported by geophysical observations. It is also known that basaltic magmas can differentiate to yield granitic to dioritic residual magmas and that volcanics such as andesites and rhyolites occur on exposed islands within the deep-sea environment. Thus even the deep-sea floor should, despite the geologic assumption of a basaltic nature, contain granitic-type intrusions to some extent.

All of the statements given in the previous sections of this report will apply to any area of the ocean in which granitic to dioritic (or even feldspathic) magmatic activity is occurring today or has occurred in the recent past. In those areas that are still exclusively basaltic, emitted or collected fluid quantities are expected to be less on petrologic grounds, but this concept of less is only relative, and basaltic emanations under the sea are expected to be rich in water and CO_2, with evidence for the latter now appearing in particular from fluid inclusion studies and with evidence for both water and carbon dioxide exhalations in quantity available from field observations of volcanic eruptions. Although basalts are considered dry rocks petrogenetically, they are not truly anhydrous and in the deep-sea environment there is no shortage of sea water that can be circulated to yield vast geothermal convection systems within deep-sea caldera complexes or along major deep-sea fracture systems. There is no reason to feel pessimistic about the geothermal potential of the vast deep-sea areas that are presumed to be generally basaltic in nature on the basis of present day evidence.

MARKET OR USE FOR PRODUCED MATERIALS

No geothermal prospect evaluation can be complete without some consideration of the market or use potential of the anticipated products. In the undersea environment, power and life support are two fundamental needs. A geothermal deposit is generally drilled in hopes of developing either steam or steam plus hot brines that can be flashed to steam. These can yield power in the range of hundreds of megawatts given a deposit no larger than a square mile or two. Since undersea installations today exist that span areas in excess of 50 square miles of accessible rock beneath the sea floor, the possibility of geothermal (or hydrocarbon for that matter) exploration over large areas now appears feasible. Besides power, per se, geothermal steam condensates can yield fresh water in large quantities. With deep development, there is the probability, especially so in shelf areas, of some degree of mineralized brine being recovered for the production of both nonmetallic salts and for metallic compound production. Within the undersea environment, geothermal deposits can yield both the power and the life support needed to make vast undersea bases and colonies economically supportable. Given useful by-product brines, such bases and colonies can conceivably become self-supporting national assets.

CONCLUSIONS

A great deal of additional factual knowledge is badly needed regarding the genesis and migration of both metamorphic and magmatic liquids and gases, and the same can be stated emphatically regarding the geology and structure of the two-thirds of the world's area that is presently ocean bottom. With respect to the evaluation of geothermal prospects, the following sequence of evaluational steps can be supported by the geologic evidence that can be obtained prior to deep drilling and by the present state of the art regarding well effluent disposal methods.

1. Select undersea geothermal sites for study. Geothermal sites are areas of steam emission, hot water emission, fumarolic- and volcanic-type gas emissions (other than from active volcanoes or contemporary lava flows), mineralized water flows of any temperature, and areas of mineral deposition indicating young-to-recent intrusions at modest depths, with emphasis on domes and caldera structures. For nearshore shelf areas, onshore data of this type can be used for projection based predictions on the sea floor adjacent to the coast.

2. Unless a geothermal site gives good promise of producing only steam, or there is firm evidence that no governmental intervention will occur if wastes are allowed to run wild, a disposal method that is proven and economical must be available to cope with well effluents before a geothermal site is selected for large-scale development. "Checkerboarding" by both industrial concerns and by governmental agencies will be warranted as a hedge against the time when future technology will provide new disposal methods or new uses for well effluents in areas of otherwise excellent geothermal potential. Disposal methods that appear practical for undersea development of geothermal deposits include storage by ponding in sea-floor depressions as density segregates, ponding on adjacent land areas, and dilution plus the in situ alternatives of avoidance (i.e., steam only) and reinjection.

3. The heat source, fluid source, fluid composition with depth, probable reservoir configuration with depth, extent of the deposit, and probable temperatures and pressures should be possible to estimate from the data in hand, with decreasing data leading to less immediate valuation for a given deposit. It should be emphasized that these will be estimates at best, not factual determinations. These estimates will provide a rational basis for the decision to pursue or drop a given geothermal development program in the light of current knowledge and theory. As new data become available, the methods of estimation should be modified as needed to fit with the new facts.

Heat and fluid sources deemed to be of value are magmatic and metamorphic in origin. Ascending hot materials beneath the sea floor can undergo any degree of mixing with fresh ground water or descending convectively circulating sea water and with connate or formational fluids prior to reaching the sea-floor proper. Heated ground water including sea water, not involved with a heat source other than the normal geothermal gradient, does not offer a useful brine potential but if on a very large scale or if artificially established or augmented by nuclear-discharge-produced heat-exchange fracture zones, such deposits could be of some power potential. Areas of young-to-recent acidic to intermediate intrusions at modest depths offer the best sources of heat and fluids, followed by areas of deep, active metamorphism cut by deep fractures. These heat-source conclusions are valid for continental-shelf areas and for any deep-sea areas where the appropriate rock types occur. For deep-sea areas, straight basaltic intrusion-sea water interactions may prove the most numerous deep-sea geothermal heat and fluid sources. Differentiation processes in the deep-sea environment should result in at least scattered geothermal deposits based upon intermediate to acidic or feldspathic rocks.

Fluid compositions at depth can be estimated from the analyses of waters emitted on the sea floor with due regard to probable fluid intermixtures and contamination, and from the concepts of hydrothermal alteration and ore deposition. Contamination by stray metal or junk is not considered a serious sea-floor problem, but should always be evaluated in sampling programs. Sea-floor areas should be free of subaqueous acid sulfate phenomenon, though "fossil" alteration zones should be expected on formerly emergent areas.

Thermal fluids depositing minerals in the recent past or at present that are typical of epithermal ores are of great interest as potential geothermal site indicators. Thermal shows involving only gases or gases and steam suggest subbottom boiling with the possibility of concentrated zones of high metal content at or just below the gas-boiling fluid interface. The probability of the flushing out of the upper part of the geothermal deposits on the continental shelves during periods of exposure and emergence should be considered when examining thermal deposits in these areas that are low in magmatic indicators or other dissolved salts.

Reservoir and conduit configuration estimates must take into account the probability that only small portions of any given tabular conduit system will be actively transporting hot gases and liquids at any given time. Fluid storage can be in fractures and in formation voids or pores but fractures are most apt to be important in deeper metamorphosed hosts.

Temperatures and pressures can be estimated on the basis of the depth and openness of the reservoir and the conduit system and on the anticipated degree of quenching by descending waters and by connate waters on other formation fluids. Pressures in deep geothermal systems, involving large flow frictions in tight covering rocks, can approach values equal to the hydrostatic rock pressure at the point where the fluids were encountered. Temperatures can vary markedly with depth, depending on the degree of active fluid conduction in any given conduit. Thus a hole cutting an active area in a fracture will experience a local temperature maxima followed by a decrease in temperature with increasing depth on a localized basis. Such a decrease need not be a reason to halt a hold still in a favorable area as other active conduit areas may well lie at greater depths. Temperatures in conduits with mixed descending waters and heat source fluids can remain nearly constant or can rise only slowly over considerable vertical spans, until the depth of mixing is exceeded or until an active unquenched portion of the conduit is penetrated. There is no evidence at all that suggests that ascending geothermal fluids follow straight near-vertical paths over any appreciable distances in conduit systems.

Geothermal sites with hot fluids at the sea floor are most apt to be steam producers at modest depths below the sea floor. Warm-to-cold geothermal fluid emissions should be evaluated on the basis of their probable extent of dilution plus the ground water-sea water and formational fluid potential of the region of interest beneath the sea floor. Cold but chemically concentrated fluid emissions are indicative of very deep heat sources at best but may indicate only the extraction of salts from stressed underlying sediments.

4. A market or economically supportable use (or else a suitable national goal) should exist for the anticipated products from any extensive geothermal development projects. Uses for undersea geothermal developments include sources of electric power, life support gases and fluids (by condensation and electrolysis), and economic by-product production using waste brines as the raw materials.

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The following bibliography provides the basis for much of the interpretive effort presented in this paper. The more readily accessible literature on hot springs and mineral waters is presented but data on radioactivity in springs are generally omitted. Also generally omitted are references on the following subjects, although these subjects are all very important to an understanding of geothermal phenomena: contemporary vulcanism, ore deposits, hydrothermal alteration, the mineralogy of springs and fumaroles, igneous and metamorphic petrology, seismology, geophysical prospecting methods and theory, the geology of most hot spring areas, the geology of the sea floor, and oceanography.

The bibliography presented does not include proprietary reports, personal communications, or other generally unavailable reports. This bibliography, though far from complete, should save much time for those who wish to pursue the subject of geothermal deposits further or for that matter who wish to challenge the author's concepts and interpretations. Readers will find that the author has drawn very freely upon his paper "Selection Criteria for Geothermal Deposits" which, however, dealt with dry-land geothermal deposits only. This paper is being published by the Nevada Bureau of Mines.

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Geothermal deposits beneath the ocean floor appear to be the principal indigenous energy source available to installations in the deep-sea environment and are the only apparent alternative indigenous power source to fossil fuels in the continental shelf and slope environment. This study presents a review of geothermal deposits from four points of view: (1) locating potential geothermal deposits at or near which undersea installations might be established; (2) waste disposal considerations; (3) the estimation of deposit structure, chemistry, and size prior to development; and (4) the use of geothermal deposits in the undersea environment including their relative merits as opposed to fossil fuels and reactors.

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