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SUBMARINE GEOTHERMAL RESOURCES

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ABSTRACT

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Approximately 20% of the earth's heat loss (or 2 × 10^{12} cal/s) is released through 1% of the earth's surface area and takes the form of hydrothermal discharge from young (Pleistocene or younger) rocks adjacent to active seafloor-spreading centers and submarine volcanic areas. This amount is roughly equivalent to man's present gross energy consumption rate.

A sub-seafloor geothermal reservoir, to be exploitable under future economic conditions, will have to be hot, porous, permeable, large, shallow, and near an energy-deficient, populated land mass. Furthermore, the energy must be recoverable using technology achievable at a competitive cost and numerous environmental, legal and institutional problems will have to be overcome.

The highest-temperature reservoirs should be found adjacent to the zones of the seafloor extension or volcanism that are subject to high sedimentation rates. The relatively impermeable sediments reduce hydrothermal-discharge flow rates, forcing the heat to be either conducted away or released by high-temperature fluids, both of which lead to reservoir temperatures that can exceed 300° C. There is evidence that the oceanic crust is quite permeable and porous and that it was amenable to deep (3—5 km) penetration by seawater at least some time in the early stages of its evolution.

Most of the heat escapes far from land, but there are notable exceptions. For example, in parts of the Gulf of California, thermal gradients in the bottom sediments exceed 1° C/m. In the coastal areas of the Gulf of California, where electricity and fresh water are at a premium, this potential resource lies in shallow water (< 200 m) and within sight of land. Other interesting areas include the Sea of Japan, the Sea of Okhotsk and the Andaman Sea along the margins of the western Pacific, the Tyrrhenian Sea west of Italy, and the southern California borderland and west flank of the Juan de Fuca Ridge off the west coast of the United States.

Many questions remain to be answered about the physical and other characteristics of these systems before they can be considered a viable resource. Until several of the most promising areas are carefully defined and drilled, the problem will remain unresolved.

INTRODUCTION

In the quest to explore and develop the geothermal resources of the earth, very little consideration has been given to submarine resources. The magnitude of these resources may be many times greater than on the continents, but at present this is only a tantalizing prospect. Because they occur beneath the bottom of the sea, submarine geothermal resources are poorly understood. This remote, hostile, high-pressure, and corrosive environment does not attract many geothermal prospectors, especially when so many promising subaerial regions remain to be explored.

Nevertheless, Lawver et al. (1975) predict that hydrothermal fluid temperatures exceeding 200° C may be found throughout the Gulf of California (> 100,000 km^2) just beneath the nominally 1 km deep basement-sediment interface. This zone is in addition to more localized zones that Lawver et al. (1975) interpreted to be recent intrusions and where measured temperature gradients exceed 1° C/m. In the coastal areas of the Gulf of California, where electricity and fresh water are at a premium, this potential resource lies within sight of land.

The estimated total rate of heat loss from the earth is 10.2×10^{12} cal/s (Williams and Von Herzen, 1974). Of this amount, approximately 4×10^{12} cal/s is a direct result of seafloor spreading. Most of the heat is released through young (Pleistocene or younger) rocks adjacent to the earth's 55,000 km long spreading system (Fig. 1). By this process, more than 20% of the earth's heat loss occurs through only 1% of the earth's surface area. This amount (2×10^{12} cal/s) is roughly equivalent to man's present gross energy consumption rate. Besides the seafloor-spreading centers, numerous volcanically active seamounts and several marginal seas (e.g., Sea of Japan or Andaman Sea) display unusually high rates of heat loss. Volcanic islands, island arcs, and geopressured zones (e.g. Texas and Louisiana Gulf Coast) are also possible energy resources but will not be considered within the scope of this discussion.

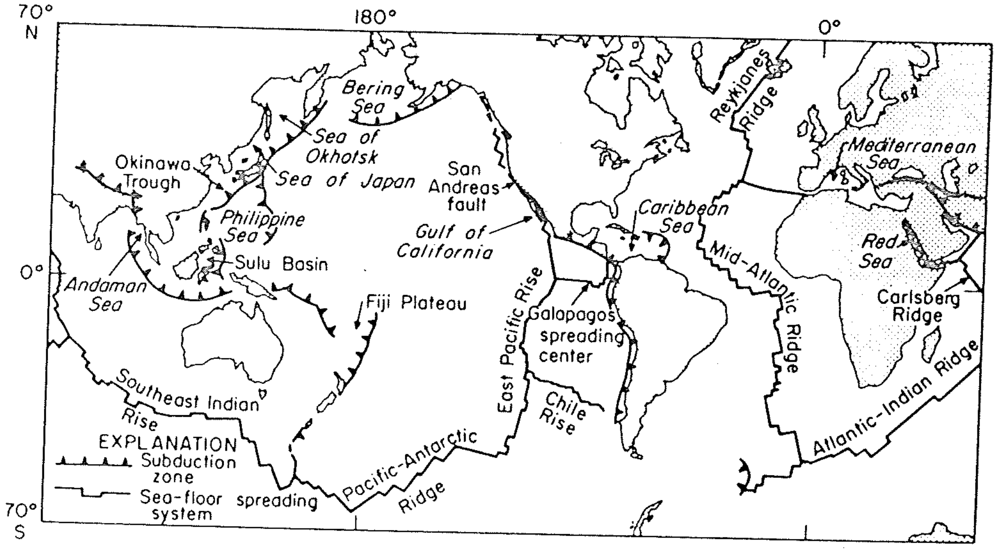

Fig. 1. World map showing the location of spreading centers, subduction zones, and marginal seas. Marginal seas displaying high heat flow are generally behind the subduction zone and their adjacent island arc (e.g., Sea of Japan and Andaman Sea).

HYDROTHERMAL HEAT LOSS

Evidence for the existence and importance of hydrothermal circulation

Most of the heat escaping from the earth's surface is lost by thermal conduction. However, near active submarine volcanic areas, the crustal rocks are apparently permeable enough to allow large quantities of heat to be lost through hydrothermal convection. Williams and Von Herzen (1974) estimated that more than 20% of the earth's heat may escape by this process. When a solidified, but hot, igneous rock is cooled, it contracts. The vertical component of contraction can be absorbed by subsidence, but contraction in the horizontal plane will result in fracturing, as long as the rock is strong enough to propagate fractures (cf. Lister, 1974). These fractures might be equivalent in volume to several percent of the total rock volume. Flow and dike contacts will add to the bulk porosity. Finally, tectonic faulting, prevalent in these areas, provides access for seawater between the porous strata and sea bottom. Given these conditions and a substantial input of heat, it is difficult to envision a system in which hydrothermal convection would not at some time be important.

There is much evidence to substantiate the existence of submarine hydrothermal convection. Elevated heat flow and bottom-water temperatures apparently related to hydrothermal discharge have been reported in the Red Sea by Erickson and Simmons (1969) and in the Galapagos spreading center by Williams et al. (1974). Numerous investigators have dredged or drilled hydrothermal metamorphic rocks from the oceanic crust (e.g., serpentinite, greenschists, and greenstones) and use hydrothermal circulation of seawater to explain the alteration (e.g., Aumento et al., 1971; Muehlenbachs and Clayton, 1971; and Hart, 1973). Mineral deposits (e.g., metalliferous sediments) from hydrothermal exhalations have been described (Corliss, 1971; Ross et al., 1972; Scott et al., 1974). Vertical profiles taken by the Geochemical Ocean Sections Program (Geosecs) of suspended matter and dissolved gases in the mid-depths have been related to hydrothermal processes. Extensive evidence of hydrothermal circulation has been found in ophiolitic rocks (cf. Spooner and Fyfe, 1973), and these rocks have been interpreted as uplifted oceanic crust. Drill holes as deep as 0.5 km have revealed evidence of hydrothermal circulation, such as alteration and precipitation in and near joints and shear zones, and flowing water (e.g., Melson, Aumento and others, 1974; Hyndman et al., 1976). Lister (1974) argues that results of seismic refraction are incompatible with pure conductive cooling of a newly created lithosphere. He also contends that the sheeted dike complexes in the ophiolite suites and the fact that the magnetic anomaly layer accurately records geomagnetic reversals are also inconsistent with pure conductive cooling.

The most compelling evidence of the importance of hydrothermal circulation

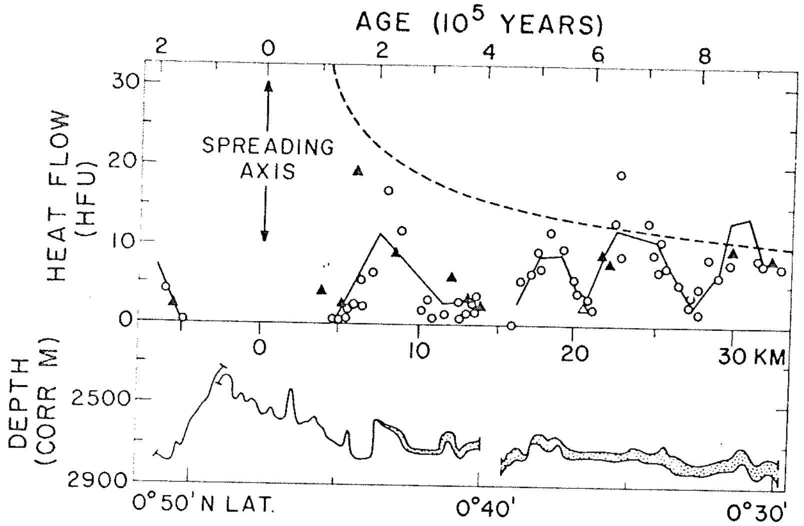

Fig. 2. Profile of heat flow, topography (corrected meters), and thickness of sediments in the Galapagos spreading center survey area (from Williams et al., 1974). Dashed line is the theoretical curve for pure conductive cooling. Heat-flow points are projected to a single north—south section approximately perpendicular to the spreading axis. Thickness of sediment is shown by stippling. Dots are actual measured heat-flow values and triangles are minimum values.

comes from the disparity between the conductive heat flow measured near seafloor-spreading centers and that predicted by theoretical conductive cooling models. With reasonable values for input parameters, the models all predict heat-flow values near the spreading axis (within a few tens of kilometers) that are much higher than are measured (Fig. 2). Furthermore, they do not predict the scatter or general pattern of conductive heat flow that is observed. Williams et al. (1974) argue that this discrepancy is due to the loss of heat through hydrothermal convection. Sclater et al. (1974; 1976), correlating heat flow and outcropping basement, find that on seafloor of almost any age, outcropping basement depresses the observed heat flow within a large adjacent area by providing a vent for hydrothermal waters. This implies lateral transfer of water over substantial distances (tens of kilometers?) even in old oceanic crust.

Magnitude of hydrothermal heat loss

With present technology it is not possible to measure directly the hydrothermal heat loss from large submarine systems. The only method so far applied to this problem has been to estimate the total rate of heat loss utilizing theoretical conductive cooling models for seafloor-spreading systems. From this quantity is subtracted the observed conductive component of the heat flow and the estimated heat loss resulting from the quenching of extrusive lavas. The remainder is assumed to be the minimum hydrothermal heat flow (Williams et al., 1974). It is a minimum because a combination of hydrothermal and conductive cooling is more efficient than conductive cooling alone, therefore, more heat will be removed near a spreading center than is predicted by the theoretical cooling models.

Near the axis of the Galapagos spreading center (within 35 km) the hydrothermal component amounts to approximately 80% of the total heat loss. Thus 2.6×10^7 cal/s is being released by hydrothermal water per kilometer of ridge length. At most spreading centers this convected percentage should be somewhat larger, because the conductive component at the Galapagos is unusually high (Williams et al., 1974).

For non-seafloor spreading systems (e.g., volcanic seamounts), estimates of the hydrothermal component of heat loss are not available, primarily because the physical system is poorly understood and no attempt has been made to develop adequate theoretical models for predicting the total heat loss.

PROBABLE RESERVOIR CHARACTERISTICS

General

In the broad sense, a submarine geothermal reservoir is a natural sub-seafloor container of hot water. To be economically exploitable, it must be possible to withdraw large volumes of hot water from the reservoir (i.e., remove heat at a much greater rate than the natural heat loss, even where this heat loss is very high). This procedure requires the accumulation of a relatively large volume of hot water. The evidence that there are such reservoirs seems persuasive, but none have been drilled; thus, their existence is admittedly debatable. Nevertheless, it is possible at this time to make some useful observations concerning potential reservoirs related to seafloor-spreading systems, including inter-arc basins.

The deep seafloor can be characterized as a nearly isothermal boundary, which, given sufficient permeability, allows free motion for discharge and recharge of fluids. Owing to the presence of the ocean above the seafloor, terrestrial system concepts such as the water table, hydrologic head differences, and boiling must be reexamined.

Temperature

Factors affecting reservoir temperatures. The highest heat input in a spreading ridge will be into the young rocks near the axis. As described in a later section, these rocks should also have the highest porosity and permeability, and on most spreading centers they will have little or no sediment cover. This combination of properties should lead to a situation in which the hydrothermal circulation flow rates are large, the recirculation ratio (flux of water moved out of the system divided by the average flux of water within the system) and water residence time is small, and the cooling is so efficient that the circulating water is scarcely heated. As the crust ages, sediment begins to blanket the seafloor, and deposition and precipitation reduce the permeability of the system. The heat input is decreasing at the same time, but apparently this effect does not become dominant for several million years. Lower permeability within the system and especially at the seafloor will tend to decrease flow rates and increase the recirculation ratio and residence time, resulting in an increase in the average reservoir temperature. These higher temperatures are most readily seen in the measurement of conductive heat flow which usually reaches a maximum between an age of 1.5—3.0 m.y. (e.g., Fig. 3).

From this analysis it seems that spreading centers and inter-arc basins having the highest sedimentation rate (e.g., Red Sea, Gulf of California, Sea of Japan) would be most apt to have the highest average reservoir temperatures. The proximity to land makes them especially attractive for exploration, test drilling, and exploitation.

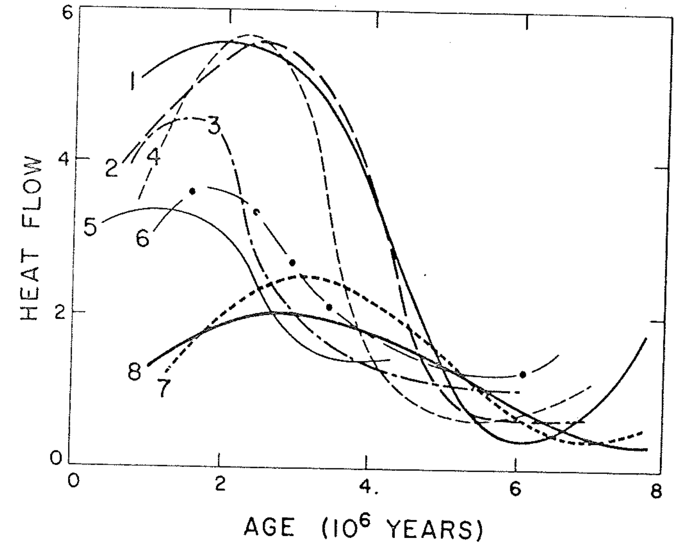

Fig. 3. Heat flow (10^{-6} cal/cm^2 s) versus age for eight different sections of the earth's seafloor-spreading system. Curves are visually smoothed fits to averages taken over 2-m.y. intervals each 1 m.y. (where data are available) and projected normal to the spreading axis. 1 = Galapagos spreading center at 86° W; 2 = Juan de Fuca; 3 = East Pacific Rise at 14° S; 4 = Central Indian Ocean Ridge at 20—22° S; 5 = East Pacific Rise at 12° S; 6 = East Pacific Rise at 39° S; 7 = Reykjanes Ridge; 8 = Mid-Atlantic Ridge at 46° N (figure from Williams, 1974).

Geochemical temperatures. Reservoir temperatures can be estimated from the geochemical thermometers for hydrothermal metamorphic rocks. From estimates of mineral stabilities, it has been inferred that the temperature of greenstone metamorphism ranges from 200 to 300° C (Melson and Van Andel, 1966; Cann, 1969; Aumento et al., 1971). Muehlenbachs and Clayton (1972), using ^{18}O fractionations between coexisting metamorphic minerals of the greenstones, found temperatures within the same range. Ophiolitic rock sequences, which are believed to be the tectonically uplifted oceanic crust, are apparently developed over a maximum temperature range of 180—400° C (Spooner and Fyfe, 1973), with temperatures as high as 400° C having occurred as shallow as 300 m below the seafloor.

Geothermal temperature gradients. Great care must be taken in attempting downward extrapolation of the temperature gradients that have been measured for heat-flow determinations. These gradients are measured in the top few meters of sediment. In a region where convection may be important, there is no assurance that they persist to any great depth. For example, Lawver et al. (1975) interpreted a narrow zone of high heat flow centered over a prominent basement high in the Gulf of California as a recent intrusion. If the basement is quite permeable, lies beneath relatively impermeable sediments, and contains recirculating hot water, then the sediment—basement interface may be a relatively isothermal surface. In this case the measured heat flow would simply be indicative of variations in the thickness of the insulating sediment blanket and not variations in basement temperature (i.e., hot intrusion). This could be the cause of the Lawver et al. (1975) Gulf of California heat flow anomaly, since the observed thermal gradients increase by a factor of 7 coincident with a sediment thickness decrease of approximately the same factor.

Another problem with extrapolating measured thermal gradients is that many of the observations have been subject to a sampling bias. On mid-ocean ridges, sediment generally first collects in topographic depressions (sediment ponds), which are commonly hydrothermal recharge areas and therefore have abnormally low heat flow (Lister, 1972). With current technology, heat-flow measurements can only be made through an adequate sediment cover. This results in many near-axis heat-flow measurements being low, having been biased toward these sediment ponds. This sampling bias does not exist in areas of high uniform sediment cover (e.g., Galapagos spreading center) or areas of high sedimentation rates (e.g., Sea of Japan, Gulf of California, Sea of Okhotsk, and the Mediterranean Sea).

However, high sedimentation rates cause a similar problem. When conduction is the dominate mode of heat transfer within the sediments, a significant fraction of the equilibrium heat flow is absorbed in warming the rapidly accumulating sediment. The result is that thermal gradients in the sediments near the seafloor are smaller than they would be without the sedimentation. If the sedimentation history is known, it is possible to make a fairly accurate correction for its effect. The corrections for the simple case of sedimentation at a constant rate for a specified amount of time are given in Von Herzen and Uyeda (1963). Since many of the economically interesting submarine geothermal areas are subject to high sedimentation rates, this effect is quite important. In these areas temperatures within the sediments may increase with depth substantially more than is indicated by measurements of the seafloor thermal gradient.

Boiling. Boiling would not be expected in most seafloor-spreading geothermal systems. Hydrostatic pressure increases about 0.1 bar per meter of depth, and most spreading ridge crests are deeper than 2 km. The critical point for seawater is approximately 304 bars/408° C (Spooner and Fyfe, 1973). Therefore, water in sub-seafloor geothermal systems probably is either at supercritical or just subcritical pressures, where boiling cannot occur except at very high temperatures or in unusually shallow systems.

Location and dimensions of reservoirs

The distribution of surface heat flow could be used to locate reservoirs. The undulations in the heat-flow pattern illustrated in Fig. 2 are interpreted as indicating the locations of rising and descending limbs of convection. Rising limbs are presumably located below heat-flow maxima. These maxima, which commonly occur on topographic highs or near faults, are regarded as the portions of the high-temperature reservoir that are nearest the seafloor. Of course, if the system has a substantial recirculation ratio, hot water should be found at depth almost anywhere in the region.

The thickness of reservoirs probably varies greatly. An interpretation of the heat-flow profile in Fig. 2 based solely on fluid dynamic considerations, suggests the observed 6-km wavelength variations in heat flow are indicative of hydrothermal convection that penetrates approximately 3.5 km into the oceanic crust (Williams et al., 1974). From microearthquake data, Ward (1972) inferred the circulation beneath Iceland might penetrate to depths exceeding 10 km.

Permeability and porosity

Sources of permeability. The upper regions of a reservoir presumably derive their permeability primarily from fractured flow and dike contacts, thermal contraction cracks, and faults (e.g., Bodvarsson, 1961; Ballard, 1975). In very young crust, this zone probably has a much higher permeability than the deeper regions. However, in a convecting system, the near-seafloor thermal gradients will be much higher, and the upper parts of a reservoir are probably subject to much higher rates of chemical precipitation and may become clogged sooner than the deeper regions. In the deeper regions, the initial permeability is probably much less, because there will be no flow contacts. However, hot seawater reacting with the fresh rocks may dissolve large quantities of rock (Bischoff and Dickson, 1975), and this could conceivably compensate for the initial lower permeability. The evidence for this is not conclusive, as the dissolution of large quantities of rocks should have a dramatic effect on the chemistry of the oceans. However, such an effect is not apparent.

The permeability of any part of a geothermal system can be renewed at any time by fault activity. Active faulting, as detected by distant seismic stations, is quite evident in young oceanic crust but apparently diminishes rapidly as the

crust ages. Ward (1972) discusses the importance of microearthquakes in providing channels for water flow in subaerial geothermal systems. Several studies have reported microearthquakes along zones of seafloor extension, but this activity could persist undetected in older oceanic crust.

Maximum depth of the permeable layer. Ultimately, water can penetrate no deeper than the depth at which lithostatic pressure exceeds the strength of the rocks and they can no longer support cracks. As mentioned earlier, the maximum depth may exceed 10 km. For any given rock, this depth is strongly temperature dependent but can easily approach the depth of the crust (Lister, 1974). However, the effects of lithostatic pressure on reservoir permeability may be quite severe at much shallower depths. Lister (1974) describes a model in which temperature-dependent static fatigue causes the brittle, permeable deeper rocks (> 1–2 km beneath the seafloor) to fail under the compressive lithostatic load. He believes that collapse results in the rocks within the collapse zone becoming relatively impermeable. The rocks over the collapse zone are left permeable but cold. Lister does not assign a crustal age to this phenomenon, but it would apparently take place after the occurrence of the heat-flow maxima (1.5–3.0 m.y.) and might even be responsible for the minima observed between 4 and 8 m.y. (Fig. 3, or Anderson, 1972).

Effects of metamorphism. Large volume changes can result from hydration and/or dehydration reactions in the reservoir rocks. The volume expansion associated with extensive serpentinization in the deep rocks of a reservoir can be massive and could completely close flow channels. Similarly, lower-temperature hydration reactions could cause a reduction in permeability in shallower parts of the reservoir. As discussed earlier, the temperature of the crustal rocks apparently does not decrease monotonically with increasing age, so the distribution of these reactions might be quite variable and any reheating of these hydrated rocks might lead to dehydration, contraction, and an increase in permeability.

Another factor that has an effect on the permeability is the seafloor-spreading rate. Observations of spreading center topography indicate that slowly spreading ridges are more highly faulted than rapidly spreading ridges. The effect on permeability is seen in conductive heat-flow averages. From empirical observations on young crust (less than 30–50 m.y. old), the conductive heat flow is generally lower on slowly spreading ridges than on rapidly spreading ones, suggesting that higher permeability may be allowing more of the heat to escape hydrothermally.

Porosity. That portion of the bulk porosity embodying water that might easily be extracted, probably has the same origin as the permeability (i.e., cracks, contacts, faults, and solution voids). Although the porosity is of critical importance in estimating the geothermal resource potential, no reliable estimates are possible, other than to say that the oceanic crust could be quite porous at times during its evolution and that changes in porosity will generally correspond to changes in permeability. Because of factors already discussed, porosity probably is subject to large spatial and temporal variations.

Reservoirs not related to seafloor spreading

Little can be said about the reservoir characteristics of systems not related to seafloor spreading. Volcanically active seamounts are the submarine equivalent of volcanic islands, and hydrothermal circulation is probably common, thus, reservoir characteristics should be affected by parameters similar to those discussed earlier. Without any data, this is simply speculation. However, hydrologic studies of volcanic islands like those in the Hawaiian chain indicate that such volcanoes are highly permeable to the flow of water (McGuinness, 1963). Furthermore, actual submarine hot springs producing metalliferous sediment were observed by Zelenov (1964) on the submarine volcano Banu Wahu in Indonesia.Similar observations have been made on the Island of Santorini in the Mediterranean (Puchelt, 1973) and in Rabaul Harbor in the Solomon Islands (Ferguson and Lambert, 1972).

Discussion

Simple laboratory and mathematical modeling investigations have been applied to studying hydrothermal convection in submarine geothermal systems (e.g., Elder, 1965, 1967; Bodvarrson and Lowell, 1972; Williams et al., 1974). These have yielded valuable insight. More sophisticated computer modeling techniques have been developed for use in studying subaerial geothermal areas. Many of these techniques could readily be applied to the submarine problem; however, without better information to constrain these models, their value is limited.

Many useful comparisons can be made between submarine geothermal systems and areas of subaerial seafloor spreading. Iceland provides the best example containing numerous geothermal areas in a predominantly basaltic environment. Especially illustrative is the Reykjanes peninsula: a well-studied, seawater-dominated, high-temperature system.

In addition, given the complexity of the factors affecting permeability and porosity, large-scale temporal and spatial variability can be expected. However, as mentioned earlier, the crust apparently remains permeable to some extent beyond an age of 50 m.y. (Sclater et al., 1974, 1976; Williams and Poehls, 1975). With our poor understanding of these factors and the lack of direct data on these quantities, the need for more work, particularly drilling, becomes obvious. It is the distribution of permeability and porosity that is primarily responsible for determining the magnitude of submarine geothermal resources, and it is this distribution that must be determined.

SPECULATIONS OF THE MAGNITUDE OF THE RESOURCE

Perhaps that the most promising submarine geothermal resource area for early exploration is the Gulf of California. In the coastal area of the gulf, where electricity and fresh water are available only at a premium, this potentially enormous resource lies within sight of land. The tectonics of the region are apparently transitional from the predominantly seafloor-spreading tectonic regime of the East Pacific Rise (on the south) to the totally transform fault motion of the San Andreas Fault on the north. The Gulf of California has an area of roughly 150,000 km^2. In the northern one-third of the gulf or roughly the 50,000 km^2 north of 28° 30′N, 74% is overlain by water shallower than 500 m. Approximately 35,000 km^2 is new seafloor, created by seafloor spreading within the last 5 m.y. (Moore, 1973). From seismic refraction studies, Phillips (1963) interpreted the upper 1.5 km of the seafloor to be unconsolidated sediments (seismic velocity ~ 2 km/s). Below this is a layer about 2.5 km thick, having a seismic velocity averaging 4.1 km/s. This layer may consist of semiconsolidated sediments and/or porous volcanic rocks. Thermal gradients have only been measured in the upper few meters of sediment; they have not been measured beneath the sediment zone that would be affected by bottom-water temperature variations. Owing to the shallow depth of this region, these variations could be quite large, and thus no reliable heat flow data are available. However, theoretical models for conductive cooling of young seafloor away from a seafloor-spreading center (e.g., Sclater and Francheteau, 1970) indicate that the average heat flow should be of the order of 4 HFU ($1 \text{ HFU} = 10^{-6}$ cal/cm^2 s). This agrees with the average heat flow observed in the central Gulf of California [3.4 ± 0.5 HFU (Lawver et al., 1975)]. (As noted earlier, the high sedimentation rates in the central Gulf of California, ~ 2 m/1000 yr, may have depressed these observations as much as a factor of two.) Assuming that the unconsolidated sediments are impermeable and have a thermal conductivity of 2×10^{-3} cal/s, the thermal gradient in the upper 1.5 km would be about 200° C/km and the temperature at the base of this layer would be 300° C. If the underlying layer is sufficiently porous and permeable (admittedly an assumption), it might be possible to extract large quantities of hot water.

Muffler (1973) estimated that approximately 1% of the heat actually stored in a geothermal system above 15° C can be converted into electricity. In this scheme he assumed that one-half the reservoir is completely inaccessible because of impermeable rocks and an insufficient number of drill holes. The remaining half of the system is utilized until it is cooled to 180°C, but much of this heat is subsequently lost due to thermal and mechanical inefficiencies.

To approximate the possible geothermal potential of the northern Gulf of California, let us assume that one-half of the 35,000 km^2 of new crust is underlain by a porous and permeable reservoir whose top is 1.5 km below the seafloor. Because of drilling costs, assume that no hot water can be extracted from below 3 km. Finally, take a reservoir temperature of 260° C versus the 300° C calculated above to account for the effects of some small amount of hydrothermal discharge. The heat contained within the reservoir is then approximately 2.2×10^{22} joules. Following the arguments of Muffler (1973), the electrical generating potential would be approximately 180,000 megawatts for 30 years. This is nearly as high as the current electrical consumption rate of the entire United States.

Analogies may be drawn between the northern Gulf of California and the Cerro Prieto geothermal field (Isita et al., 1975) about 100 km to the north. In Cerro Prieto, production is from a sedimentary stratum lying within the same sedimentary basin as the northern gulf. Nevertheless, an assumption of the existence of this high-temperature, porous, and permeable reservoir in the northern gulf may be optimistic. An extensive system of submarine hot springs could keep the upper several kilometers too cool to be useful. In contrast, extremely low permeability could prevent the economic extraction of the heat, or the thermal anomaly could be much smaller than assumed here. The model used here is admittedly an oversimplification of the problem. To cite conflicting observations, Bischoff and Henyey (1974) reported crystalline basement within 50 m of the seafloor in the lower Delfin Basin, an inferred spreading center of the northern gulf. They also dredged pumice from the edge of this basin. Although this is not exactly the same area as Phillips (1963) investigated in his seismic refraction work, the sub-seafloor structure in the northern gulf is obviously more complicated than Phillips described. Also these zones of recent intrusion, like the one in the central gulf described by Lawver et al. (1975), are almost certainly localized areas of shallow high temperatures (e.g., measured thermal gradients of 1750° C/km). Therefore, any estimate of the geothermal potential based on present knowledge is subject to large uncertainties. The one offered here is only to be an order-of-magnitude calculation designed to emphasize the possibility of a resource of very large proportions.

Numerous areas similar to the northern Gulf of California exist throughout the world, especially around margins of the Pacific Ocean (cf. Grose and Keller, 1975). Many are potential candidates for exploitation of heat energy. For example, much of the southern two-thirds of the Gulf of California, although not nearly as shallow, still has high heat flow and a kilometer of sediment cover. The marginal basins of the western Pacific generally display high heat flow (Sclater, 1972). The most attractive geothermal resources are the ones Sclater called "inactive basins with high heat flow". Being inactive, they tend to develop a thick sediment cover, thereby forcing the high heat flow to produce high temperatures at shallow depth. In the Sea of Japan, an area of roughly 1×10^6 km^2, heat flow is generally high (> 2 HFU), with values greater than 3 HFU not uncommon (Yasui et al., 1968a). Most of this area has a sediment cover from 0.7 to 1.7 km thick. One area in the Sea of Japan having especially high heat flow (average 2.54 HFU) is the Korea Plateau, which is immediately adjacent to Korea in water approximately 1 km deep. Similarly, the Sea of Okhotsk has an average flow greater than 2 HFU with values to 4.5 HFU (Yasui et al., 1968b) and sediment thickness to 5 km (Kosminskaya and Sverev, 1968). The Okinawa Trough has an average heat flow of 4 HFU (Yasui et al., 1970) and sediment thickness from 2.2 km in the north to 1.4 km near Taiwan. The seafloor there lies in a depth range from 2.2 to 3.2 km.

The average heat flow in the western Mediterranean Sea is 2.33 HFU (Erickson, 1970). Within this region Erickson (1970) shows an area of more than 50,000 km^2 in the south central Tyrrhenian Sea (north of Sicily) where the average heat flow is about 3.4 HFU. He further states that corrections for the effect of the high sedimentation rate (~ 0.5 m/1000 yr) could double this value. The area of known high heat flow lies at depths between 2.5 and 3.5 km and has an average sediment thickness of about 1 km. However, the available data do not accurately define the boundaries of the area, and it could be much larger, extending into shallower water nearer to the Italian coast.

Several of the basins and troughs in the southern California continental borderland display high heat flow. For example, the San Diego Trough, approximately 30 km west of San Diego, California, has an average heat flow of 3.3 HFU (corrected for topography and sedimentation) with values to 4.9 HFU. The seafloor lies at a depth of about 1 km and is locally covered with about 1 km of sediment. The east flank of the Juan de Fuca Ridge has an average heat flow of 7.1.HFU and sediment depth of several hundred meters (Lister, 1972). It lies in deep (> 2 km) water, approximately 400 km for the coast of the U.S. Pacific Northwest. Some other examples are the Andaman Sea (measured heat flow as high as 7 HFU in sediments 1.5 km thick), Sulu Basin (adjacent to the Philippine Islands), the Red Sea, and the Fiji Plateau.

EXPLORATION AND EXPLOITATION

With an existing ability to identify such potentially attractive areas, the next logical step would be to explore several of them. This exploration should consist of geophysical and geochemical surveys to characterize and identify the most promising localities, followed by drilling. Initial drilling could be most simply accomplished within the scope of the IPOD research drilling program, utilizing the drilling ship "Glomar Challenger".

As discussed earlier, drill holes penetrating the ocean's basaltic basement have generally revealed signs of hydrothermal activity, such as extensive alteration and precipitation in and near joints and shear zones, and flowing water. The deepest penetration (up to 583 m) was made in a topographic depression on the west flank of the Mid-Atlantic Ridge in crust about 3.5 m.y. old (Melson, Aumento and others, 1974). This hole penetrated the ponded sediment and went deep into the volcanic layer. Preliminary results indicate that these volcanic rocks, at some time, had been quite porous and permeable. The heat-flow was low (~ 0.5 HFU), implying that, as expected, this had been and probably still is a recharge area. In order to drill hard rock on the ocean floor with current drilling technology, something on the order of 100 m of sediment cover is required to stabilize the drill stem. On young rocks of the

Mid-Atlantic Ridge, and on most other spreading centers, this amount of sediment generally occurs only in topographic depressions (sediment ponds). If a recharge area is to be avoided and hot water encountered at a reasonably shallow depth, heavily sedimented spreading centers should be chosen and the drilling site selected in zones of high heat flow.

It seems reasonable that resource exploitation could follow technology already developed by the geothermal and offshore oil industries. Special consideration would have to be given to power and water transmission, to possible pollution problems associated with discharging hydrothermal fluids into the sea, to insulating submerged production piping, and to deep-water platforms. One distinct advantage, however, is the simple access to almost limitless supplies of cooling water.

CONCLUSION

The existence of a substantial and exploitable submarine geothermal resource and, certainly, the magnitude of such a resource remain to be determined. The evidence is persuasive that enormous quantities of heat are removed from the oceanic crust by hydrothermal circulation; however, high temperatures at shallow depths, adequate permeabilities and porosities, and several other qualities are important prerequisites for an economically feasible energy resource. With the world's pressing need for alternative energy sources, submarine geothermal resources deserve a closer look. It is hoped that the results derived from such research would answer many of the questions raised in this paper and allow an assessment to be made of the submarine geothermal resource potential.

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Book Review

Volcanoes of the Earth, Moon and Mars, G. Fielder and L. Wilson (Editors). Paul Elek (Scientific Books) Ltd., London, 1975, 126 pp., £ 6.00.

During the past few years our knowledge of the Solar System has grown at a remarkable rate. In 1974, for example, spacecraft travelled to Mercury, Venus and Jupiter, and landed on Mars, while the instruments on "Skylab" provided a wealth of new data on the Sun. The huge increase in data on the nature of the planets and their satellites is forcing volcanologists, and others working in related fields, to re-examine the significance of volcanism, both in the evolution of planets, and in the production of their atmospheres. The book "Volcanoes of the Earth, Moon and Mars" is important in that it demonstrates that volcanology is a significant branch of the planetary sciences rather than a neglected branch of the earth sciences.

This relatively short book (126 pages) contains contributions from nine authors. Eight of them are members of the Lunar and Planetary Unit of the Department of Environmental Sciences in the University of Lancaster, U.K. The book is divided into nine chapters and each chapter contains a discussion of a separate topic. While the overall objectives of the book are admirable, the book does contain some unsatisfactory sections.

In the first chapter Dr. G. Fielder gives a succinct account of the origin of the planets. He also demonstrates that volcanic activity is important in both the development of the surface layers of the planets, and in the evolution of the atmospheres that are found on the planets. In contrast with the first chapter much of the material presented in the second chapter is disappointing. This chapter contains an elementary discussion of "volcanic types and their distribution". The discussion is, however, marred by a numbers of misleading statements. The following are a few examples of such statements: sedimentary rocks are defined as being "formed by the lithification of rock detritus and animal remains" (p. 11); it is stated that "diatremes which tap magma chambers situated at depths of 200 to 300 km are called kimberlite pipes" (p. 13); and on p. 16 it is stated that "seventy-five per cent of the active terrestrial volcanoes are situated in the Pacific ring of fire", later in the discussion it is stated that most active volcanoes occur in the "ocean basins", and then this statement is followed by the claim that a "high proportion" of the volcanoes of the ocean basins "occur on or near mid-ocean ridges". This chapter does, however, contain a short but useful section on the viscosity of magmas (pp. 12—13).

The third chapter is on "lava flows and flood lavas" and it contains a most interesting theoretical discussion on the rheology, thickness and width of lava flows. About half of this chapter is devoted to a well-illustrated account of the flood lavas of the Mare Imbrium region of the Moon. Chapter 4 contains a concise and useful description of "explosive eruptions and pyroclastic flows".