

Fundamental Characteristics of Hydrothermal Submarine Systems and Preliminary Evaluation of its Geothermal Potential in Mexico

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ABSTRACT

Hydrothermal submarine reservoirs contain essentially an infinite energy potential. Seafloor hydrothermal circulation is the principal agent of energy and mass transfer from the Earth's crust to the ocean and one of the primary modes of interaction between the solid earth and the ocean/atmosphere system. The fluid discharged from seafloor geothermal reservoirs cools the submarine hot rock, builds mineral deposits, modifies seawater circulation patterns, supports strange biological communities, and influences oceanic Chemistry and Biology. Convective circulation of seawater through oceanic crust at mid-ocean ridges and on ridge flanks has important effects on the heat transport, on the chemical and isotopic compositions of ocean crust and seawater, on the mineralization of the crust and on the physical properties of oceanic basement. Deep submarine energy is related to the existence of hydrothermal vents emerging in many places along the oceanic spreading centers between tectonic plates. These systems have a total length of about 65,000 km in the oceanic crust. Non-traditional geothermal energy sources in Mexico include the hydrothermal submarine systems located close to the Mexican coast of the Pacific Ocean. We calculate its thermal potential to be around $1123 \text{ MW}_T / \text{km}^3$, at an average temperature of 350°C . At the same time, submarine geothermal energy supports rich biological communities at depths where living organisms cannot use sunlight for photosynthesis. The heated seawater containing H_2S is ejected upward through hydrothermal vents. Chemosynthetic bacteria use the hydrogen sulfide as a metabolic source of energy and form food for clams, mussels and worms. In this way, geothermal energy becomes the basis of rich food chains at places where photosynthesis is impossible. Recent research suggests that possible locations for the synthesis of chemicals needed for the origin of life could be submarine hydrothermal vents. In this paper we summarize results obtained from different researchers about the fundamental characteristics of submarine geothermal systems.

1. INTRODUCTION

Any natural phenomenon or artificial process that is formed by two or more interacting parts is a Complex System. The properties and behavior of a complex system cannot be thoroughly explained by the isolated understanding of each one of its single components. These systems act as a whole and is not possible to understand their operation without considering the interactions among all their parts. In

geothermics there are many examples of complex systems. Hydrothermal circulation at the ridges of the deep sea (Fig. 1) is a fundamental complex process controlling mass and energy transfer from the interior of the Earth through the oceanic lithosphere, to the hydrosphere and to the biosphere. Submarine hydrothermal interactions influence the composition of the oceanic crust and the chemistry of the oceans. The fluid circulating in seafloor hydrothermal systems is chemically altered due to processes occurring in its passage through the oceanic crust at elevated temperatures and pressures. This mechanism produces hydrothermal vent fields which support diverse and unique biological communities starting from microbial populations that link the transfer of the chemical energy of dissolved chemical species to the production of organic carbon, Humphris *et al.* (1995). The eventual transfer of some gases input by hydrothermal activity from the ocean to the atmosphere, extend the influence of hydrothermal activity to beyond the oceans themselves, Damm (1995).

To understand the mass and energy flows among these complex geological, chemical, geophysical and biological subsystems requires the development of integrated models that include the interactions between them, Gallagher and Appenzeller (1999). From the point of view of their accessibility, there are two kinds of such systems: deep resources, located at certain places along the rifts between tectonic plates of the oceanic crust at more than 2000 m below sea level, and shallow resources near to continental platforms at 20-50 meters depth. Submarine geothermal energy in Mexico embraces both near-surface reservoirs and deep geothermal resources at more than 3000 meters depth. Both types of resources exist in the Gulf of California and in the Pacific Ocean (Fig.1). This condensed, bibliographical work has two central purposes: to trace the outline of the fundamental characteristics of submarine hydrothermal systems and to present a preliminary evaluation of the geothermal potential that these systems represent to Mexico.

2. SUBMARINE GEOTHERMAL DISCHARGES, PLUMES AND CHIMNEYS

2.1 Geothermal Discharges or Venting

Vents exist on land in the form of hot springs and geysers. Most of the known vents in the ocean are at the global mid-ocean ridge systems (MORs) in the deep sea. The crest of the MORs is the place where new lithosphere is created through igneous activity. Such magmatic processes provide the energy to drive hydrothermal circulation of seawater through the oceanic crust, originating rock-seawater

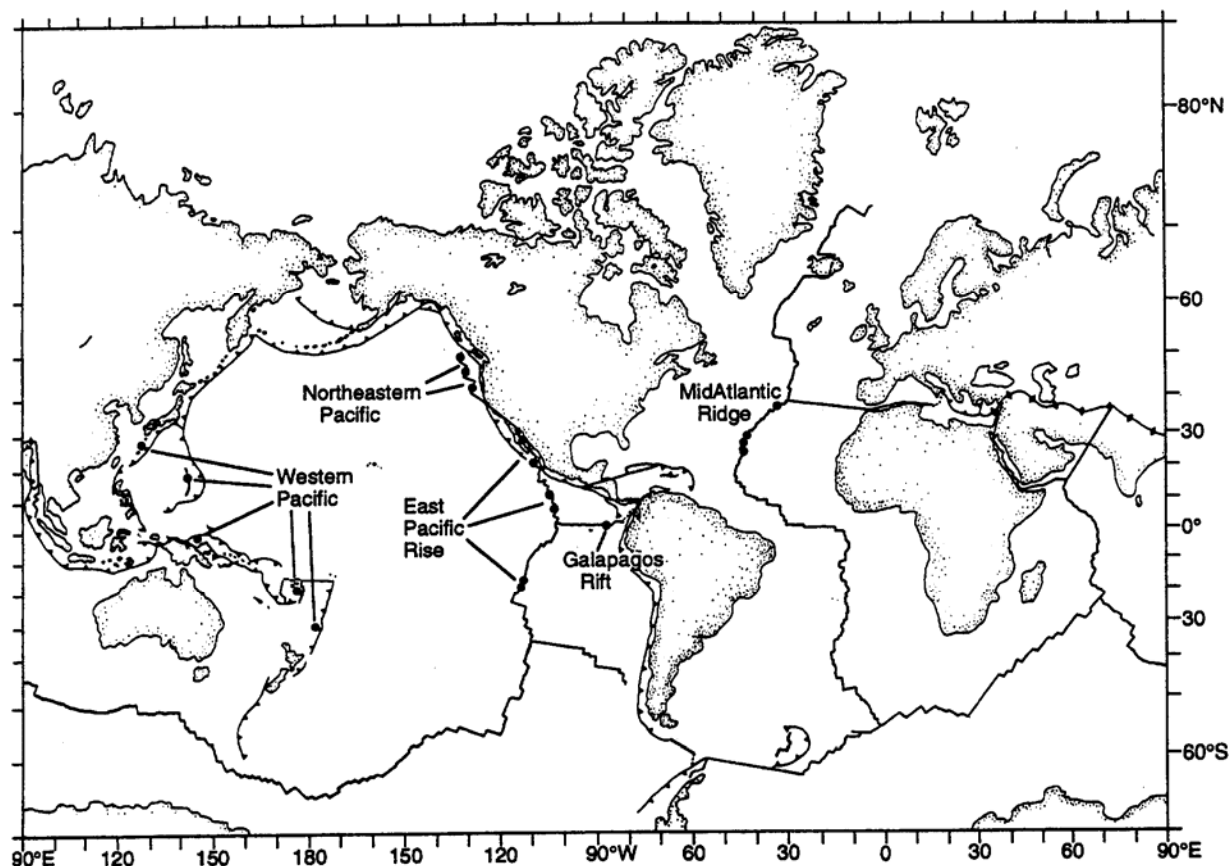


Figure 1: Mid-Ocean Ridges on Earth. From Hessler & Kaharl, (1995). American Geophysical Union, *Geoph. Mon.* 91.

Temperature is the single most important physical parameter in the chemistry of the fluids present. The resulting mechanism gives rise to venting at seafloor deepness, ranging between 840 and 3600 meters depth and contributing considerably to the global balance of the total Earth's heat, Fornari and Embley (1995). This venting is associated to fissures located directly above magma injection zones. The observed vent fields are typically tens of meters in diameter ranging in size between 4 m² to 800 m², Hessler and Kaharl (1995). The heat input from those systems affects the mid-depth circulation of the oceans. Hot rocks of the marine bottom cause chemical reactions, altering the natural chemical composition of sea water. The geochemistry of the marine manifestations at 350°C could help to better understand the chemistry of terrestrial geothermics. Analysis performed by Mercado (1993), described processes involving water-rock interaction and mixing with magmatic fluids that cause variations of salts dissolved in seawater. For example, lead, manganese and iron of the hydrothermal fluid, are higher than same elements in normal seawater by about 8000, 50,000 and 59,000 times respectively. Seyfried and Ding (1995) reported results of mineral solubility experiments and theoretical phase relations for all or a portion of the CaO-Na₂O-Al₂O₃-SiO₂-FeO-Fe₂O₃-CuO-H₂S-H₂O-HCl system, which indicate that temperatures and pressures of approximately 375°C and 400 bars respectively are required to account for the chemistry of hot spring fluids at mid-ocean ridges. Other higher pressure and temperature are possible, but these conditions "best represent conditions of last equilibration between hydrothermal fluid and altered

oceanic crust, prior to ascent of the fluid to the seafloor". The two principal factors affecting the development of these hydrothermal systems are heat from a magmatic source and the permeability structure of the oceanic crust. The vents in the deep sea are markedly short-lived and ever changing. The depth and size of the heat source and the type of permeability, for example related to faults and fractures acting as recharge conduits, will determine the longevity of a vent area, Fornari and Embley (1995).

2.2 Hydrothermal Plumes and Mega Plumes

The plumes hold many clues to the characteristics of hydrothermal venting and its effect on the ocean. Hydrothermal plumes are a direct result of the thermal and chemical input from submarine hot spring systems into the sea, Lupton (1995). The rising plumes entrain deeper and saltier water, carrying it up in the water column affecting the thermoaline circulation of the oceans, Damm (1995). The plumes' active discharge orifices cover only a minuscule percentage of the seafloor. But there is an enormous range of temporal and spatial scales involved in these events. Baker *et al.* (1995) found that the hydrothermal fluids discharged from vents form plumes that are rapidly diluted in the seawater and the mixture rises hundreds of meters and spreads laterally from tens to thousands of kilometers. Those plumes formed by mixing of seafloor vent fluids and ambient seawater are easily detectable by physical and chemical tracers. That is why the careful study of plumes is a useful tool for hydrothermal exploration and geological interpretation. Bemis, *et al.* (1993) achieved an experiment using the submersible Alvin

to collect data while the vessel was stationed at different locations close to a vent source on the Juan de Fuca ridge in the Pacific Ocean (JFr). With their meticulous investigation they were able to calculate the vertical heat flow in a buoyant plume. Many other measurements have been done subsequently to that year. The dynamics of a buoyant plume ascent in a stably stratified seawater is shown in figures 2 and 3.



Figure 2: Plume with vortices emerging from a black smoker at 342°C. Lupton (1995). American Geophysical Union, *Geoph. Monograph*. 91.

This image shows only some meters of plume ascent because the optical depth of seawater is very limited. It corresponds to a portion of a plume from a black smoker with a heat flux of about 60 MW_T (thermal mega-Watts), venting into an ocean with a constant density gradient given by the following equation reported by Lupton (1995):

$$N^2 = -\frac{g}{\rho_0} \frac{d\rho}{dz} = 1.5 \times 10^{-6} \text{ s}^{-2} \quad (1)$$

→ $d\rho/dz \approx 1.53 \times 10^{-4} \text{ kg/m}^4$; g is the gravity acceleration, ρ_0 is the average local density and $d\rho/dz$ is the vertical density gradient. N is called the Brunt-Väisälä buoyancy frequency. Turner (1973) established another useful equation to estimate the maximum height Z_M of rise of a plume as a function of the buoyancy flux F_0 and the frequency N :

$$Z_M = 5 \left(\frac{F_0}{\pi} \right)^{\frac{1}{4}} N^{-\frac{3}{4}} \quad (2)$$

From measured data reported by Lupton (1995), we obtain $F_0 = 0.17 \text{ m}^4 \text{ s}^{-3}$; using the frequency N , it is possible to estimate a maximum height for the plume: $Z_M \approx 370 \text{ m}$ above seafloor. After these models, a plume of 750 m height will correspond to a heat flux of about 1000 MW_T. Other thermal fluxes measured at black smokers range from 1 to 93 MW_T, with an accepted average value for a single orifice of about 8 MW_T, Lupton (1995), Bemis, *et al.* (1993). In 1986 a Mega-plume was discovered in the same region of the JFr; it had an extension of about 20 Km, 600 m thick and included 10^{11} MJ of excess heat. The weak dependence of Z_M on the heat flux indicates that the mega plume observed to affect the water column up to 1000 m above the seafloor, could be the impressive result of an instantaneous and huge release of heat flux at the

corresponding source. The fact that other mega plumes have been observed, leads to the conclusion that the total convective heat outflowing from the ocean is discharged in the form of both, continuous steady state venting and mega plumes. Alt (1995) estimated that submarine hydrothermal discharges remove about 30% of the heat lost from oceanic crust. The average heat flow in the Mexican Volcanic Belt is about $0.10 \text{ W}_T/\text{m}^2$ (García, 2000). The submarine heat flow measured in the Gulf of California is of the order of $0.34 \text{ W}_T/\text{m}^2$ at an average temperature of 330°C (Mercado, 1990). Using two models, Stein *et al.* (1995) predicted an average hydrothermal heat loss for the oceanic crust of about $1.5 \text{ W}_T/\text{m}^2$. The same parameter predicted for the ridges is between 2 and 100 MW_T/Km (per unit ridge length). The first value is for a slow ridge and the last value corresponds to a plume with a heat content of 1000 MW_T. Thus, the plumes remove more heat than the steady state surface flux for the cooling lithosphere (*ibid.*).

2.3 The Black Smoker Chimneys

Divergent plate movements in the deep sea produce fissures, allowing vertical transfer of magmatic heat toward the ocean floor. As cold seawater enters those fissures, it becomes hot and is chemically changed during its contact with the rock. In this way the oceanic crust is cooled significantly by convection. Recharge areas where seawater enters the crust are diffuse and widespread, Alt (1995). At seafloor hydrothermal vent sites, hot, acidic hydrothermal fluid is injected into cold, alkaline seawater, resulting in precipitation of vent deposits and particle-rich plumes, Kingston (1995). These deposits and plumes are the surface expression of large hydrothermal systems that transfer significant heat and mass from the mantle and crust to the hydrosphere. Many vent fields have vertical structures forming chimneys built of materials which precipitate from the heated vent fluid as it mixes with seawater. Black smoker chimney walls are initially emplaced as hydrothermal fluid mixes turbulently with seawater. This occurs because it “*is the subsequent dominance of horizontal transport across the wall, mineral dissolution and precipitation within pore spaces of the wall, and deposition of Cu-Fe sulfide along the inside of the flow conduit*”, (*ibid.*).



Figure 3: A black smoker with some vent organisms.

The effluent emanating from these constructions may be as hot as 403°C Grijalva (1986), Mercado (1990), Hannington *et al.* (1995). The metal zonation within black smoker chimneys and hydrothermal mounds is a consequence of the precipitation of sulfide minerals, in open spaces or as replacements of preexisting minerals, (*ibid.*). Kingston (1995) mentioned that initial models describing formation

of black smoker chimneys were based on petrologic studies of samples recovered from deposits venting 350°C fluid at 21°N on the East Pacific Rise. These growth models separate the formation of chimneys into stages. The first stage is precipitation of porous anhydrite walls that contains fine inclusions of sulfide (Figs. 3 and 4). This stage occurs when hydrothermal fluid at 350°C exits the seafloor at velocities of about 100 cm/s and mixes with seawater at 2°C. Velocities measured in the hydrothermal plumes 3 to 5 cm above the orifices of chimneys at 21°N EPR varied from 70 to 236 cm/s, (*ibid*).

In the 1980s, detailed oceanographic studies were made in the pull-apart basins of the Gulf of California, including thirteen dives in the submarine Alvin. This cruise was organized by the Scripps and Woods Hole Oceanographic Institutions, in a region located between 21°N and 109°W, at 200 km south of Cape San Lucas (Fig. 1), covering an area of 50 km radius. During the dives with the Alvin, diverse hydrothermal manifestations were observed. The so called "*Hanging Gardens*" were discovered 2600 m depth. Impressive natural chimneys up to 6 meters high, approximately at the same depth, were also observed. Those almost metallic natural chimneys are formed in part by iron and copper sulfides, and discharge spouts of water at 350°C, Mercado (1990 & 1993). Mercado (1990) reported sampling of sea water containing anomalies of methane, helium and hydrogen associated with geothermal fluids were measured. The flow of hot water expelled by white and black chimneys, has an approximate speed of 2.5 m/s flowing through diameters between 10 and 20 cm (*ibid*).



Figure 4: A white smoker chimney, 1 m high, at 3660 m, 26°8'N in the Mid-Atlantic Ridge. Fluid temperature between 250°-300°C. (reprinted with permission of the Am. Geophysical Union – WHOI, Humphris *et al.* (1995).

2.4 Influence of Vent Organisms on the Chimneys

Divergent plate movements in the deep sea produce The influence of organisms on the physical environment, particularly on exteriors of chimneys has been documented at many sites, Kingston (1995). For example, Haymon and Kastner (1981; *in* Kingston 1995) noted fossilized tubes of Pompeii worms which influence texture in white smoker chimneys. Segonzac *et al.* (1993; *in* Kingston 1995) discussed the influence of clusters of shrimps on exteriors of vent structures and proposed that their presence can modify structure morphology. Since the presence of

organisms can affect fluid flow processes, and can modify the chemical environment (Fig. 4) and thus affect mineral precipitation, there is clearly a need for integration of studies of biological, chemical and physical processes and for incorporation of biological processes into more quantitative models of transport and chemical reaction.

2.5 The Isotope ³He and other Gases

Clarke *et al.* (1969; cited by Lupton, 1995) were the first researchers to report the presence of excess ³He in the southwest Pacific ocean, at a location thousands of kilometers from the nearest active spreading ridge. Those scientists detected magmatic He incoming to the oceans from the interior of the Earth. It is known that natural rich sources of ³He exist only in the mantle below the Earth's crust (Truesdell, 1998) and therefore this isotope is indicative of magmatic sources. Physical conditions in reaction zones are near the critical point of seawater, where fluids become buoyant and rapidly rise to the surface through upflow zones. This water is enriched with He, H₂, CH₄, H₂S and CO₂. The first and the last gases are clearly from magmatic origin, while the other gases may come from various mixed sources, Kadko *et al.* (1995).

The isotope ³He is of primordial or juvenile origin; residing in the mantle, is enriched in MOR vent fluids through degassing from the mantle and crystallizing magmas. Its presence is the best evidence of input of magmatic volatiles into the deep sea. ³He is a conservative tracer and has been used to discover and track hydrothermal plumes and to confirm reaction of fluids with basaltic rocks. In MOR vent fluids the concentration of ³He can reach 0.06 cm³/kg which is a factor of 10⁴ greater than background seawater concentrations, Alt (1995). The ascending plumes contribute to the distribution of ³He in the global ocean.

Between August and November of 1986 an oceanographic investigation was done in the Wagner Depression of the Gulf of California, Grijalva (1986). This site is located between 31°00' N and 31°15' N and at longitudes between 113° 50' and 114° 10' (Fig. 7). The zone is situated in sedimentary deposits, with approximate dimensions of 10 km wide by 20 km long and 180 meters thick. Water samples collected during the cruise in the Wagner depression were enriched with ³He. This isotope, after being carried near the surface of mantle rocks, must be dissolved by infiltrating seawater and carried upwards in ascending heated seawater plumes. In spite of mixing with marine waters with different densities and the effects of strong tidal action (up to 10 m height), the values of ³He/⁴He found in the basin were significantly higher than the atmospheric value. This isotope ratio coming from submarine hydrothermal springs can be up to nine times greater than the same ratio in the terrestrial atmosphere, whose value is 1.4 10⁻⁶.

Grijalva (1986), estimated an average ³He/⁴He ratio 4.5 times higher than the same ratio in seawater at 150 m depth for the entire Gulf. The cruise accomplished studies of geomorphology, oceanography, geophysics, geology, geochemistry and sedimentology. Mounds of mud, discharging gases, hydrocarbons, bubbles of butane gas and hot water flowing from the seafloor to the sea surface were observed. At 180 m depth water temperatures were higher than 200°C. Water samples contained manganese, and sulfur, iron and nickel were found in the samples of sediments.

3. DEEP SEA LIFE AND GEOTHERMAL ENERGY

3.1 Chemosynthetic Organisms in a Sunless Desert

The discovery of the first geothermal vent communities in the deep sea off the coast of Ecuador in the winter of 1977 (02/15) astonished scientists around the world, Ballard (1992), Corliss and Ballard (1977). *Entire communities of bizarre creatures were observed in an aquatic sunless desert.* These deep-sea oases, which are fueled by the heat energy from within the planet, are the only communities on Earth whose immediate energy source is not direct sunlight. Vent bacteria, which are the first primary producers of food for the entire vent community, must have oxygen to reduce inorganic material to organic matter. Jannasch (1995), demonstrates that “*Incoming solar energy turns CO₂ and H₂O into two biogeochemically active compounds, the reductant CH₂O and the oxidant O₂, thereby starting endless possibilities of respiratory and other energy yielding dark reactions*”.

Hessler and Kaharl (1995) explained that the necessary oxygen, which is present in abundance throughout the ocean, “*is a waste product of photosynthesis, which uses sun=s energy. The pre-existent bacteria use sulfide and other reduced ions to convert CO₂ + H₂O and nitrate NO₃⁻ into essential organic substances. In the same way, green plants use sunlight as their energy source to make organics from the same inorganic materials during photosynthesis*”.

The process for the oxidizing bacteria, which use the chemical energy of the vent effluent, is *Chemosynthesis*. The importance of chemosynthesis at hydrothermal vents has enlarged the perception of biologists of how ecosystems might be supplied with energy. The inputs of Earth's heat provide the energy for communities of chemosynthetic organisms, unknown until the discovery of venting. Most of the vent biomass is at the vent openings, where the animals are so crowded together that often they totally hide the seafloor. “*The density of life there is so great that space, controlling population size*” (*ibid*).



Figure 5: A typical vent community of tubeworms.

It is because of nutrition that the vent community concentrates near the chemically altered sea-water outflowing from the seafloor. The boundary of the inner living zone is abrupt because of the steep temperature gradients of the environment. As the heated vent effluent rises, it entrains and mixes with the bottom water that is at the ambient deep-sea temperature of 2°C. The result is a local circulation pattern of cold water converging on the vent openings (Fig. 3). Only very near the vent opening does the water have sufficient sulfide or other reduced ions to support symbiosis with oxidizing bacteria. Vents are colonized by chemotrophic bacteria that derive energy from chemical reactions involving H₂S in the hydrothermal fluid,

Felbeck (1981); Le Pennec *et al.* (1983). Other bacteria appear to use as their energy source reduced metals from sulfide mineral surfaces, mainly pyrite, Hannington *et al.* (1995).

3.2 Chains of Life in Geothermal Vent Communities

The studies of seafloor hydrothermal systems activity began with the discovery of warm springs and new biological communities and copious populations of animals clustering around deep-sea hydrothermal vents at the Galapagos Spreading Center, Corliss and Ballard (1977). This opened a new window to the understanding of the origin of life on Earth. In 1997 an expedition took place at the 9N (9° 50'), 2600 m depth in front of the Mexican coast of the Pacific Ocean, Gallo & Rummel (1998). The members of the expedition witnessed the evolution of a biological community since the formation of a geothermal crack. After a year of the initial eruption, the crack was totally covered with life. The bacteria living in the cracks adapt to temperatures higher than the boiling point. The bacteria are not eliminated by the high temperature but by the molecular activity of the steam. Due to the high pressure in those places the water does not produce vapor and then bacteria can survive, growing and forming the first link of a food chain based on geothermal energy. The vent food chain appears to be short, although there are probably many hidden complexities, Hessler and Kaharl (1995). The bacteria are the primary producers. The primary consumers are the tubeworms and the suspension-feeders or serpulid worms (Fig. 5 and 6). The secondary consumers include crabs, fishes, shrimps and many other worms. The octopi are the last predators of this food chain. They feed from crabs and other creatures. The white crabs feed directly from those bacteria as their own breed. Some of the worms, for example the Pompeii worm or *Alvinella*, and a white tubeworm (*polychaete albinelo*) can live in tubes built directly on vent chimneys at recorded temperatures between 80°C and 110°C. Both worms have the biggest tolerance to high temperature of all animals in this planet. The worms of Jericó adhere directly to the geothermal cracks.



Figure 6: A primary consumer or tubeworm.

Due to the lack of solar light, many of those organisms are blind, although surprisingly, some have eyes that don't see (Ballard, 1992; Gallo, 1998). Most of the organisms living in the geothermal cracks depend on H₂S to subsist. The

tubeworms live in the H_2S producing their own food by carrying bacteria inside their body in a sort of bag. The bacteria process the H_2S providing energy to the worm. The giant clams have also a symbiotic relationship with these bacteria. Hundreds of photographs taken by Corliss and Ballard (1977) and by Mercado (1990) show that, close to a vent, the joints and fissures in the seafloor are encrusted by bright yellow and white accumulations of chemical precipitates. Within 15-20 meters of the fissure there are communities of large and abundant benthic organisms. The plumes of warm water produce conditions in adjacent water rich in suspended materials and nourishment for large suspension-feeding bivalves. In the Hanging Gardens and at the East Pacific Rise, photographs show large sea-anemones and sea-pens. There are local pockets of sediment burrowed and tracked by deposit-feeding animals, Felbeck (1981); Le Pennec *et al.* (1983), Ballard, (1992). More than 300 new species of organisms living near the hydrothermal cracks have been identified by several biologists, and the list grows with the discovery of every new vent.

3.3 Primitive Life and Biogenesis in the Deep Sea

Organic material in the deep seas cannot be made through photosynthesis from solar energy. It is now clear that energy and material derived from geothermal sources is the basis of rich food chains at many places along the MORs. Besides the eruption of lava at these places, sea water enters fissures, becomes hot and is chemically changed by interaction with the rock. This heated seawater is ejected upward through chimneys and hydrothermal vents. It contains hydrogen sulfide derived from the reduction of oceanic sulfate. Chemosynthetic bacteria that use hydrogen sulfide as a metabolic source of energy are thus able to flourish, forming food for suspension feeding invertebrates such as clams, mussels and polychaete worms, Marshall (1979). These prolific places can be regarded as “*oases in a cold sunless desert*”. Recent experimental research clearly points out that *one possible location for the synthesis of chemicals needed for the origin of life is submarine hydrothermal systems*, where sea water circulates through and reacts with the oceanic crust. This hypothesis is supported by various researchers, Humphris *et al.* (1995), Gallo & Rummel (1998), Imai (1999).

These results are coherent with the very well-known situation of the aggressiveness and original toxicity of the primitive atmosphere on Earth, very different from the one we know today and that was incompatible with life. This way compared, the general conditions of the oceans were much more favorable to allow the emergence of the biological phenomena. The organisms that lived in the primitive Earth didn't need the solar light because they were protected and covered by thousands of meters of water above them. The changes in the terrestrial surface and in the atmosphere had little effect in the life of the deep sea. Impacts of meteorites such as that one that made the dinosaurs to disappear, were not perceived in the oceanic bottom. Far from the cracks in the bottom of the oceanic crust life is hardly found. But near to the hydrothermal fissures there is an explosion of life, its growing speed is as high as in the tropical forests. In the hydrothermal cracks there are forms of life that are probably the most primitive of the planet and they still contain organisms that coexisted with the dinosaurs, Gallo & Rummel (1998). Fauna fossils have been found of -400 My old. This fact suggests that life could originate at these depths. These hydrothermal ecosystems could act as a refuge for life in moments of extremely high geological violence in the history of the

Earth. They acted as oases of life in hard times where outside of the oceans or very far from them, the conditions were really bad to survive. Biogenesis is creation of life. In the case of the hydrothermal cracks, it is creation of life from inside the planet, associated to volcanic activity. The unique conditions of very rich hot hydrothermal minerals, flowing together with oceanic cold water at very high pressure, provided the appropriate atmosphere to an inorganic compound to transform into organic. The discovery of chemosynthetic microbial activities in the permanently dark deep sea, based on terrestrial rather than solar energy, adds a new dimension to this general notion. Some fascinating works of creation of organic compounds have been carried out in places that resemble the conditions at the hydrothermal cracks. According to some chemists the high pressure and temperature of the geothermal water is able to produce organic compounds starting from the available inorganic substances. Is the Earth able to generate the necessary energy to create life by itself? A theory accepted by some biologists is that the primitive life evolved in a medium with high temperatures. It has not still been proven that life was originated in geothermal cracks, but the most accepted pattern of a biosphere in which life can prosper has been enlarged significantly by the discovery of this incredible phenomenon.

4. GEOTHERMAL POTENTIAL OF SUBMARINE SYSTEMS IN MEXICO

Submarine geothermal systems in Mexico are located between two extreme depths: shallow resources near the continental platform at 20-50 m depth and deep resources at more than 2000 m below sea level (Suárez, 1998). Both types of systems exist close to the Mexican coast of the Pacific Ocean. In particular, several submarine hydrothermal manifestations are found along both coasts of Baja California, especially in the Gulf of California (Fig. 7).

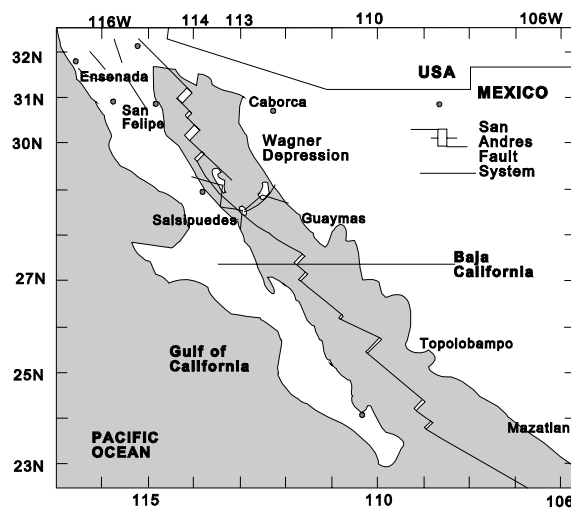


Figure 7: Gulf of California and Wagner Depression.

In these regions a considerable geothermal potential was discovered in past years that could be exploited in the near future (Grijalva, 1986; Mercado, 1990). In the Wagner Depression, submarine hydrothermal reservoirs are located at less than 30 m depth. Other accessible submarine thermal areas are located offshore from Punta Banda, close to the port of Ensenada, Baja California, where temperatures up to 140°C have been measured at 30 m depth and less than 0.5 km from the coast. Both geothermal zones are accessible to exploitation by installing offshore platforms, similar to those used by the oil industry in the Gulf of Mexico. The

construction of a dual injection-extraction system would be very simple and relatively cheap.

4.1 The Wagner Depression

The geothermal reservoirs of the Gulf of California were formed by divergent movements between the Pacific and North American plates where the East Pacific Rise is divided into segments (Fig. 7). The divergent relative tectonic movement of the plates causes breaks in the oceanic crust called *pull-apart* basins, transporting deep magma upwards. The temperature of this magma is about 1000°C. The geothermal potential of these heat sources are estimated roughly to be hundreds of times larger than the energy contained in the Cerro Prieto reservoirs, Grijalva (1986), Mercado (1990), Suárez (1998). Other studies indicated that the Wagner basin could be a geothermal field of great magnitude. In contrast with the profound fissures in the south of the Gulf, whose immense resources are inaccessible, the basin presents reachable resources, whose exploitation is possible with the existent technology. From unpublished data Grijalva estimated that the geothermal potential of this submarine zone could be 100 to 500 times larger than the thermal energy contained in Cerro Prieto. Mercado (1990) estimated for the Gulf of California a geothermal potential of about 97,000 MW_T for 30 years, assuming reservoir dimensions of 5 km wide by 1600 km longitude and 0.6 km thickness, at an average temperature of 330°C.

4.2 Geothermics In Punta Banda, Baja California

In Punta Banda, Ensenada, Baja California (Fig. 7), at 400 m from the coast and 20-30 m depth, submarine thermal manifestations are observed at several places. These manifestations are formed by discharges of hot water escaping through fissures associated with the Agua Blanca fault, a major transverse structure in northern Baja California of about 130 km length. The average discharge of water was estimated to be 100 lt/min, in the intertidal hot springs, Bustos-Serrano (1983). In some places a recorded temperature of 102°C at 4 bar was obtained, Vidal *et al.* (1978). In other areas, temperatures of discharges are between 90°C and 140°C; the last value could be possibly the shallow temperature of the submarine reservoir, Lira (1999) and Bustos-Serrano (1983). Parallel to the coast, at Todos Santos Bay, several vents have been observed with temperatures between 30°C and 98°C, Bustos (1983). The Punta Banda hydrothermal vents are very similar to those existing in tectonically active oceanic spreading centers at greater depths (Vidal *et al.*, 1981) and described in previous sections. At this place total hot water discharge of 3.3×10^5 m³ per year at 102°C and convective heat flow of 4190 W_T/m² was estimated by Vidal *et al.* (1978).

4.3 A Coarse Estimation of the Geothermal Energy Resources of Mexico

Non-traditional geothermal energy resources in Mexico include the deep portions and boundaries of traditional hydrothermal reservoirs, systems in hot dry or wet rock, geopressed reservoirs in the Gulf of Mexico and hydrothermal submarine systems located mainly close to the Mexican coast of the Pacific Ocean. Table (1) summarizes the total geothermal potential estimated for this country by Suárez (1998). The present installed capacity for classic geothermics, corresponds to an updated report of CFE by Gutiérrez and Quijano (2004). The potential of submarine systems correspond to the estimations of Grijalva (1986) and Mercado (1990).

Table 1.- Potential Energy of Different Geothermal Type Systems in Mexico

Type of Resource	T1	T2	T3	T4	T5
Installed Capacity	953	0	0	0	0
Estimated Potential	2000	2000	5×10^5	8000	4×10^4

Notes: T1 = Classic (MWe), T2 = Deep traditional (MWe), T3= Submarine Systems (MW_T), T4 = Hot Dry/Wet Rock (MW_T), T5= Geopressed Reservoirs (MW_T).

Even with the scarce available information, it is possible to make a preliminary estimation of the submarine energy potential of Mexico. We used a simple mathematical model for submarine reservoirs developed by Suárez (2000). In all cases we considered a density average of volcanic rock of 2500 kg/m³, a porosity of 10% and a specific heat C_R of 1000 J/kg°C, and a fixed rock volume of one cubic kilometer (1.0×10^9 m³). This operation is necessary because the volume of porous hot rock is the main unknown in this type of systems. We have in the following equations the traditional parameters: ϕ is porosity, ρ is density, S is saturation, e and h are specific energy and enthalpy, subscripts α and R hold for liquid or vapor and rock respectively, T is temperature in °C and V is the rock volume in m³.

For the fluid Energy Density:

$$E_{fluid} = \frac{\text{Internal energy}}{\text{fluid volume}} = \sum_{\alpha} \phi S_{\alpha} \rho_{\alpha} e_{\alpha} \left(\frac{kJ}{m^3} \right) \quad (3)$$

Where α = liquid, vapor. For the Rock Energy Density:

$$E_{rock} = \frac{\text{rock energy}}{\text{solid volume}} = (1 - \phi) \rho_R C_R T_R \left(\frac{kJ}{m^3} \right) \quad (4)$$

Thus the Total Energy in the Reservoir is:

$$E_0 = (E_{fluid} + E_{rock}) \cdot V_{rock} \quad (kJ) \quad (5)$$

The final energy corresponds to the Thermodynamic State calculated with the abandonment pressure of 5 bar in Punta Banda. The algebraic differences between both states are considered equal to the available energy, and is given by the following formulas.

For the Rock:

$$\Delta E_{rock} \int_{initial}^{final} \approx (1 - \phi) \rho_R C_R (T_{initial} - T_{final}) \quad (6)$$

For the Fluid:

$$\Delta E_{fluid} \int_{initial}^{final} \approx (\phi \rho_F h_F) \int_{liquid}^{initial} - (\phi \rho_F h_F) \int_{2-phase}^{final} \quad (7)$$

The Total Energy available in the Reservoir is:

$$\Delta E_{Total} = \Delta E_{rock} + \Delta E_{fluid} \quad (8)$$

The transformation coefficient for the available energy (Suárez, 2000) that can be used directly in the form of heat (MW_T) is given by:

$$C_E = \frac{1.0 \times 10^{-6}}{31,557,600 t_A} \quad (9)$$

Where t_A is the payoff time of the investment realized for the project. If we need to calculate the recoverable electric power from the reservoir (Suárez, 2000), then it is necessary to multiply the available energy given by equation (8), by the coefficient C_E given by equation (9) and by the coefficient f_E of recoverable electric energy:

$$G_E = f_E \cdot C_E \Delta E_{Total} \quad (MW_e) \quad (10)$$

These calculations are restricted to the submarine areas close to the coast of the Pacific Ocean and to the region defined by the following coordinates: latitudes between 32°N and 23°N; longitudes between the 117°W and 106°W (Fig. 7). The last column of Table 2 is the Thermal Potential per km³ of oceanic rock in the vicinity of the hydrothermal vents. With the available data, we obtained the figures in Table 2. The thermodynamic properties of Punta Banda were estimated with a linear model (z is the depth sea in meters):

For the pressure:

$$p(z) = 1.0 + 0.1 z \quad (bar) \quad (11)$$

For the temperature:

$$T(z) = 97.082 + 0.246 z \quad (^\circ C) \quad (12)$$

Considering that only 1% of the thermal submarine energy could be transformed into electricity ($f_E = 0.01$), during $t_A = 30$ years, and using the data of the references of Mercado (1993), Grijalva (1986) and Bustos (1983), the minimum capacity in MW_e of the Mexican submarine resources just described is about 26,100 MW_e .

5. CONCLUSIONS

Deep geothermal energy has essentially an infinite potential. Hydrothermal reservoirs along the rifts between tectonic plates forming the oceanic crust are notable examples. Volcanic and tectonic processes control hydrothermal activity at mid-ocean ridge spreading centers, influencing all aspects of Oceanography. It includes both, general ocean circulation and the chemistry of the oceans and atmosphere. The key idea is that high temperature hydrothermal venting can force horizontal circulation on a variety of spatial and temporal scales. On those scales the rotation of the Earth becomes an important factor.

The hydrothermal fluid differs significantly in composition from seawater, because of its continuous interaction with the oceanic crust. The seawater-rock reactions in the recharge and discharge zones determine the nature of the oceanic lithosphere and the chemistry of hydrothermal fluids flowing out the seafloor. Seawater experiences progressive reaction as it penetrates the crust and is heated. The heat removed from the crust raises the temperature of the deep sea and gives rise to the precipitation of mineral deposits on the seafloor building chimneys. These natural chimneys discharge spouts of water at 350°C at 2600 m depth in the Gulf of California and in many other places. There are different styles of mineralization found at sites of hydrothermal venting.

Spreading centers throughout the oceans are confirmed by the presence of hydrothermal plumes and mega plumes. There may be a direct relationship between the incidence of plumes and the spreading rate activity. Stable isotope geochemistry has been applied to studies of mid-ocean ridge hydrothermal systems. The fractionation of stable isotopes between co-existing phases provides a powerful tool for understanding interactions among chemical, physical and biological processes. The high temperature hydrothermal vents provide unique deep seawater biological communities of organisms associated with seafloor hydrothermal activity. At hydrothermal vents, the food source is rich and life is abundant.

That hot water, enriched with H_2S , is expelled through openings, cracks and hydrothermal vents. These plumes generate conditions in adjacent water to produce suspended materials as source of nourishment for different living organisms. Chemosynthetic bacteria use hydrogen sulfide as a source of metabolic energy from the heated sea water, forming food for suspension feeding invertebrates such as clams, mussels, crabs and tubeworms. Within 20 m of fissures and chimneys large communities of strange plants and animals exist, forming some kind of sunless deep sea oases, supporting abundant populations of organisms living at temperatures near 17°C. The global distribution of hydrothermal activity has associated biological processes that need to be included into the models of physical and chemical interactions at these sites. Deep marine water circulating through and reacting with oceanic rocks could have produced the first chemicals needed for life to emerge.

In the Gulf of California and in the Mexican coast of the Pacific Ocean, a considerable geothermal potential exists. The basin of the Wagner Depression is in shallow waters and conventional methods could be used for the extraction of its geothermal energy. This resource is probably part of a gigantic hydrothermal system embracing the Gulf itself, Cerro Prieto and the California geothermal fields, all related to the San Andrés Fault. The system is the superficial manifestation of lateral motions in process, causing the separation of Baja California from the Mexican continental portion.

The energy of the interior of the Earth is a planetary resource, virtually infinite and equitable distributed worldwide, more equally than any other source of energy. Due in fact to its nature, geothermal energy is inextricably bound to the origin, evolution and destiny of this planet. Geothermal energy will finish the day in which the Earth arrive to its end. As source of primary energy, this resource is an immense hope for the future.

6. REFERENCES

- Alt, J. Subseafloor Processes in Mid - Ocean Ridge Hydrothermal Systems. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 85-114.
- Baker, E., German, C. and Elderfield, H. Hydrothermal Plumes over Spreading-Center Axes: Global Distributions and Geological Inferences. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 47-71.
- Bustos-Serrano, H. Caracterización Física, Química y Morfológica de la Zona Hidrotermal Marina de La Jolla, Punta Banda, B.C., México. *Thesis of Oceanology*, pp. 114. Esc. Sup. de Ciencias Marinas, Universidad Autónoma de Baja California (1983).

- Ballard, R. D. Oases of Life in the Cold Abyss. *Presentation* at the IX National Congress of Oceanography, (1992), Veracruz, México.
- Bemis, K., Von Herzen, R. and Mottl, M. Geothermal Heat Flux from Hydrothermal Plumes on the Juan de Fuca Ridge. *Journal of Geophysical Research*, **98**, (1993), 6351-6365.
- Corliss, J.B. and Ballard, R.D. Oases of Life in the Cold Abyss. *National Geographic Magazine*, 152, No. 2, (1977), 441-453.
- Damm, K. Controls on the Chemistry and Temporal Variability of Seafloor Hydrothermal Fluids. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 222-247.
- Felbeck, H. Chemoautotrophic Potential of the Hydrothermal Vent Tube Worm. *Riftia pachyptila* Jones (Vestimentifera). *Science*, **213** (1981), 336-338.
- Fornari, D. and Embley, R. Tectonic and Volcanic Controls on Hydrothermal Processes at the Mid-Ocean Ridge: An Overview Based on Near-Bottom and Submersible Studies. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 1- 46.
- Gallo, D. - Oral communication, Special Projects WHOI, (1998).
- Gallagher, R. and Appenzeller, T. Beyond Reductionism, *SCIENCE*-American Association for the Advancement of Science, **284**, No. 5411, (1999).
- García, G. H. Modelo del Estado Térmico Inicial del Campo Geotérmico de Los Azufres, Michoacán, México. *Tesis de Doctorado*, Instituto de Geofísica, UNAM, (2000), pp.184. México, D.F.
- Grijalva, N. *Investigación de la Energía Geotérmica en la Depresión de Wagner en el Golfo de California. Latitud 31° 00' al 31° 15' y Longitud 113° 50' al 114° 10'*. Unpublished reports prepared for the Comisión Federal de Electricidad, Cerro Prieto, B.C. Date of 1st Report: 10/1/86, 22 pp. Date of 2nd Report: 11/22/86, 38 pp. Under Contract No. CCP-CLS-002/86, (1986), Mexico.
- Gutiérrez, N.L. and Quijano, J.L. Update of Geothermics in Mexico. *GEOTERMIA, Revista Mexicana de Geoenergía*, **16**, No. 1, (2004), 22-31.
- Hannington, M., Jonasson, I., Herzig, P. and Petersen, S. Physical and Chemical Processes of Seafloor Mineralization at Mid-Ocean Ridges. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 115-157.
- Hessler, R. and Kaharl, V. The Deep-Sea Hydrothermal Vent Community: An Overview. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 72-84.
- Humphris, S.E., Zierenberg, R.A., Mullineaux, L. S. and Thomson, R.E., Editors. Seafloor Hydrothermal Systems. Physical, Chemical, Biological and Geological Interactions. *Geophysical Monograph* **91**, American Geophysical Union, ISBN 0-87590-048-8, (1995), 466 pp.
- Imai, Cited in *Science*, **283**, No. 5403, issue of 5 Feb. (1999), p. 831, AAAS.
- Jannasch, H. Microbial Interactions with Hydrothermal Fluids. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 273-296.
- Kadko, D., Baross, J. and Alt, J. The Magnitude and Global Implications of Hydrothermal Flux. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 446-466.
- Kingston, M. Modeling Chimney Growth and Associated Fluid Flow at Seafloor Hydrothermal Vent Sites. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 158-177.
- Le Pennec, M., Lucas, A. and Petit, H. Etudes Preliminaires sur un Mytilidae des sources Hydrothermales du Pacifique. *Haliotis* **13**, (1983), 69-82.
- Lira, H., Personal Communication, CFE, (1999).
- Lupton, J. Hydrothermal Plumes: Near and Far Field. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 317-346.
- Marshall, N.B. Hydrothermal Oases: Developments in Deep-Sea Biology. Blandford Press, London, (1979), 284-307.
- Mercado, S. Manifestaciones Hidrotermales Marinas de Alta Temperatura (350 °C) Localizadas a 21°N, a 2600 m de Profundidad en la Elevación Este del Pacífico. *GEOTERMIA, Revista Mexicana de Geoenergía*, **6**, No. 3, (1990), 225-263.
- Mercado, S. Geotermoquímica de Manifestaciones Hidrotermales Marinas de Alta Temperatura, *Revista Mexicana de Geoenergía*, **9**, No. 2, (1993), 155-164.
- Rummel, John D. Oral communication, (program in the Discovery Channel). Planetary Protection Officer – Nasa (1998).
- Seyfried, W. and Ding, K. Phase Equilibria in Subseafloor Hydrothermal Systems: A Review of the Role of Redox, Temperature, pH and Dissolved Cl on the Chemistry of Hot Spring Fluids at Mid-Ocean Ridges. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 248-272.
- Spiess, F.N., K.C. MacDonald, T. Atwater, R. Ballard, A. Carranza, D. Cordoba, C. Cox, V.M. Díaz García, J. Francheteau, J. Guerrero, J. Hawkins, R. Haymon, R. Hessler, T. Juteau, M. Kastner, R. Larson, B. Luyendyk, J.D. MacDougall, S. Miller, W. Normark, J. Orcutt and C. Rangin. East Pacific Rise: Hot springs and Geophysical experiments. *Science* **207**, (1980), 1421-1433.
- Stein, C., Stein, S. and Pelayo, A. Heat Flow and Hydrothermal Circulation. *Geophysical Monograph* **91**, American Geophysical Union, (1995), 425-445.
- Suárez, M.C. Deep Geothermal Systems in Mexico: An Integral Diversified Resource for the Energy of the Future. *Geothermal Resources Council*, Transactions, **22**, (1998), 327-331.
- Suárez, M. C. Modelo Volumétrico para la Evaluación de Reservorios Geotérmicos con Información Incipiente. Informe Técnico No. DEX-013/2000, Dpto. de Exploración – CFE, (2000), México.
- Truesdell, A. - Oral communication, (1998).
- Turner, J. S. Buoyancy Effects in Fluids, Cambridge University Press, 368 pp. (1973).
- Vidal, V. M., Vidal, V. F., Isaacs, J. D. and Young, D. R. Coastal Submarine Hydrothermal Activity off

Northern Baja California 1. *Journal of Geophysical Research*, **83**, No. B4, (1978), 1757-1774.

Geochemistry. *Journal of Geophysical Research*, **86**, No. B10, (1981), 9451-9468.

Vidal, V. M., Vidal, F. V. and Isaacs, J. D. Coastal Submarine Hydrothermal Activity off Northern Baja California 2. Evolutionary History and Isotope

Table 2. - Estimated Geothermal Submarine Potential In Mexico

Hydrothermal Zone	Pressure (bar)	Temperature (°C)	Energy Density (MJ/m ³)	Available Energy (1× 10 ¹⁵ J)	Geothermal Potential (MW _T /km ³)
Punta Banda	51	220	574	232	245
Wagner	55	260	674	332	350
Gulf of California	220	360	906	500	528
TOTAL	-	-	-	1064	1123

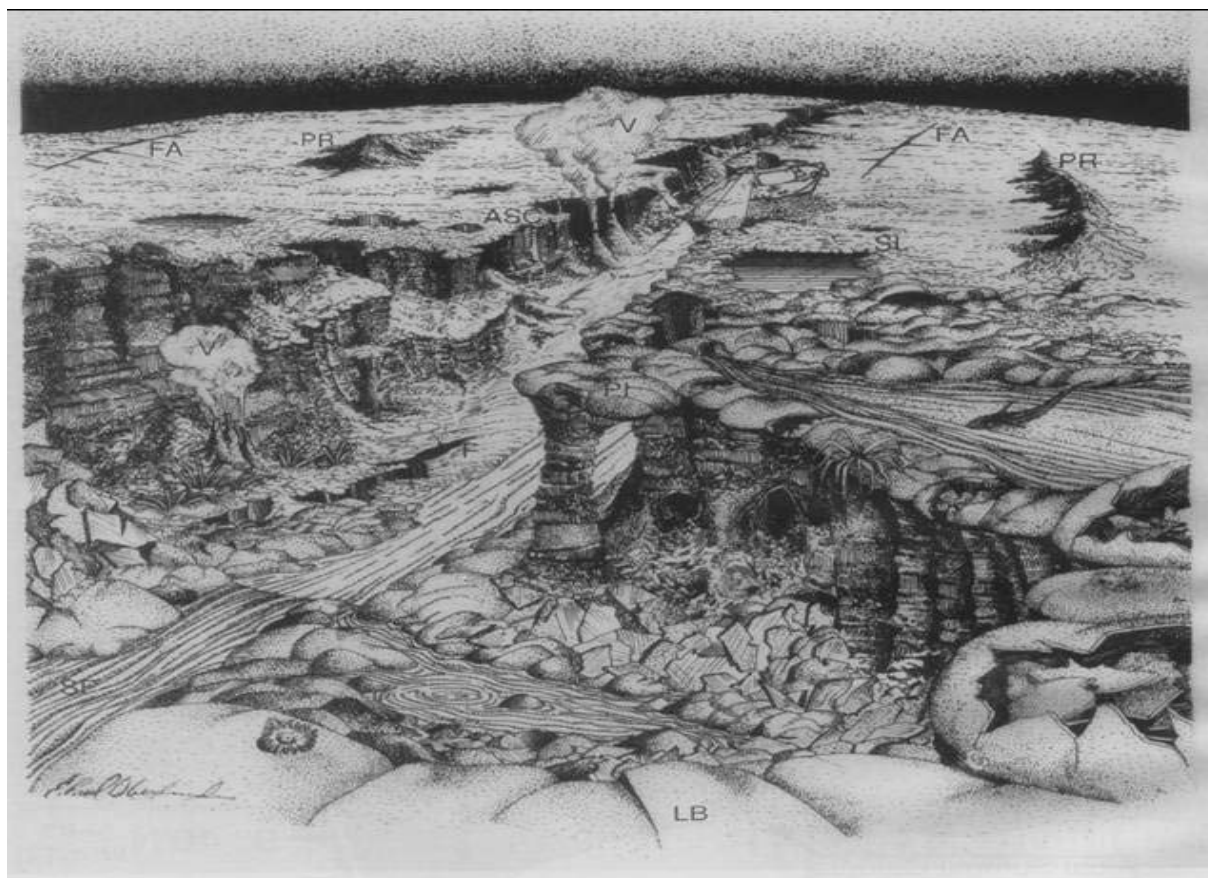


Figure 8: A drawing of a Submarine Hydrothermal Vent. Artist: P. Oberlander, Woods Hole Oceanographic Institution.
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