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A PRELIMINARY EVALUATION OF THE CONVECTIVE ENERGY ESCAPING FROM SUBMARINE HYDROTHERMAL CHIMNEYS

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ABSTRACT

Hydrothermal submarine reservoirs contain an infinite energy potential. This 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 Earth's oceanic crust and are located at more than 2000 m below sea level. Shallow submarine geothermal heat is related to faults and fractures in the sea bottom close to some coasts. Shallow resources are found near to continental platforms between 1 and 50 m depth. Both types of resources exist, for example, in the Gulf of Calfornia, Mexico. The specific chemical characteristics of the submarine hydrothermal waters indicate that water-oceanic rock interactions occur at high temperature-pressure conditions. In this paper we present a description and preliminary estimation of the amount of geothermal energy contained in some submarine systems that is escaping through fissures in the oceanic floor. Hydrothermal fluid at 350- 400°C exits the seafloor at velocities of about 70 to 236 cm/s and mixes with seawater at 2°C. Thermal fluxes measured at some chimneys range from 1 to 93 MW_T, with an average value for a single orifice of about 8 MW_T. Some heat fluxes of about 1000 MW_T have been estimated.

INTRODUCTION

Hydrothermal circulation at the deep ridges of the sea 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 atmosphere. The properties and behavior of such 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.

Submarine hydrothermal interactions influence the composition of the oceanic crust and the oceans' chemistry. The fluid circulating in seafloor hydrothermal systems is chemically altered due to processes occurrig during its passage through the oceanic crust at elevated temperatures and pressures. This mechanism produces hydrothermal vent fields which support diverse 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 far beyond the oceans themselves. The understanding of this mass and energy flows among those complex geological, chemical, geophysical and biological subsystems requires the development of integrated models that include the interactions between them. There are two kinds of submarine hydrothermal 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 between 1 m and 50 meters depth. This condensed work has two purposes: to trace the outline of the fundamental characteristics of submarine hydrothermal chimneys and to present a preliminary evaluation of the convective energy escaping from them.

SUBMARINE GEOTHERMAL DISCHARGES, CHIMNEYS AND PLUMES

Geothermal Discharges, Plumes and Venting

Hot springs and geysers are vents and plumes located on the continental land. Most of the known vents in the ocean are at the mid-ocean ridge systems (MORS) in the deep sea (Damm 1995). 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 interaction at temperatures between 200°C and 400°C, (Grijalva, 1986; Mercado, 1990; Damm 1995). 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 areas between 4 m^2 to 800 m^2 , (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. Analysis performed by Mercado (1993) in the Gulf of California, described processes involving water-rock interaction and mixing with magmatic fluids that cause variations of salts dissolved in seawater. Lead, manganese and iron dissolved in the hydrothermal fluid, have higher concentrations than the same elements found in normal seawater by factors of about 8000, 50,000 and 59,000 times respectively. Seyfried and Ding (1995) reported results of mineral solubility experiments and theoretical phase relations for the $CaO-Na_2O-Al_2O_3-SiO_2-FeO-Fe_2O_3-CuO-H_2S-H_2O-HCl$ 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*", (*ibid*.).

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).

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 created by the thermal and chemical fluid input from submarine hot spring systems into the deep sea (Figures 1 and 2). The rising plumes entrain deeper and saltier water, carrying it up in the water column affecting the thermoaline circulation of the oceans (Damm, 1995).

Figure. 1. The bird of a plume at the top of a submarine chimney located 3000 m depth in the Pacific Ocean (BBC, 2004).

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.

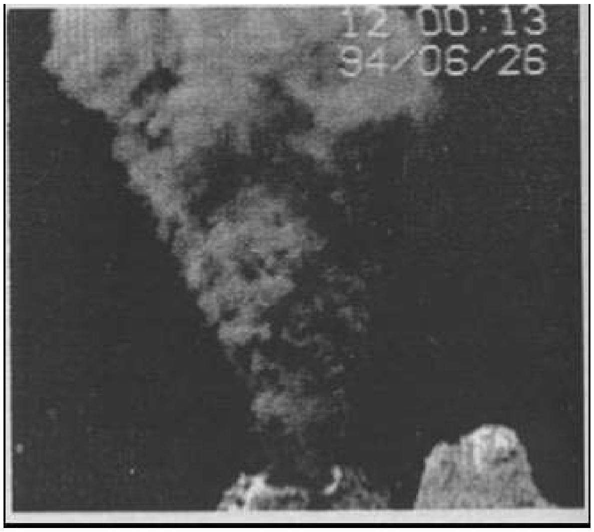
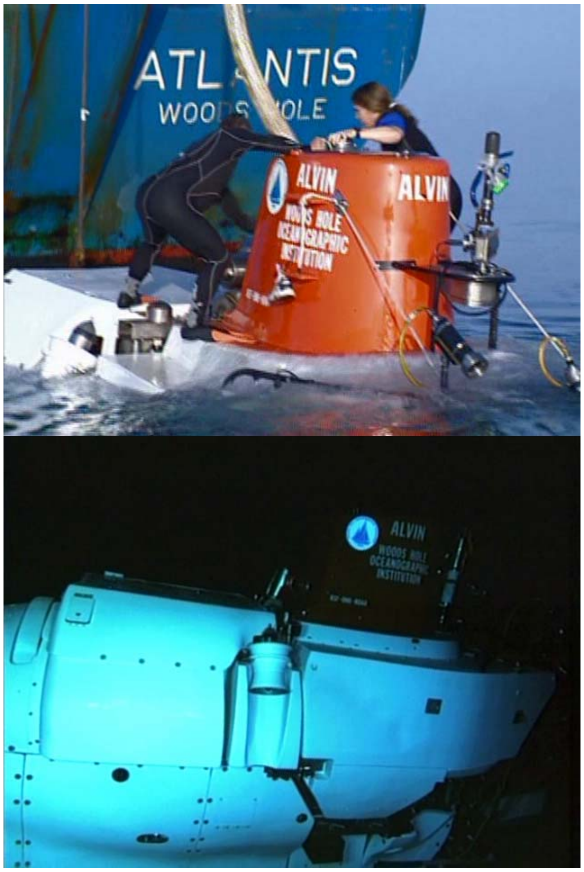


Figure 2. Plume with vortices emerging from a black smoker at 342°C. (Lupton, 1995).

In 1986 a Mega-plume was discovered in the region of the Juan de Fuca ridge in the Pacific Ocean (JFR) having an extension of about 20 Km, 600 m thick and included 10^{11} MJ of excess heat. Bemis, *et al.* (1993) achieved an experiment using the submersible Alvin from the Woods Hole Oceanographic Institution (Figs. 3a, b) to collect data while the vessel was stationed at different locations close to a vent source on the JFR. 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 buoyant plumes ascent in a stably stratified seawater is shown in figures 4, 7, 8 and 9.



Figures 3a, 3b. The special submarine Alvin, made of titanium and able to submerge 5000 m depth into the sea (BBC, 2004).

Black and White 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. The recharge areas where seawater enters the crust are diffuse and widespread (Alt, 1995). At seafloor hydrothermal vent sites, hot, acidic hydrothermal fluids are injected into cold, alkaline seawater, resulting in precipitation of vent deposits and particle-rich plumes (Mercado, 1990; 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 (Figs. 1, 2 and 4). Black smoker chimney walls are initially emplaced as hydrothermal fluid mixes turbulently with seawater (Fig. 4). 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*).

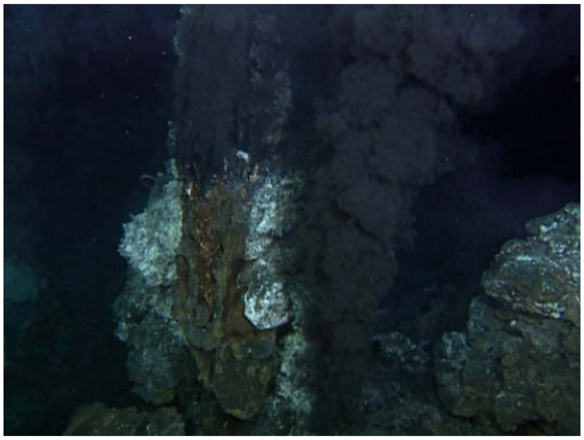


Figure 4. Submarine hydrothermal discharges forming a chimney (BBC, 2004).

In the 1980s 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. 5), covering an area of 50 km radius.

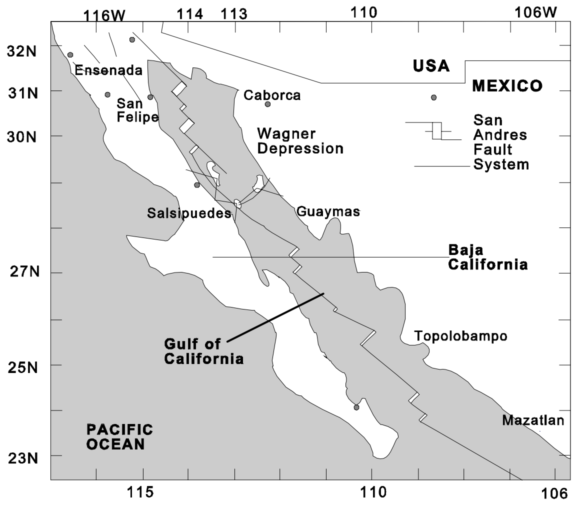


Figure 5. The Gulf of California or Sea of Cortes.

During the dives with the Alvin, diverse hydrothermal manifestations were observed. The so called "*Hanging Gardens*" were discovered 2600 m depth (Fig. 6). Similar impressive natural chimneys up to 6 meters high, approximately at the same depth, were also observed (Figs. 7 and 8). Those almost metallic natural chimneys are formed in part by iron and copper sulfides, (Mercado, 1990 & 1993) and discharge spouts of water at 350°C. 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 6. A strange "flower" or tube-worm opening in a submarine garden, (BBC, 2004).

Figure. 7. Two natural chimneys in the Pacific Ocean, discharging fluids at temperatures of about 350°C (BBC, 2004).

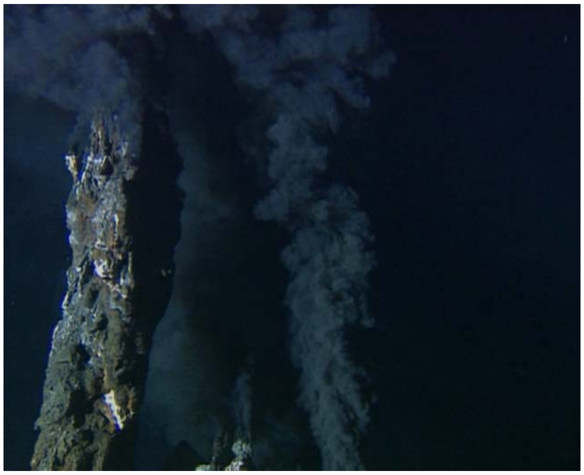


Figure 8. Another perspective of a double chimney system in the Pacific Ocean (BBC, 2004).

Figure 9. Illustration of the upper portion of a black smoker chimney (BBC, 2004).

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 (Fig. 10).

Figure 10. Illustration of the first step in the formation of a chimney (BBC, 2004).

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 (Kingston, 1995). Also, in the Mid-Atlantic Ridge, small white smoker chimneys with measured temperature between 250°C and 300°C have been observed (Fig. 11).

All the images in figures 7, 8, 9 and 11 show only some meters of plume ascent because the optical depth of seawater is very limited. They correspond to portions of plumes from black smokers 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 (Lupton, 1995):

$$N^2 = -\frac{g}{\rho_0}\frac{d\rho}{dz} = 1.5\times10^{-6}\ s^{-2} \qquad (1)$$

Where g is the gravity acceleration, ρ_0 is the average local density and $d\rho/dz$ is the vertical density gradient, → $d\rho/dz \approx 1.53\times10^{-4}$ kg/m^4. 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:

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

From measured data reported by Lupton (1995), we obtain F_0 = 0.17 m^4 s^{-3}; using the frequency N, it is possible to estimate a maximum height for the plume: $Z_M \approx$ 370 m above seafloor. After these models, a plume of 750 m height will correspond to a heat flux of about 1000 MW_T.

Figure 11. A white smoker chimney, 1 m high, at 3660 m, 26°8'N in the Mid-Atlantic Ridge. Humphris et al., *1995. (Reprinted with permission of the American Geophysical Union – WHOI).*

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). The weak dependence of Z_M on the effective heat flux indicates that the mega plume observed in the region of the Juan de Fuca ridge in 1986, was able to affect the water column up to 1000 m above the seafloor. Such megaplume could be the impressive result of an instantaneous and huge release of heat flux at the corresponding source. The fact that other megaplumes 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 W_T/m^2 (García, 2000). The submarine heat flow measured in some places of the Gulf of California was of the order of 0.34 W_T/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 W_T/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.

EXPLORA1: A SIMPLE MATHEMATICAL MODEL TO EVALUATE THE GEOTHERMAL POTENTIAL OF CHIMNEYS’ DISCHARGES

With the available information extracted from different sources, it is possible to make a preliminary estimation of the global convective energy escaping from submarine hydrothermal chimneys and its geothermal potential. We used a simple mathematical model for submarine reservoirs developed by Suárez (2000). For the application of the model we considered, in all cases, a density average of volcanic rock of 2500 kg/m^3, a porosity of 10% , a specific heat C_R of 1000 J/kg/°C and a fixed rock volume of one cubic kilometer (1.0×10^9 m^3). 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, subscritps α (L, V) and R hold for liquid or vapor and rock respectively, T is temperature in °C and V is the rock volume in m^3 . We have for the fluid Energy Density:

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

For the Rock Energy Density:

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

The Total initial Energy in the submarine reservoir is:

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

The final energy corresponds to the Thermodynamic State calculated for an abandonment pressure of 5 bar and other data collected in the zone of Punta Banda, close to the port of Ensenada in Baja California, Mexico (Fig. 5). The algebraic differences between both states are considered equal to the available energy and is given by the following formulas.

For the Rock:

$$\Delta E_{rock} \Big]_{initial}^{final} \approx (1-\varphi)\, \rho_R\, C_R\, (T_{initial} - T_{final}) \tag{6}$$

For the Fluid:

$$\Delta E_{fluid} \Big]_{initial}^{final} \approx (\varphi\, \rho_F\, h_F) \Big]_{liquid}^{initial} - (\varphi\, \rho_F\, h_F) \Big]_{2-phase}^{final} \tag{7}$$

The Total Energy available in the submarine reservoir is:

$$\Delta E_{Total} = \Delta E_{rock} + \Delta E_{fluid} \tag{8}$$

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

$$C_E = \frac{1.0\times10^{-6}}{31{,}557{,}600\, t_A} \tag{9}$$

Where t_A is the payoff time of the investment realized for the hypothetical submarine project. To calculate the recoverable electric power from the reservoir 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:

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

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 117°W and 106°W (Figure 5). With the available data the following values shown in Table 1 were obtained.

Table 1.- Potential Energy of Two Submarine Geothermal Systems in Baja California, Mexico.

Zone	**P** (bar)	**T** (°C)	**Energy Density** MJ/m^3	**Available Energy** (10^{15} J)	**Geothermal Potential** (MW$_T$/km^3)
Punta Banda	**51**	**220**	**574**	**232**	**245**
Gulf of California	**220**	**360**	**906**	**832**	**880**

The thermodynamic properties of Punta Banda were estimated with a linear model (z is the sea depth in meters). For the pressure:

$$p(z) = 1.0 + 0.1\, z \ \ (bar) \tag{11}$$

For the temperature:

$$T(z) = 97.082 + 0.246\, z \ \ (°C) \tag{12}$$

The last column of Table 1 is the geothermal potential per km^3 of oceanic rock in the vicinity of the hydrothermal vents. 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 different references available (Suárez, 2004), the minimum electric capacity of these mexican submarine resources is about 26,100 MW$_e$.

CONCLUSIONS

- Deep submarine geothermal resources contain practically an infinite energy potential. 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 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 Earth′s oceanic crust and are located at more than 2000 m below sea level. Shallow submarine geothermal heat is related to faults and fractures in the sea bottom close to some coasts. Shallow resources are found near to continental platforms between 1 and 50 m depth.

- Spreading centers activity occurring throughout the oceans is confirmed by the presence of chemical traces from hydrothermal plumes and mega plumes. There may be a direct relationship between the size and type 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.

- This 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 temperatures of about 350°C at 2600-3000 m depth in many places located in both main oceans.

- Using available data from different sources, we performed a preliminary estimation of the amount of convective geothermal energy contained in submarine systems escaping through fissures in the oceanic floor: Hydrothermal fluids at temperatures between 350°C and 400°C exits the chimneys on the seafloor at velocities of about 70 cm/s to 236 cm/s and mixes with deep seawater at 2°C. Thermal fluxes measured at some chimneys range from 1 to 93 MW_T, with an average value for a single orifice of about 8 MW_T. Using some practical formulas it is possible to estimate maximum heights for the plumes formed at the chimneys: 370 m above seafloor for heat fluxes of about 60 MW_T; a Mega-plume of 750-1000 m height will correspond to a heat flux of about 1000 MW_T.

- The observed megaplumes are the spectacular result of an instantaneous and huge release of heat flux at a focal submarine source. The total convective heat outflowing from the ocean is discharged in the form of both, continuous steady state venting and mega plumes. As a comparison, the average conductive heat flow in the Mexican Volcanic Belt is about 0.10 W_T/m^2. The same submarine heat flow measured in the Gulf of California is 0.34 W_T/m^2 at an average temperature of 330°C. Other researchers predicted an average hydrothermal heat loss for the oceanic crust of about 1.5 W_T/m^2. The same parameter predicted for the ridges is between 2 and 100 MW_T/Km (per unit ridge length). It is estimated that submarine hydrothermal discharges remove about 30% of the total heat lost from oceanic crust.

- The energy of the interior of the Earth is a planetary resource, virtually infinite and equitable distributed all around the world, more 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. As primary energy source, the geothermal submarine systems are an immense hope for the future.

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