

# **Chapter 3**

## **TERRESTRIAL RADIOACTIVITY AND GEOTHERMAL ENERGY**

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### **3.1 INTRODUCTION**

The status of the Earth under our feet as a radioactive heat engine is considered. It can be argued that biological life on Earth owes its existence to three nuclear phenomena: fusion reactions in supernovae or in colliding nuclear stars in the distant past that formed the rocky planets, radioactivity in the Earth's core at the present time, and fusion reactions in the sun generating solar radiation. The radioactivity in the Earth's core, its primordial energy content and to a lesser extent, the tidal force from the moon, are believed to keep its outer core molten.

Humans have been using geothermal energy sources for several millennia. Ancient tribes congregated near hot springs and geysers on the inhabited continents. The Romans built baths near thermal springs from Scotland to Turkey. Italy has been producing electricity from geothermal sources since 1904. Iceland is entirely electrified with its geothermal power after a 25 years dedicated national effort.

Geothermal energy in the Earth's crust accounts for about 9,300 megawatts of the world's electricity generation. Sixty million people in 24 countries are getting their power from the Earth's heat. In the USA, more than 2,800 megawatts of electricity from geothermal plants supplies 4 million people in Alaska, California, Hawaii, Nevada and Utah. Six percent of the state of California's power comes from geothermal sources.

Because of the existence of the Earth's magnetic field, a dynamo effect results in its outer core rotation. The core's rotation in the past has slowed down and changed direction quite frequently from a geological point of view. If the Earth's magnetic field would decay away like on the planet Mars, which has only localized magnetic fields, it would take several thousand years for the core to stop spinning. This magnetic field dynamo protects life on Earth from the solar wind. In addition, radioactivity in the Earth's interior is a source of volcanic activity, which is a potential source of energy in the form of geothermal energy.

Methane, the most abundant hydrocarbon in the Earth's crust is found in the great ocean rifts, igneous and metamorphic rocks, and around active volcanoes. These are improbable locations since known sedimentary hydrocarbon deposits of oil and natural gas were formed as the result of the decomposition of plants and animals. Non-biogenic hydrogen may have been generated in the Earth's mantle as suggested in the 1970s by the astronomer Thomas Gold since significant amounts of methane and hydrocarbons can be detected in the atmospheres of Jupiter, Saturn, Uranus, Neptune and on some moons such as on Titan, Saturn's largest moon. Research shows that methane bubbles could form when iron oxide, calcite and water are heated to 1,500 degrees C and at a pressure of 5.7 gigapascals and then decompressed at room temperature to 0.5 gigapascals.

In a science fiction movie: "The Core" reminiscent of Jules Verne's "Journey to the Center of the Earth," scientists and "terranauts" travel to the center of the Earth to save it from pending

annihilation. The script suggests that the core could stop spinning as a reversal of the magnetic poles occurs; an event that would temporarily destroy the Earth's magnetic field. This in turn would cause superstorms, northern and southern lights appearing closer to the equator, and unshielded solar wind and cosmic radiation that would scorch life on Earth. The aim is to jump-start the core with nuclear devices. The movie takes a lot of liberty with some physics: the intensity of the solar wind and cosmic radiation would indeed increase causing just some excess skin cancers since the atmosphere provides enough protection against them, charged particles from the solar wind would not be diverted to the poles maybe eliminating the Auroras Borealis and Australis. However such a trip would require a staggering amount of energy for the terranauts' vehicle, which would be crushed by the intense pressure and would be melted by the temperature inside the Earth, and no amount of nuclear explosive power would be capable of accelerating the core if it were to stop. Moreover, the core is rotating because of the existence of the magnetic field, and not vice versa.

### 3.2 EARTH'S POWER GENERATION

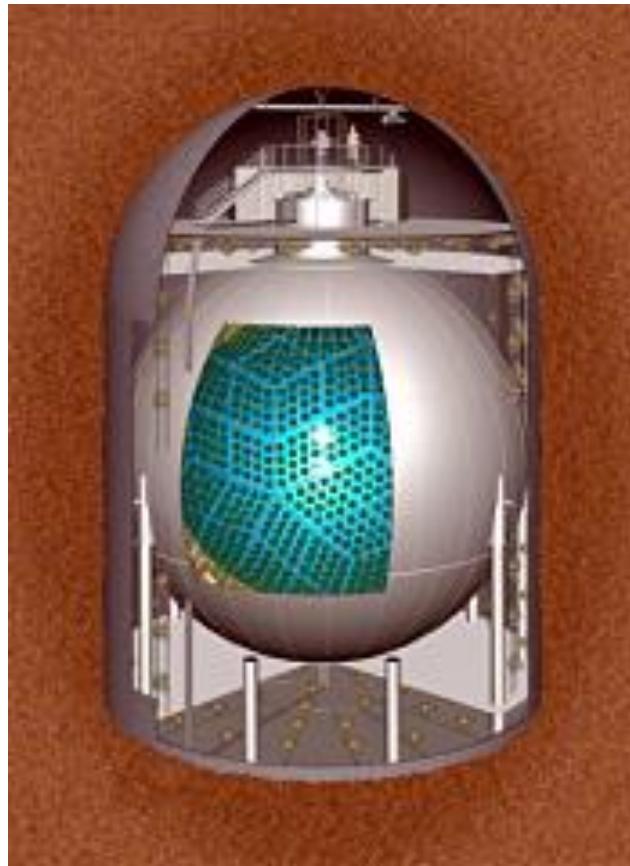


Figure 1. Liquid Scintillator Antineutrino Detector KamLAND, Japan. Source: Kamioka.

The total power generation from the Earth's interior is estimated as  $44.2 \pm 1$  TerraWatts (TW) based on calorimetric data [11] and as  $31 \pm 1$  TW based on chemical analysis [2]. The

decay of the radiogenic isotopes, in particular of U, Th and K provides a continuous power source. The flux of geo-neutrinos at the Kamioka Liquid-Scintillator, Japan and the Borexino detector, Italy [3] allows the estimation that the decay of  $U^{238}$  and  $Th^{232}$  together contributes 20 TW to the power generation. The neutrinos emitted from the decay of  $K^{40}$  are thought to contribute 4 TW of power, even though they are below the detection limit. This suggests that the rest of the power generation could be attributed to other sources such as the primordial heat supply from the gravitational potential energy that was converted into heat.

The power generation is radiated into the Earth's atmosphere and then into space. The mineral oil -filled detector observed 841 antineutrinos at energies corresponding to  $U^{238}$  or  $Th^{232}$  decay. The experiment benefited from the shutdown of the Kashiwazaki-Kariwa nuclear power plant for 21 months following a 6.6 Richter scale magnitude Earthquake, eliminating a significant background antineutrinos source from fission power generation.

### **3.3 THE FORMATION OF THE EARTH**

The classical theory about the formation of the Earth is that it was formed from a large body, maybe a star passing near the sun. The sun gravitationally pulled material from it that formed the Earth and the planets. The pulled material would have been initially gaseous then condensed into a liquid. The outer layer of the liquid would have later condensed into a solid forming the Earth's crust. This perspective does not explain the presence in the Earth's crust of elements such as iron, cobalt, nickel, calcium, magnesium and aluminum. These, however, do not occur in stars like the sun. Our sun is known to consist primarily of 80 percent hydrogen, 20 percent helium, and small amounts of 1 percent carbon, nitrogen, oxygen and other light elements. Thus another model must be invoked.

The relative abundance of the various nuclides as a function of the mass number A is shown for the Solar System in Fig. 2. These abundances in terrestrial, lunar and meteorites are usually the same as the abundances from cosmic rays from outside the solar system. The synthesis of deuterium and helium is thought to have occurred minutes after the postulated Big Bang. Other nuclei up to Iron<sup>56</sup>, which is the most stable nucleus, are thought to have been produced in nuclear fusion in the stars.

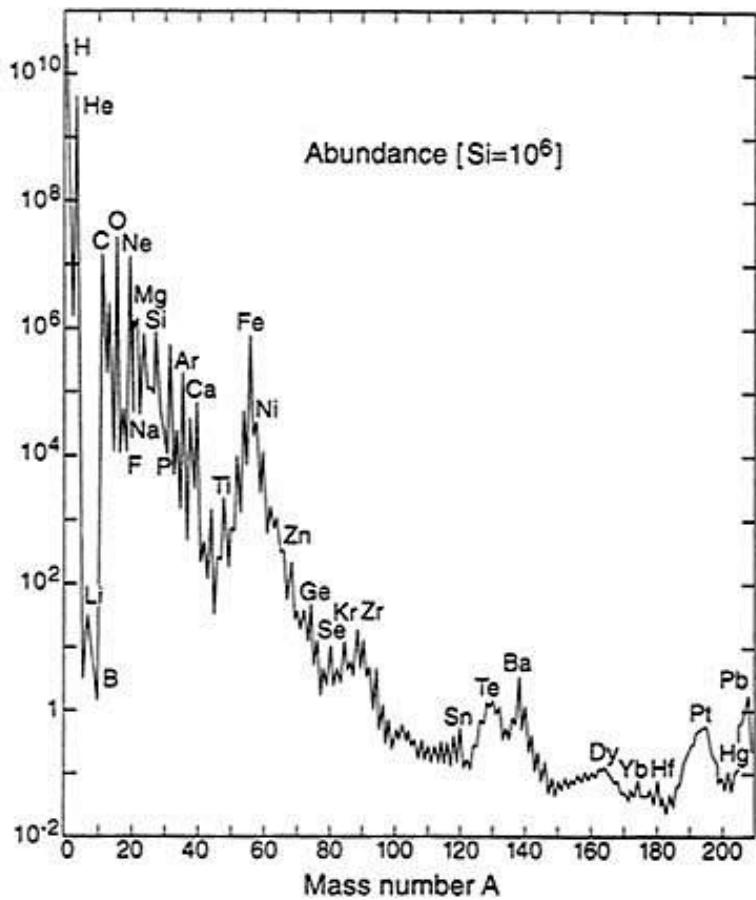


Figure 2. The abundance of the different elements in the Solar System normalized to the abundance of Silicon as equal to one million.

To generate heavier elements from the light elements, the process of nucleo-synthesis must be invoked. To create elements like carbon and neon requires temperatures around  $2 \times 10^8$  °C. Elements like iron, nickel and cobalt require even higher temperatures around  $4.5 \times 10^9$  °C. Since these temperatures do not occur in the sun, which has a surface temperature of 6,000 K and a core temperature of about  $1.5 \times 10^7$  K, the heavy elements could not have been created in our sun. These temperatures, on the other hand, do occur in supernovae, which are events generating tremendous temperatures and pressures where giant stars, after burning most of their nuclear fuel in the form of hydrogen and helium, collapse and implode under the effect of their own gravity. This suggests that the life in general, and the human race on its planet Earth are the ashes and the products of nuclear reactions that occurred in supernovae explosions in the distant past in the history of our universe.

Deviations from the universal abundances of the Earth's forming elements occur locally through the process of radioactive decay. Table 1 shows a list of elements found on Earth which are radioactive with long half-lives. They decay by alpha, beta, gamma, and spontaneous fission processes.

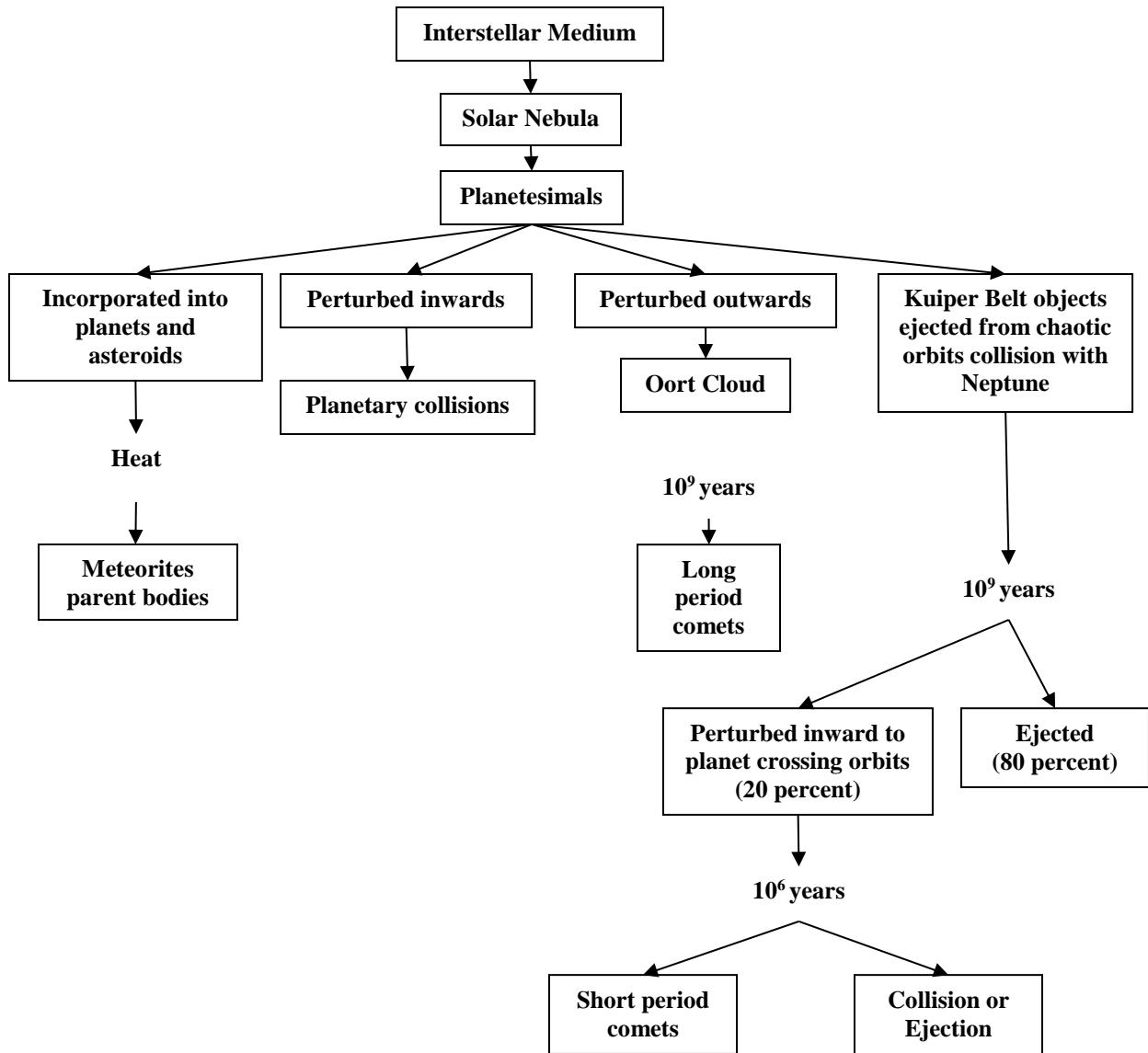


Figure 3. Formation of the solid bodies in the early solar system from the interstellar medium.

The modern theory of the formation of the Earth suggests a two-stage process. In the first stage, the sun would have acquired into its gravitational field a nebula, as shown in Fig. 3, which is a collection of gases and dust particles resembling the rings of Saturn as a result of passing through an interstellar dust cloud, or as result of the sun interacting with a nearby supernova remnants.

In the second stage, the nebular dust collapsed into solid spheres, which formed the inner planets and the asteroids, and into gaseous spheres which formed the outer planets. This is thought to be the process by which other planetesimals were also formed. These include the Oort cloud

containing the long period comets, and the Kuiper belt objects including the short period comets. The Kuiper belt is a region between 30-50 Astronomical Units (AU) from the sun, where:

$$1 \text{ AU} = \text{Distance between the Earth and the sun.}$$

The interior of the Kuiper Belt objects is thought to be composed of pristine interstellar material unchanged since the dawn of the solar system. Centaur objects in the Kuiper belt are believed to be objects about 50,000 times the size of a comet and they can be classified as minor planets. The most evolved, Chiron, is considered to be a cometary type body. The Kuiper belt could become a valuable source of chemical and nuclear materials. These could be in the future used by humanity in its exploration of the outer solar system.

The new theory of Earth formation, in contrast to the old theory, envisions an Earth that was initially a solid and cold body. So how can the past and present volcanic activity of the Earth and the molten state of its core are explained?

### 3.4 THE EARTH AS A RADIOACTIVE HEAT ENGINE

The heat generated through the process of radioactivity can explain the currently accepted explanation for how the Earth's outer core became molten, and how it remains nowadays in the molten state, except for the thin solid Earth's crust. This radioactivity occurs in the isotopes of heavy elements such as thorium, uranium, potassium and their daughter nuclides.

In Table 1, some of the naturally radioactive isotopes that generate heat through radioactive decay, together with their half-lives, are shown. Aluminum<sup>26</sup> and Palladium<sup>107</sup>, which have decayed long ago, are an exception. These listed isotopes still exist in the Earth's crust with different abundances. Some of them are members of the radioactive decay chains, such as Radium<sup>226</sup>.

Table 1. Some naturally-occurring radioactive isotopes that have long half-lives. Aluminum<sup>26</sup> and Palladium<sup>107</sup> have disappeared due to their relatively short half-lives.

| Isotope                         | Half Life [years]      |
|---------------------------------|------------------------|
| <sup>13</sup> Al <sup>26</sup>  | 7.30x10 <sup>5</sup>   |
| <sup>19</sup> K <sup>40</sup>   | 1.28x10 <sup>9</sup>   |
| <sup>23</sup> V <sup>50</sup>   | >4.00x10 <sup>16</sup> |
| <sup>37</sup> Rb <sup>87</sup>  | 4.90x10 <sup>10</sup>  |
| <sup>46</sup> Pd <sup>107</sup> | 6.50x10 <sup>6</sup>   |
| <sup>48</sup> Cd <sup>113</sup> | 9.00x10 <sup>15</sup>  |
| <sup>49</sup> In <sup>115</sup> | 5.00x10 <sup>14</sup>  |
| <sup>52</sup> Te <sup>123</sup> | 1.20x10 <sup>13</sup>  |
| <sup>57</sup> La <sup>138</sup> | 1.05x10 <sup>11</sup>  |
| <sup>58</sup> Ce <sup>142</sup> | >5.00x10 <sup>16</sup> |
| <sup>60</sup> Nd <sup>144</sup> | 2.10x10 <sup>15</sup>  |
| <sup>60</sup> Nd <sup>145</sup> | >1.00x10 <sup>17</sup> |
| <sup>62</sup> Sm <sup>147</sup> | 1.08x10 <sup>11</sup>  |

|                        |                        |
|------------------------|------------------------|
| $^{62}\text{Sm}^{148}$ | $8.00 \times 10^{15}$  |
| $^{62}\text{Sm}^{149}$ | $1.00 \times 10^{16}$  |
| $^{64}\text{Gd}^{152}$ | $1.10 \times 10^{14}$  |
| $^{66}\text{Dy}^{156}$ | $>1.00 \times 10^{18}$ |
| $^{71}\text{Lu}^{176}$ | $2.90 \times 10^{10}$  |
| $^{72}\text{Hf}^{174}$ | $2.00 \times 10^{15}$  |
| $^{73}\text{Ta}^{180}$ | $>1.60 \times 10^{13}$ |
| $^{75}\text{Re}^{187}$ | $5.00 \times 10^{10}$  |
| $^{76}\text{Os}^{186}$ | $2.00 \times 10^{15}$  |
| $^{78}\text{Pt}^{190}$ | $6.10 \times 10^{11}$  |
| $^{82}\text{Pb}^{204}$ | $1.40 \times 10^{17}$  |
| $^{83}\text{Bi}^{209}$ | $2.00 \times 10^{18}$  |
| $^{88}\text{Ra}^{226}$ | $1.60 \times 10^3$     |
| $^{90}\text{Th}^{232}$ | $2.90 \times 10^{10}$  |
| $^{91}\text{Pa}^{231}$ | $3.28 \times 10^4$     |
| $^{92}\text{U}^{234}$  | $2.44 \times 10^5$     |
| $^{92}\text{U}^{235}$  | $7.04 \times 10^8$     |
| $^{92}\text{U}^{238}$  | $4.47 \times 10^9$     |
| $^{94}\text{Pu}^{244}$ | $8.3 \times 10^7$      |

The decay of these isotopes releases particles with high kinetic energy with velocities in the range of 8,000 [km / sec], which eventually degrades into heat as a result of collisions with the surrounding media.

The activity of the i-th radioactive isotope taking part in the heat generation process can be written in terms of the decay constant  $\lambda_i$  and the number of the nuclei of the i-th isotope  $N_i(t)$  as:

$$A_i(t) = \left| \frac{dN_i(t)}{dt} \right| = -\lambda_i N_i(t) \text{ [transformations/sec] or [Becquerels]} \quad (1)$$

where the number of nuclei at any given time t is given by the law of radioactive decay:

$$N_i(t) = N_{i0} e^{-\lambda_i t}. \quad (2)$$

If each radioactive isotope releases an average energy per decay of  $E_i$  in [MeV / transformation], the rate of energy release or power generation of the i-th isotope would be:

$$P_i(t) = \lambda_i N_i(t) E_i \text{ [MeV / sec].} \quad (3)$$

For all the radioactive isotopes, the power generation would entail a summation over all the isotopes present:

$$\begin{aligned}
P(t) &= \sum_i P_i(t) \\
&= \sum_i \lambda_i N_i(t) E_i [\text{MeV/sec}].
\end{aligned} \tag{4}$$

The integral total energy release at time  $t$  is thought to have caused the Earth's interior to melt down and remain molten as:

$$\begin{aligned}
E(t) &= \int_0^T P(t) dt \\
&= \int_0^T \sum_i \lambda_i N_i(t) E_i dt \\
&= \sum_i \lambda_i E_i \int_0^T N_{i0} e^{-\lambda_i t} dt \\
&= \sum_i \lambda_i E_i N_{i0} \int_0^T e^{-\lambda_i t} dt \\
&= \sum_i E_i N_{i0} (1 - e^{-\lambda_i T}) [\text{MeV}]
\end{aligned} \tag{5}$$

where  $T$  is the time elapsed.

Using Avogadro's law, we can express  $N_{i0}$  as:

$$N_{i0} = \left( \frac{g_i}{M_i} \right) A_v \tag{6}$$

where:  $A_v$  is Avogadro's number equal to  $0.6 \times 10^{24}$  nuclei per gram molecular weight or mole,  
 $g_i$  is the mass fraction of the  $i$ -th isotope.

We can thus write:

$$E(t) = \sum_i E_i \left( \frac{g_i}{M_i} \right) A_v (1 - e^{-\lambda_i T}) [\text{MeV}] \tag{7}$$

The decay of these elements is extremely slow for the most part. However a great quantity of heat is being generated in the process. This heat is being conducted to the surface as heat loss and radiated into space at the rate of:

$$P(t) = 25,000 \text{ [GJ/sec], or [GWatts]}, \quad (8)$$

which is significant compared with the total worldwide electrical power production of about 570 GWatts.

Although the surface of the Earth is maintained at low temperature through radiation, the interior of the Earth remains molten due to the continuous heat generation. The melting is thought to have occurred suddenly in the distant past. The initial melting of the Earth's core is thought to have decreased the radius of the Earth by 100 kilometers, which could have lead to the creation of mountains as part of a great upheaval. This is so since the liquid state is more compressible than the solid state, through gravitation at 3.5 million atmospheres in the interior. Since that initial melting, the radius of the molten zone is thought to continue to shrink, with the formation of the more recent mountain ranges.

### 3.5 THE EARTH'S MAGNETIC FIELD

A cross section of the Earth would show a core consisting of two regions: a metallic inner core enclosed by a liquid outer core (Fig. 4). The inner mantle followed by the outer mantle surround the core (Fig. 5). Turbulent convection in the liquid outer core creates the geomagnetic field shown in Fig. 6. Solid here refers to a mostly crystalline state, and liquid refers to a mostly molten state.

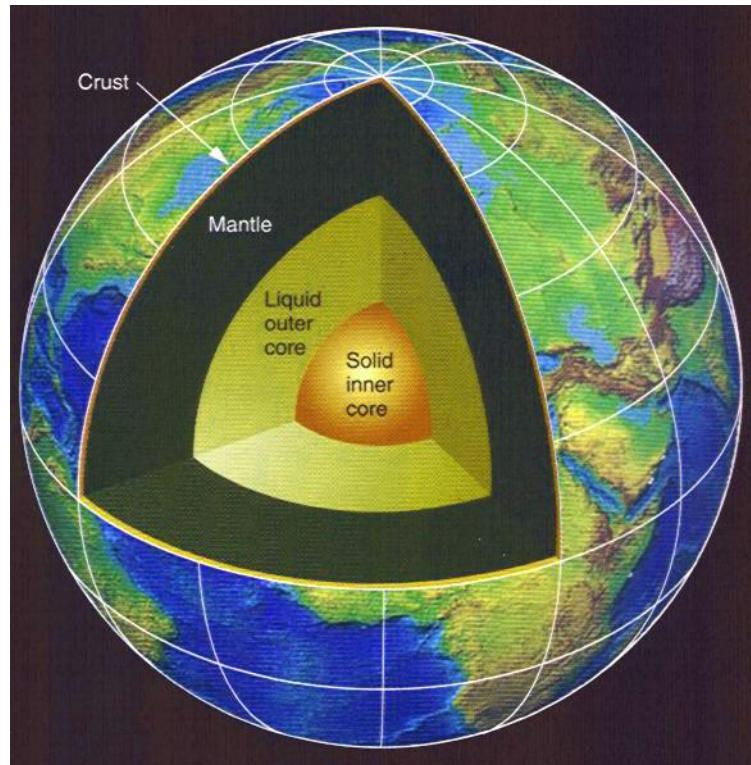


Figure 4. Earth's core inner structure.

An oxide shell surrounds the metallic core. This oxide shell is the mantle and the crust and is 2,890 km thick. The metallic core is partly molten and partly crystalline. The molten outer core is 2,260 km thick and is where the Earth's geomagnetic field is produced. The outer core surrounds the crystalline inner core, which has a radius of 1,215 km. The total radius of the Earth is thus:

$$R_{\text{Earth}} = 2,890 + 2,260 + 1,215 = 6,365 \text{ kms.}$$

The inner core is rotating faster than the Earth's surface by about  $2 \pm 1$  degrees per year. It has a hexagonal close-packed (hcp) crystalline structure, which is the stable form of Fe under the condition prevailing in the inner core. The hcp iron can develop a strong texture at the mega-atmospheres pressures in the core, and leads to anisotropy in the propagation of acoustic waves. This anisotropy is oriented roughly along the Earth's rotation axis. The inner core is about 0.5 [gm / cm<sup>3</sup>] denser than the outer core.

Over 98 percent of the field at the surface of the Earth is due to sources deep in the planet. Geomagnetic storms caused by rapid changes in the solar wind activity can increase the external geomagnetic field. This temporarily decreases the contribution of the core to about 90 percent.

The mantle, being composed of the electrically insulating silicate and oxide rocks, has a low electrical conductivity. Because the bulk of the mantle is insulating, only the radial component of the core's magnetic field is observed at the surface. The tangential component does not propagate through the mantle. There exists here a theoretical problem that needs a solution, since the theoretical calculations suggest that the tangential component is as strong as the radial component.

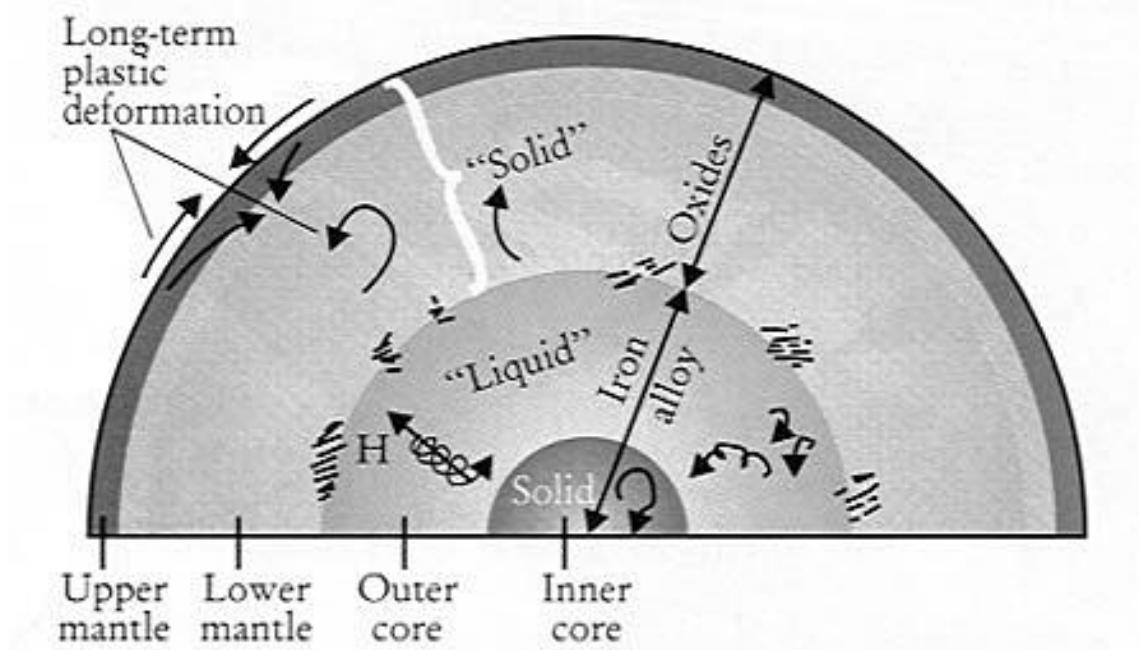


Figure 5. Cross section through the Earth showing its inner structure.

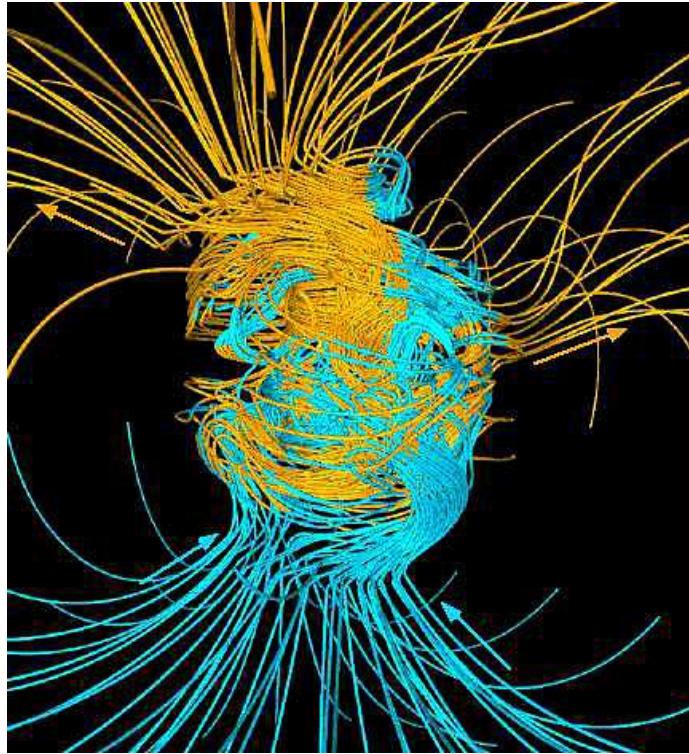


Figure 6. The magnetic field lines generated in the Earth's liquid outer core. Source: LANL.

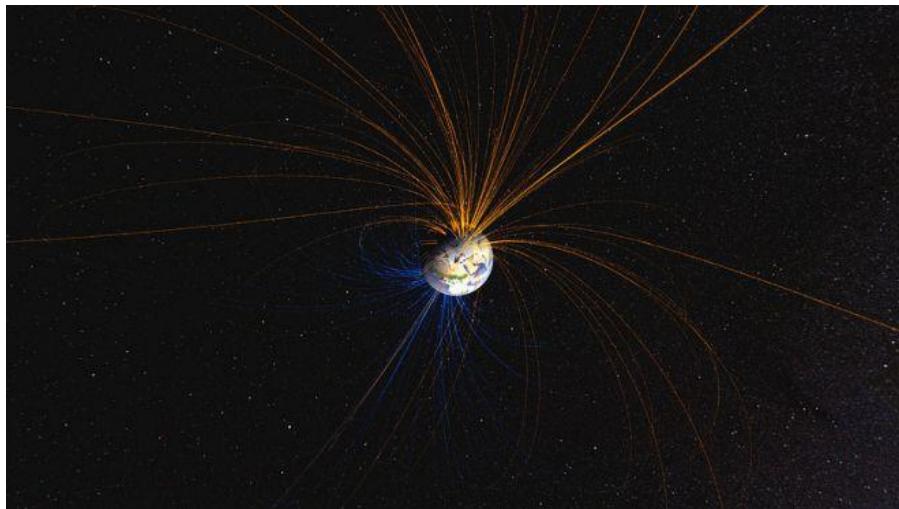


Figure 7. Earth's magnetic field configuration. Source: NASA/Goddard.

Flow velocities of 1-10 km/year exist at the top of the outer core. In contrast, the flow velocities in the mantle, the inner core, and the surface tectonic plates is only in the range of centimeters per year.

Seismological measurements of densities and elastic waves infer that the average atomic number of the core is 26, close to that of iron at 26. The only credible mechanism that can produce

the geomagnetic field is magneto-hydrodynamics. This requires the presence of an electrically conducting fluid. Only molten iron alloys can be involved at the existing pressures and densities. Iron is an abundant element in the Solar System. It is not plausible that rare elements such as chromium or vanadium would compose the Earth's core. Further evidence exists in the composition of meteorites. Even though most of the meteorites are rocky, 10 percent of them are metallic. The metallic ones are composed of an iron-nickel alloy.

The core is not pure iron or an iron-nickel alloy. It is 10 percent less dense than pure iron. The constitution of the contaminant elements is suggested to be sulfur, oxygen, and hydrogen. Oxygen and hydrogen alloy with iron at high pressures. It is possible that they infiltrated the core metal over geological times.

Numerical simulations of the magneto-hydrodynamic dynamo process that creates the geomagnetic field shown in Fig. 7, suggest a magnetic field reversal after 120,000 to 220,000 years. The Earth's magnetic field appears to reverse its polarity a few times every million years. The Earth's rotation causes the outer core fluid to be spun up as it descends from the mantle toward the polar caps of the inner core. The magnetic field lines in the liquid core are dragged forward. Since they also penetrate the solid inner core, a super rotation occurs at about 2-3 degrees per year.

Without radioactivity in the Earth, it would have no magnetic field generated by its rotating molten iron and nickel outer core. It would thus not be protected from the solar wind, as shown in Fig. 9 like the moon, and our form of organic life would not exist on its surface. This solar wind stripped away 90 percent of the surface water and oxygen on Mars, which lacks an internal radioactivity driven dynamo, and consequently lost its magnetic armor billions of years ago.

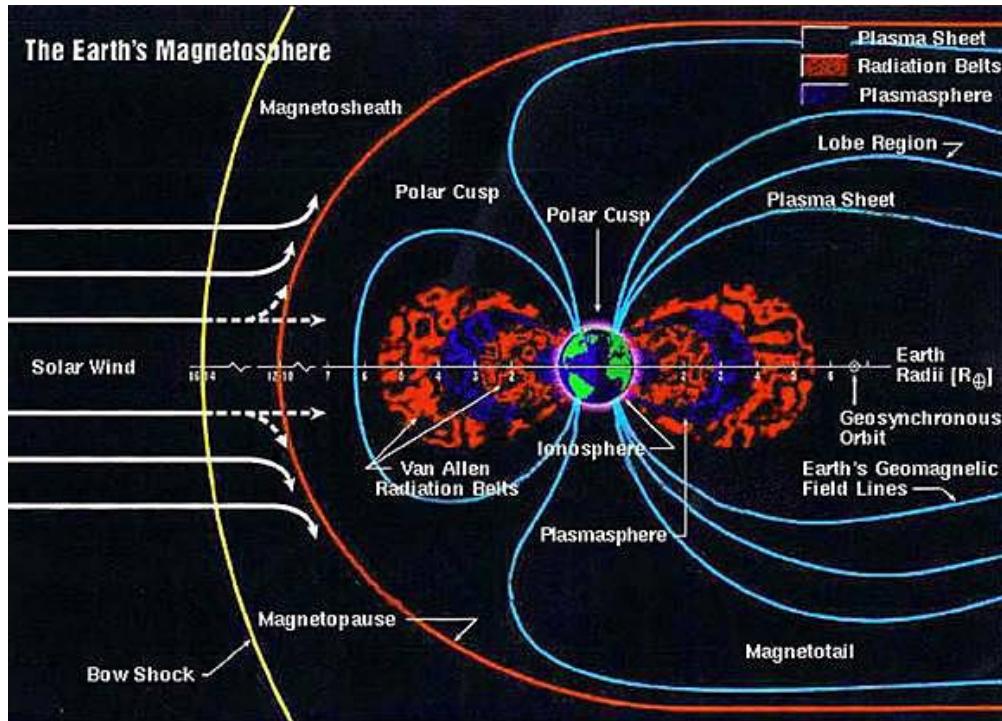


Figure 8. The Earth's magnetic field and its interaction with the solar wind.

Mars and Earth were similar when they were 1 billion years old: they both had water kept liquid with an atmospheres containing carbon dioxide. The habitable zone around the sun within which the surfaces of planets can maintain liquid water essential for life has been expanding outward as the sun is getting hotter. Mars is within that zone, but its atmosphere is only 1 percent that of the Earth and cannot hold enough heat to keep water liquid. Geologic evidence suggests that Mars was warmer and wetter about 3.8 billion years ago, before it lost most of its atmosphere. Past wet spots like the Gusev crater, might have the best odds of having fossilized life. This would have depended on the past presence of water, which being liquid over a wide range of temperatures, is the best-known precursor to life.

Within our Solar System, Earth is in a narrow zone permitting life. It is at the right distance for water to remain in the liquid state. Another important factor is its tectonic activity, which recycles the planet's carbon, keeping it warm. Mars has no such mechanism, and this deficiency is another reason why Mars lost most of its atmosphere.

Thus biological life on Earth owes its existence to three nuclear phenomena: fusion reactions in supernovae in the distant past, radioactivity in the Earth's core at the present time, and fusion reactions in the sun generating solar radiation.

### 3.6 GEOTHERMAL ENERGY

The pressure at the center of the Earth's solid core is estimated at 3.6 million atmospheres. It falls to 1.4 million atmospheres at the top of the liquid outer core. Iron alloys melt at about 4,000-6,000 K, at the core pressure. The consensus is that the temperature is 3,500-4,500 K at the top of the core, and they go up to 5,000-6,000 K at the center of the core. The uncertainty is related to the uncertainty in the composition of the core. The temperature near the surface is much lower than these values.

It has been observed in the mining industry that the temperature gradient from the Earth's interior to the surface is 3 degrees Celsius per 100 meters. The crust insulates the core, and this heat leaks very slowly at a rate of:

$$0.06 \text{ [Joule / (sec.m<sup>2</sup>)].}$$

This leads to a total leakage of:

$$8 \times 10^{20} \text{ [Joules / year].}$$

This is minor in comparison to the heat energy incident on the Earth from the sun at about:

$$170 \times 10^6 \text{ GWatts.}$$

Table 2 shows the order of magnitudes of some power flows on Earth, including the gains and losses. It can be noticed that tidal energy is an order of magnitude less than terrestrial energy.

It can thus be observed that the heat generation in the Earth and the heat received from the sun, are very large in comparison to the human energy needs. Thus there is no shortage of primary energy. The problem lies in the economics of exploiting energy sources. Solar, tidal and geothermal sources are quite dispersed and diffuse, and the costs involving in their concentration

and exploiting them are significant. It is clear that we must try to use all energy sources when the circumstances allow doing so, subject to their limitations, such as the need for energy storage with solar and wind energy, and any special circumstances that make them extractable.

Some natural concentration mechanisms such as hot springs allow limited use of geothermal sources whenever they occur. Hydroelectric power can also be regarded as a concentration source for solar energy.

The Earth is composed of three layers: the crust, the mantle and the core. The crust is primarily granite on top and basalt at the bottom. The crust is only 35 kilometers thick under the continents, and is just 5 kilometers thick under the oceans, where it is primarily basalts. The crust floats on top of the denser mantle, which consists of plastic materials of peridotitic characteristics. As shown if Fig. 9, the crust is split into 8 main tectonic plates which move relative to each other:

1. The Eurasian Plate,
2. The Indian Plate,
3. The Pacific Plate,
4. The Nazca Plate,
5. The Antarctic Plate,
6. The American Plate,
7. The African Plate, and the
8. The Eurasian Plate.

Table 2. Power flows in the Earth.

| Source  | Power Flow<br>[Watts] |
|---|-----------------------|
| <b>Terrestrial Energy</b>                               |                       |
| Conduction in rocks                                     | $3.20 \times 10^{13}$ |
| Convection in volcanoes and hot springs                 | $3.00 \times 10^{11}$ |
| <b>Tidal Energy</b>                                     |                       |
| Tides, Tidal currents                                   | $3.00 \times 10^{12}$ |
| <b>Solar Radiation</b>                                  |                       |
| Incident radiation                                      | $1.73 \times 10^{17}$ |
| Direct reflection as short wave radiation               | $5.20 \times 10^{16}$ |
| Direct conversion to heat                               | $8.10 \times 10^{16}$ |
| Winds, waves, convection and currents                   | $3.70 \times 10^{14}$ |
| Evaporation, precipitation and storage in water and ice | $4.00 \times 10^{16}$ |
| Photosynthesis, storage in plants, and fossil fuels     | $4.00 \times 10^{13}$ |

The mantle materials ascend to the surface along the mid-oceanic ridges, leading to the growth of the adjacent plates as shown in Fig. 10. The plates move there away from each other at the rate of 2-20 cms per year; a large speed on the geological time scale.

At the subduction zones, one plate sinks below the adjacent plate into the mantle. The subduction zones correspond to the oceanic trenches. Island arches surround these subduction zones and mountain ridges along the continents edges. The mid-oceanic spreading ridges and the subduction zones are the areas where the internal heat of the Earth reaches the surface, and where

most volcanic and magmatic phenomena occur. This is also where the possibly exploitable geothermal fields occur.

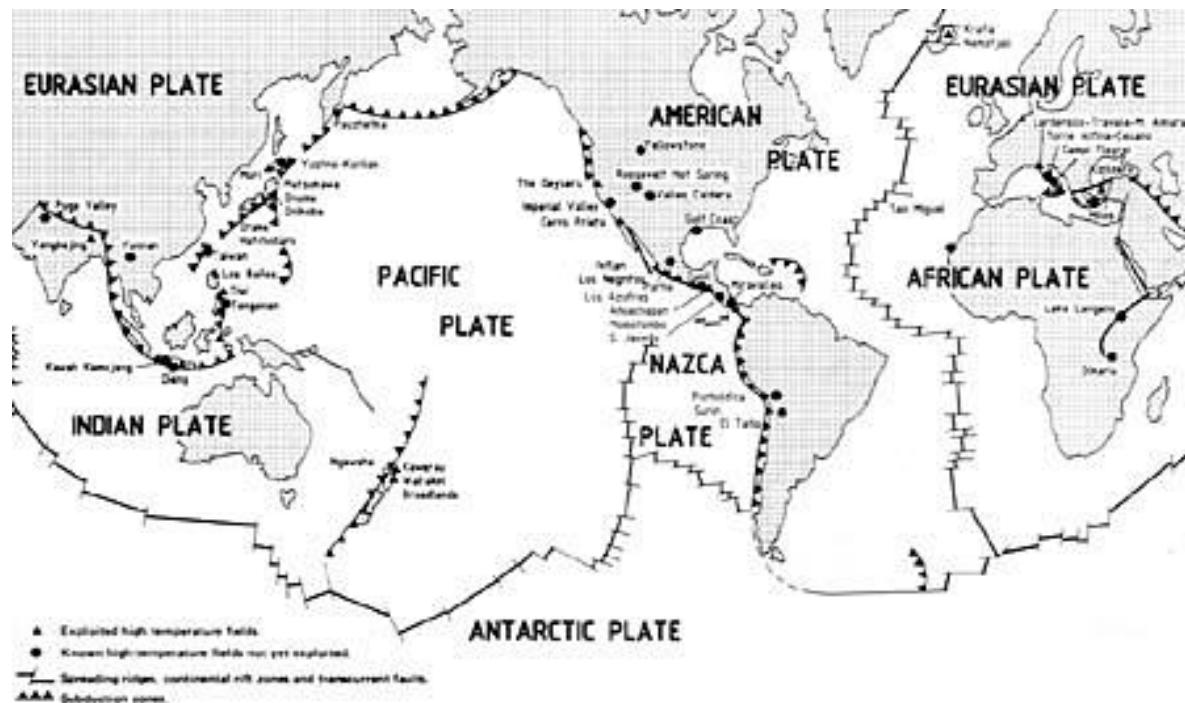


Figure 9. The Earth tectonic plates surrounded by the geothermal fields.

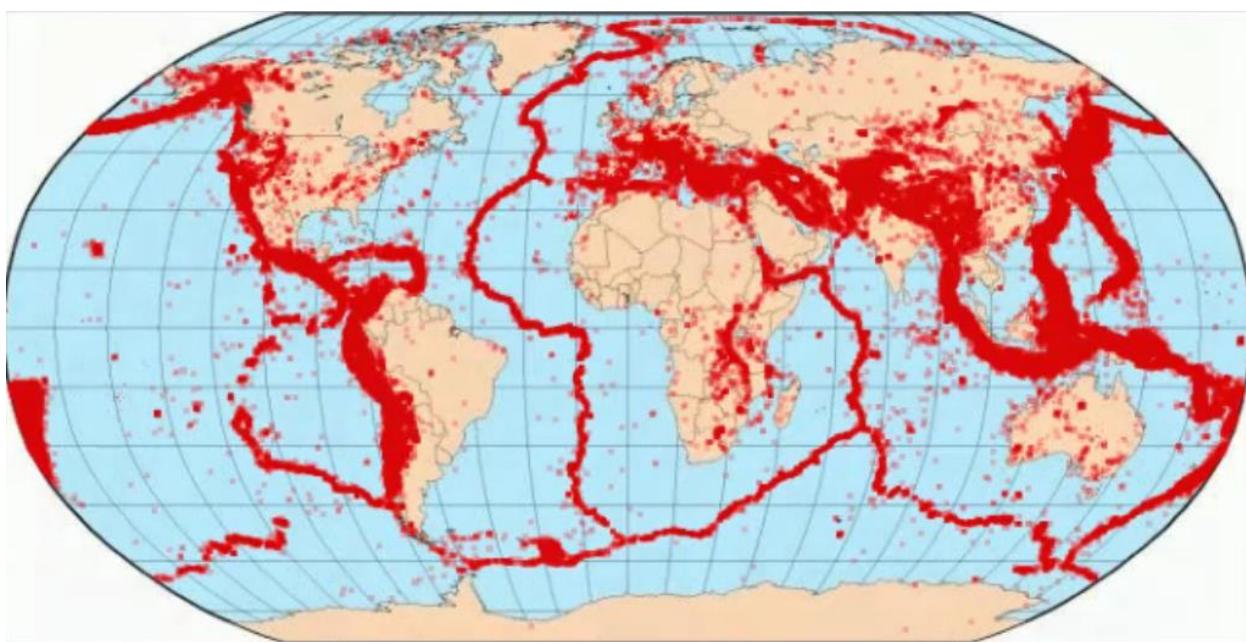


Figure 10. Seismically active areas along the tectonic plates boundaries.

### 3.7 GEOTHERMAL RESOURCES

Geothermal resources have been used since the dawn of history for healing and physical therapy, cooking and heating. The use of geothermal energy for electricity production started in 1904 when Prince Piero Ginori Conti invented the first geothermal power plant at the Larderello dry steam field in Italy. Geothermal power plants produce about 8,200 MWe of electricity in 21 countries.

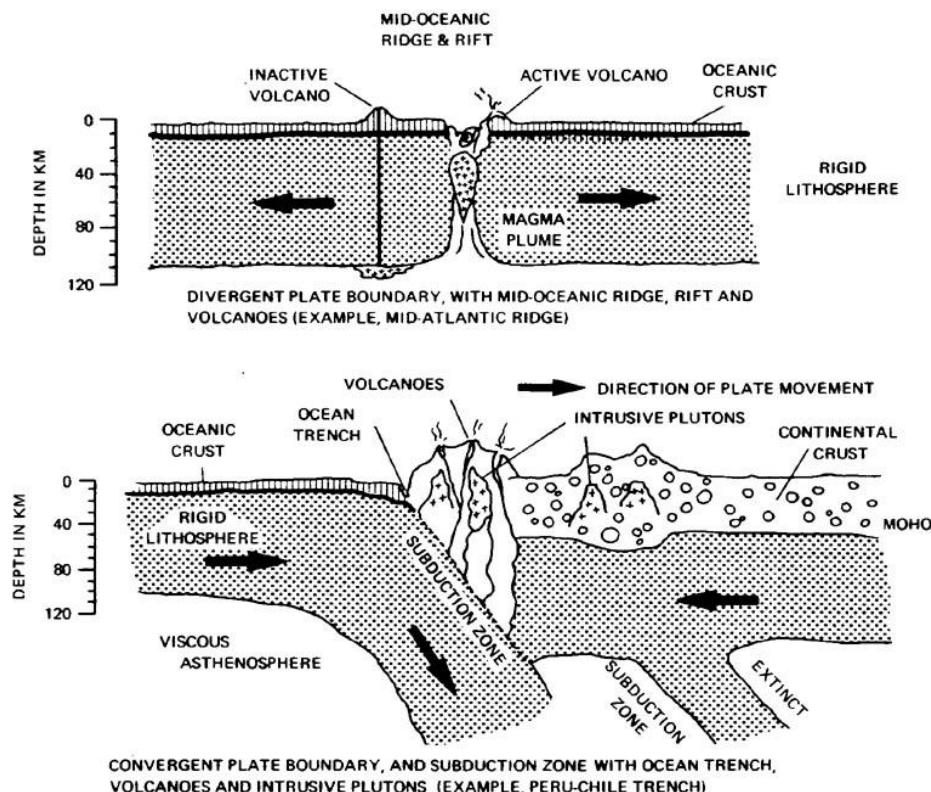


Figure 11. Formation of the mid oceanic spreading ridge, and the subduction zones.

In 1962 the first geothermal power plants were built in the USA at the Geysers dry steam field in Northern California. This still remains the largest producing geothermal field in the world. Fast growth occurred in this field between 1980 and 1990 after the enactment of a federal law compelling utilities to purchase electricity from independent power producers. The goal in the USA is to achieve a geothermal energy lifecycle of electricity of 3 cents per kw.hr of energy.

Water that comes close to magma intrusions seeps to the surface through faults and cracks as hot springs or geysers. When it is trapped in permeable rocks under a layer of impermeable rocks, it is called a geothermal reservoir. These reservoirs are sources of geothermal energy that can be tapped for electricity generation or direct heat energy use. A typical geothermal power plant withdraws heated geothermal fluid and uses injection wells to return the cooled fluids to the reservoir.

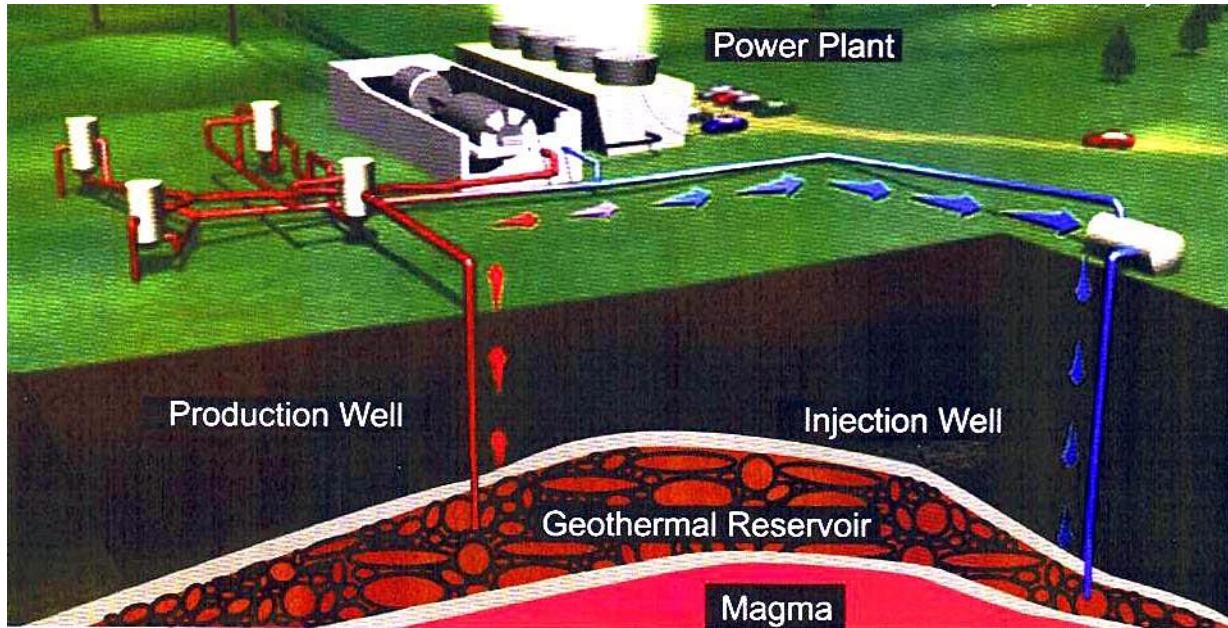


Figure 12. Geothermal power plant where the condensed steam is reinjected into the reservoir to sustain the field's life.

### 3.8 NATURAL GEOTHERMAL FIELDS

The geothermal fields are those areas on the Earth's surface where the groundwater temperature is above 150 degrees C, and can be exploited for space heating and power production. The Lardello geothermal field in Tuscany, Italy is shown in Fig. 14 as seen from the village of Montecerboli. The origin of the name is Mons Cerberi, or the mountain of Cerberus, the three-headed watchdog of hell. The fumaroles and hot sulfurous springs are gone after the economical exploitation of the fields started. One can notice the cooling towers of the steam power plants and the steam plumes of wells discharging steam into the atmosphere.

The heat sources could be the mantle itself where the crust is thin or magma intrusions at depths of 7 -15 kms, elsewhere. The heat is initially transferred by conduction, then by convection by the groundwater. The geothermal reservoir contains the permeable rock formations containing the hot water. Normally, impermeable rocks limiting the heat losses and keeping the entrapped water under pressure cover it. By drilling holes into the geothermal reservoir, the hot and pressurized fluid can be extracted for different purposes. Heating and electrical power generation is the main uses. In Iceland, agriculture is another application where the hot water is used for warming greenhouses for growing vegetable crops.

Under favorable conditions, power generation is carried out with superheated dry steam at temperatures exceeding 250 degrees C. This steam is directly conveyed to turbines attached to alternators producing electricity. Examples of these power producing geothermal fields are the Lardello and Monte Amiata in Italy, the Geysers in California, USA, and Matsukawa in Japan.

Some geothermal fields deliver a mixture of steam and hot water. The water in this case is separated from the steam before it is directed to the turbines. Examples are Wairakei in New

Zealand, Cerro Prieto in Mexico, and fields in Japan and the Philippines. Problems of corrosion and incrustations are caused by the salt laden hot water.



Figure 13. Castle natural geyser at the Yellowstone National Park. Source: National Geographic.



Figure 14. Fumarole exhausting superheated steam.



Figure 15. Geothermal station at Wairakei, New Zealand, 1990. Source: Getty.



Figure 16. Geothermal plant.



Figure 17. Views of the Larderello geothermal field in Tuscany, Italy.



Figure 18. Geothermal plant in Iceland.

At water temperatures in the range of 50-100 degrees C, applications in heating apartment blocks and greenhouses are common in Iceland, France, China, France, Hungary and Russia. There is a number of identified but still unexploited geothermal fields in Chile, Greece Guatemala, India, Nicaragua, and the West Indies. Other prospects exist in Argentina, Bolivia, Bulgaria, Columbia, Costa Rica, Djibouti, Ecuador, Ethiopia, Iran, Israel, Jordan, Egypt, Peru, Poland, the Canary Islands, and Thailand.

An oil company, Unocal, now owned by Chevron in the USA, has been a producer of geothermal energy with more than 30 years experience in geothermal resource exploration, reservoir delineation and management. It operates projects at Tiwi and Mak-Ban in the Philippines and Gunung Salak in Indonesia. It operates a 110 Megawatt power plant near Bandung, West Java, Indonesia. Three power projects are in commercial operation in Thailand.

### 3.9 ARTIFICIAL GEOTHERMAL FIELDS

In the future it is hoped that the terrestrial heat could be extracted from deeper formations including rocks that are dry. In this case engineering projects would drill two holes, one to inject water into the formation, and one to extract the heated steam as shown in Fig. 19. The wells would extract the heat from a fractured zone that is created artificially. The extraction zone would contain hydraulically interconnected fractures created by injection of water under pressure or by the use of peaceful nuclear explosive charges. Experiments were conducted at Los Alamos, New Mexico, USA at depths of 3,000 and 4,000 meters and in Cornwall, England.

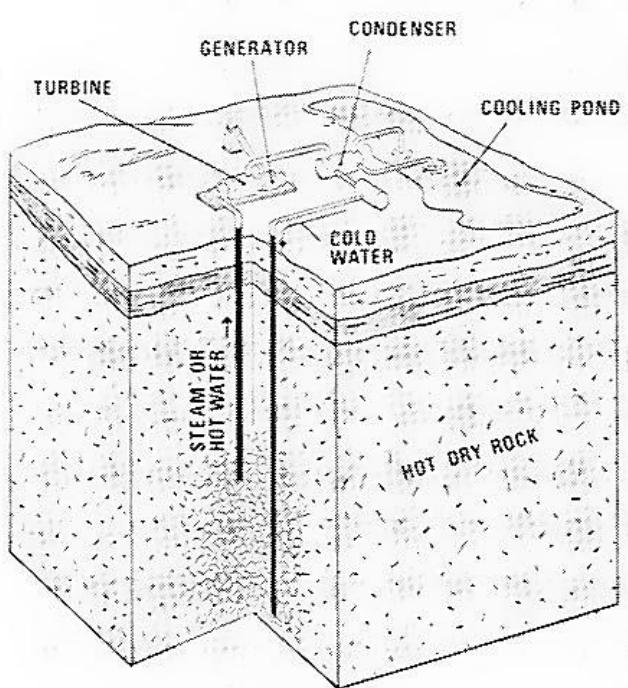


Figure 19. Artificial geothermal field showing injection and extraction wells and the fractured zone.

Gaseous components such as carbon dioxide at 0.5-5 percent; hydrogen sulfide, ammonia, nitrogen, methane, hydrogen at 2-3 percent; boric acid, and some noble gases such as helium evolve from the geothermal fields. The extraction of valuable boric acid and helium may help the economics of the process. Separating methane and hydrogen and burning them separately may also help the economics. However the corrosion problems caused by the dissolved chemicals constitute an engineering challenge, and the dissolved gases are a potential source of pollution.

### **3.10 YELLOWSTONE SUPERVOLCANO**

NASA scientists designed a plan to drill up to 10 kms down into the Yellowstone supervolcano, and pump down water at high pressure extracting heat from it. The cost of this project is estimated at \$3.46 billion. The volcano leaks around 6GW in heat that can be converted into a geothermal plant which would generate electric power at competitive prices of around \$0.10/kWh. The generated electricity can power the surrounding area for a period of potentially tens of thousands of years. The long-term benefit is to prevent a future supervolcano eruption which would devastate humanity.

The drilling project must be handled with utmost care as a slightest mistake might actually trigger the eruption the scientists are trying to prevent.

As BBC points out, a powerful supervolcano eruption might trigger a “prolonged volcanic winter”, with the resulting crop failure putting mankind on the brink of starvation as “food reserves worldwide would last 74 days”, according to the 2012 UN estimates.

### **3.11 NONBIOGENIC HYDROCARBONS**

Geochemists used to think that hydrocarbons could not occur in the Earth’s mantle which begins in depth between 7 and 70 kilometers below the Earth’s surface and extends to 2,850 kilometers in depth, since they would interact with other elements and oxidize into CO<sub>2</sub>. In fact, oil and natural gas wells are drilled between 5 and 10 kilometers in depth. Recent research in high pressure thermodynamics suggests that the mantle radioactivity-generated heat and its pressure could allow hydrocarbons to form and exist to a depth 100 to 300 kilometers. The Earth’s mantle could contain hydrocarbon reserves larger than in its crust.

Theoretical thermochemical simulation studies predict that methane bubbles could form when iron oxide, calcite and water are heated to 500-1,500 degrees C and at a pressure of 5.7-7 gigapascals and then decompressed at room temperature to 0.5 gigapascals. In an experiment, a microgram sample of iron oxide, calcite and water were heated to 600-1,300 degrees C at a pressure of 2-11 gigapascals. The experiment showed the presence of calcium oxide and magnetite, which is a reduced form of iron oxide. Raman spectra of the sample showed a carbon-hydrogen stretching vibration at 2,932 cm<sup>-1</sup>, corresponding to the methane signature. The bond vibration between carbon and hydrogen becomes apparent when the sample reaches 500 degrees C, and becomes strong around 600 degrees C.

### **3.11 DISCUSSION**

In the steam fields of California and Nevada both naturally occurring and man-made steam is mined from the hot rocks. A typical field would have a surface area of 1,000 to 1,500 acres

including a multitude of steam wells, injection wells and steam transmission, water injection and condensate collection pipelines. The geothermal reservoir rock consists of fractured greywacke and greenstone heated to a temperature of 460-480 °F. The fractures are filled with superheated steam at pressures that vary according to location but range from 100-240 psig. The geothermal heat production in the USA predominates in its western states.

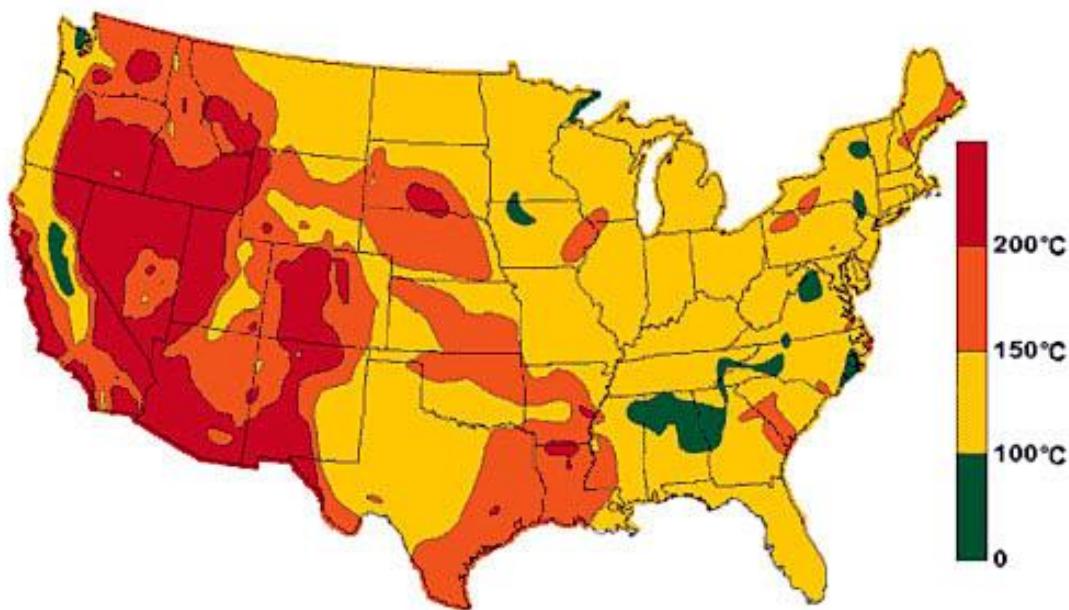


Figure 20. Geothermal heat potential in the USA predominates in the western states.

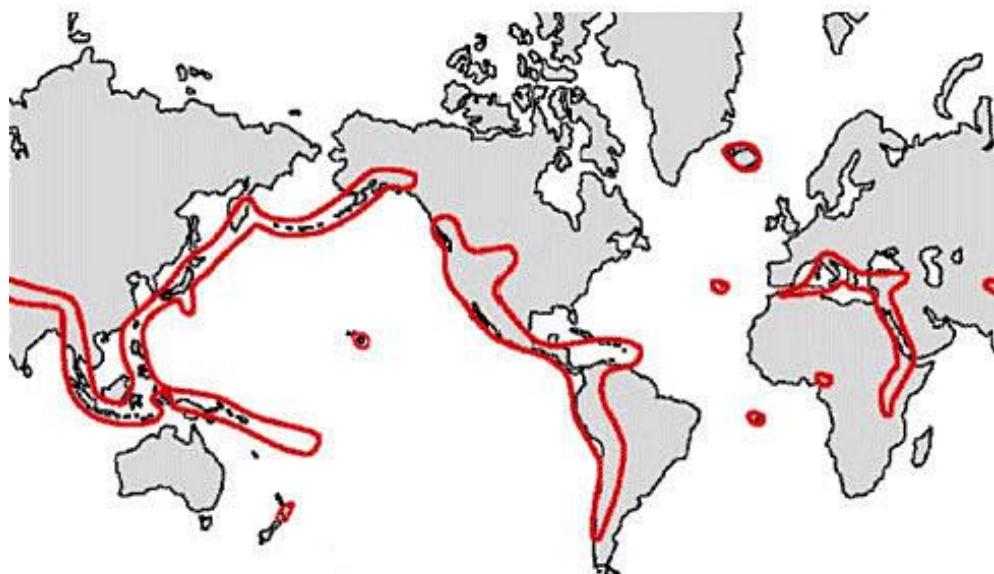


Figure 21. Global areas of geothermal heat potential follow the boundaries of the tectonic plates.

In the past, some people were convinced that geothermal water was of fossil origin and that once used, it will be depleted. However, recent isotopic studies using the water content in the isotopes of tritium, deuterium and Oxygen<sup>18</sup>, have determined that the hot water originates from rainwater infiltrating from the outcrops of the geological formations surrounding the geothermal reservoir. As long as recharge by rainwater continues, exploitation of the reservoir can proceed uninterrupted.

Methane production seems to be thermodynamically stable at temperatures near 500 degrees C and at pressures up to 7 gigapascals, which exist in the Earth's mantle, and suggest the possibility of the Earth's heat and pressure generating vast hydrocarbon reserves in the Earth's mantle with a practically unlimited half-life in the millions of years. Globally, the potential for geothermal heat production concentrates along the boundaries of the tectonic plates.

If the contributions of the radiogenic and the formational energies are separated, one should be able to deduce the Earth's surface temperatures at times past. If the combined source from U<sup>238</sup> and Th<sup>232</sup> is 20 TW today, and Th<sup>232</sup> is 4 times as abundant as U<sup>238</sup>, the U<sup>238</sup> contribution would be  $20 / 5 = 4$  TW. If the half life of U<sup>238</sup> is 4.47 billion years, its power source would have been  $4.47 \times 2 = 8.94$  TW at that time. The formational energy that is decreasing at a rate of 21 TW today, can be integrated back in time to determine the original total heat generation source at the time of the Earth's formation and a temperature curve over its lifetime, deducing when the crust formed and when biological life would have started.

## EXERCISE

1. Calculate the ratio of heat convection in rocks to that of incident solar radiation. Compare the result to the ratio of energy available in photosynthesis, storage in plants, and fossil fuels to the incident solar radiation.  
Discuss the implication concerning geothermal energy and bioenergy and fossil sources.

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