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1 Heat from within: energy supporting the dynamic Earth

THE ENERGY HIDDEN IN ROCKS

Granite is one of the most common and well-recognized rocks to occur at the surface of the Earth. Let us suppose that we put a fragment of granite in a small container, which is then completely sealed. We will assume that the container is made of an ideal thermally insulated material, and that heat can neither escape from within nor enter from outside. What changes will occur in the granite inside the box?

If the contents of the box were examined after one or two years, probably no changes at all would be observed. However, if it were examined after the passage of several hundreds or thousands of years, a careful observer would no doubt realize that the temperature within the container was rising very slightly. After a few hundred thousand years, this rise in temperature would be apparent to any observer. If the calculation described later is carried out, it is clear that the granite in the sealed container would melt completely after several tens of millions of years owing to the rise in temperature.

Where is this energy hidden in the seemingly commonplace granite? Granite contains minute quantities of uranium and thorium, and these radioactive elements are the source of the energy. In general, granite contains several parts per million (ppm) of uranium and about 10 ppm of thorium. The nuclei of these elements undergo radioactive decay, and over their very long half-lives, which span 700 million to 14 billion years, gradually change into isotopes of lead, which have stable nuclei. When the uranium and thorium nuclei decay, alpha-particles, electrons, and other particles are emitted at high speed. These particles are able to move through the mineral's crystals for just a few micrometers (millionths of a meter, often called microns), colliding with the surrounding atoms and coming to a halt once all of

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their kinetic energy has been transferred as heat to the mineral crystals. This heat is what melts the granite within the sealed box.

In addition to uranium and thorium, one isotope of potassium, potassium-40, is another important radioactive nuclide in rocks. It has a half-life of 1250 million years, and undergoes natural radioactive decay into argon-40 and calcium-40, by electron capture and electron loss (beta decay) respectively. Potassium-40 accounts for only about 0.01 percent of all potassium, but since granite contains quite a lot (several percent) of potassium, potassium-40 is also present in significant quantities.

If the energy released by such radioactive elements is totalled, approximately two-hundredths of a joule of heat is generated per year per kilogram of ordinary granite. The existence of radioactive elements is not limited to granite. Basalt also contains uranium, thorium, and potassium, but in amounts about one order of magnitude less than those in granite. Several hundredths of the amount of radioactive elements in ordinary granite are also contained in peridotite, which is the main component of Earth's mantle, though it is not usually seen on the surface. The amount of radiogenic heating within the Earth is extremely slight, being on average about a ten-thousandth of a joule per year per kilogram. In the long run, however, an enormous amount of heat has been produced throughout Earth's history. Repeated volcanic eruptions, earthquakes, mountain-building, and tectonic movements – these events that characterize the dynamic Earth would not happen today without the energy released by the nuclear disintegration of these radioactive elements, which keeps the Earth's interior burning hot.

THE AMOUNT OF RADIOACTIVE ELEMENTS IN ROCKS

Uranium and thorium are part of the third group in the periodic table, and they are also very heavy elements. In normal conditions, both of these elements become ionic with a valence of +4. The ionic radius for uranium is 0.85 Å, and that for thorium is 0.94 Å. The electronic charges of uranium and thorium are equal, and they are almost the same size, so chemically they behave in a very similar way. Consequently, in rocks and

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Table 1.1 *Amounts of uranium, thorium, and potassium contained in rocks (typical values)*

	Uranium (ppm)	Thorium (ppm)	Potassium (percent)
Granite	3.0	12.0	3
Basalt	1.0	4.0	0.5
Peridotite	0.001	0.004	0.04
Sandstone	0.45	1.7	1.4
Deep ocean-floor sediment	1.3	7	2.5

ores in which uranium is concentrated, thorium is also concentrated. Even if the type of rock or ore differs, usually the ratio of uranium and thorium is almost the same (Table 1.1). But in an environment extremely susceptible to oxidation, uranium sometimes becomes ionic with a valence of +6. This uranium forms an ion (UO_2^{2+}) which is water-soluble; it is gradually washed from the rock and thus the uranium is depleted, so in some cases the ratio of uranium to thorium changes greatly.

Owing to their large ionic valence, it is difficult for uranium and thorium to be introduced into mineral crystals. When magma is generated by partial melting of the mantle material, therefore, almost all of the uranium and thorium are expelled from the original mineral crystal to enter the magma. The solidification of such magma near the Earth's surface forms the crust, and this is why uranium and thorium are much more concentrated in crustal rocks such as granite and basalt than in mantle rocks such as peridotite. Potassium is also incompatible with mineral crystals because of its large ionic radius (1.33 Å) and so is more concentrated in crustal rocks. A summary of the abundance of these three elements is given in Table 1.1.

The solid Earth is divided into three basic layers. The part closest to the surface is the crust, which accounts for less than 0.4 percent of

Earth's total mass. Below this is the mantle, which makes up approximately two-thirds of Earth's total mass, and the remainder is the central part, called the core. The average chemical composition of the crust is one in which granite and basalt are mixed in a ratio of roughly one to three. The chemical composition of the mantle is believed to be similar to that of peridotite. If that is the case, it is clear from Table 1.1 that the average amount of potassium contained in the crust is about 1 percent, and in the mantle about 0.04 percent. Likewise, there is about 2 ppm (parts per million) of uranium in the crust, but this falls to a few ppb (parts per billion) in the mantle.

RADIOACTIVE ELEMENTS IN THE WHOLE EARTH

We have already said that rocks and Earth are heated from within by the energy released when uranium, thorium, and other radioactive elements naturally undergo nuclear disintegration. We also said that if this energy is sealed up in the rock without escaping outside at all, the heat generated is sufficient to melt granite completely within several tens of millions of years. What would happen in the case of the whole Earth? In considering this question, it is first necessary to estimate the quantities of radioactive elements, such as uranium and thorium, in the whole Earth.

Although Earth's crust accounts for an extremely small part of the whole Earth in terms of mass, it is mainly composed of granite and basalt, in which radioactive elements are highly concentrated. The mantle also contains radioactive elements, though at a much lower level than the crust. The main component of the core is believed to be an alloy of iron and nickel. Though we do not have a direct sample from the core, we can still estimate its gross properties by studying how seismic waves propagate through the Earth and by considering the Earth's density as well as the similarity of its composition to that of meteorites. Elements like uranium and thorium hardly dissolve at all in the iron–nickel alloys found in meteorites. So the amount of radioactive elements in the whole Earth – that is, Earth's internal heat source – can be approximately estimated from the amount present in the crust and

Table 1.2 *Heat generation of radioactive isotopes (in unit of joules per year per kilogram)*

Uranium-238	2955
Uranium-235	17 944
Uranium as a whole*	3063
Potassium-40	880
Potassium as a whole†	0.112

* At present uranium-238 and uranium-235 form uranium in the ratio of 137.88 : 1.

† At present potassium-40 accounts for 0.0117 percent of total potassium.

mantle.[1] From Table 1.1 it is calculated that there is about 0.01 ppm each of uranium and thorium; that is, each gram of Earth as a whole contains approximately a hundred-millionth of a gram of uranium and thorium, respectively.

Table 1.2 shows the energy released when each of these radioactive elements undergoes natural nuclear disintegration. The uranium in nature consists of two isotopes, uranium-238 and uranium-235. The ratio between these two uranium isotopes ($^{238}U/^{235}U$) is surprisingly uniform, having a value of 137.88. Actually, all the isotopic ratios of elements in nature have fairly uniform values (with the exception of isotopes added by the process of radioactive decay). This is an extremely important constraint when considering the origin of the Earth and the Solar System, but we will leave this to be taken up in Chapter 2, and now proceed to discuss heat generation in the Earth's interior.

From the data shown in Table 1.2, the amount of heat generation in Earth's material is calculated to be approximately one ten-thousandth of a joule per year per kilogram. This is the present value, and naturally it increases as one goes back in time because radioactive elements were more abundant in the past. The total energy released through nuclear disintegration over the Earth's history would be more

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than several hundred kilojoules per kilogram of Earth material. The specific heat of normal rock is about one kilojoule per kilogram per degree, so this amount of nuclear energy could potentially raise the temperature of rock by more than a thousand degrees: that is, up to a point where it starts to melt.

HEAT GENERATION IN THE EARTH'S INTERIOR

With the exception of part of the core (from seismic observations, the outer part of the core, which accounts for about half the core radius, is known to be in a liquid state), the Earth is still a solid despite this enormous internal heat production. Why? This is of course because a considerable amount of energy has escaped from the Earth into space. Just as a cup of hot coffee gradually cools by releasing heat into the surrounding air, the Earth cools down by transferring heat from its hot interior to cold space. The internal heat production by radioactive elements slows this cooling, or if the heat production is greater than the heat release, the Earth can heat up. The balance between internal heat generation and surface heat loss thus determines the thermal fate of a planetary object.

The size of a planetary object places a first-order control on this balance. The loss of heat from the surface is proportional to the square of the radius of an object, while the amount of heat generated within an object is proportional to the cube of the radius. Therefore, the ratio of heat loss to heat generation is inversely proportional to the radius; the larger an object, the more heat can be retained within the object. For example, let us compare the Moon and Earth. Even if they contained roughly the same amount (per unit mass) of radioactive elements, the Moon cooled more rapidly than the Earth because it is much smaller. This is why almost no mountain-building or tectonic movements as seen on Earth occur on the Moon. As another example, consider meteorites found on the Earth, which are thought to be fragments of tiny proto-planets called "planetesimals". On these meteorite parent bodies, with average sizes far smaller than the Moon (they are believed to have radii of several to several hundred kilometers), the cooling rate should have been even faster. Before falling down to Earth, therefore, these meteorites have drifted for a long time through space as "dead bodies" that stopped "breathing" at the time of their birth. This is why meteorites are called the fossils of the early Solar System.

For a relatively large planetary object such as the Earth, the cooling history would not be so simply dominated by surface heat loss, and the balance between heat generation and heat loss can be a delicate one.[2] While the amount of heat generation is determined from the Earth's chemical composition, the rate of heat loss from the surface can be measured by geophysical techniques. Doctors diagnose the human body by means of tapping and body temperature. Using this analogy, analysis of the Earth's internal structure by use of seismic waves is equivalent to the doctor's tapping, with the earthquakes as the sources of signal, and measurement of the amount of heat escaping is similar to measuring body temperature. These measurements are an essential geophysical method in "diagnosing" the Earth.

The amount of heat escaping from the Earth can be estimated by measuring changes in temperature with descent through a mine shaft. As one descends through the mine levels deep underground, one can feel that the temperature gradually rises. The temperature increase varies from mine to mine, but usually the temperature has risen by about 10 to 20 °C at a depth of about 1 km. The amount of heat escaping from the interior to the surface can be calculated by multiplying the thermal conductivity of rock by the temperature difference between upper and lower levels per unit length as one proceeds downwards. Since the thermal conductivity of rock when actually measured in a laboratory is about 3 joules per meter per second per degree, the amount of heat escaping from the Earth is $3 \times 20/1000 = 0.06$ joules per square meter per second. That is, six-hundredths of a joule of heat escapes to the surface of the Earth per square meter every second.

The amount of heat escaping from the Earth's surface can be measured both for the land surface and for the ocean floor. The principle behind this measurement is the same as for measuring on land. A thermometer is inserted into the mud on the ocean floor, and the temperature difference between depths of about 1–2 m apart is measured. Here the amount of heat escaping is calculated by multiplying the thermal conductivity of the mud on the ocean floor by the temperature difference. Unlike continents, the temperature of the sea floor is unaffected by seasonal variations because the heat capacity of the ocean water keeps the sea floor at a relatively even temperature, so we do not have to dig deeply to obtain stable temperature measurements. A vast quantity of data thus has been gathered so far from ocean basins. The average amount of heat escaping on the ocean floor is approximately one-tenth of a joule per square meter per second, which is not much different from the average value on land.

From these measurements, the total heat loss from the entire surface of the Earth is estimated to be about 46 trillion joules per second.[1] As mentioned before, the average heat production of the Earth is approximately a ten-thousandth of a joule per year per kilogram, which is equivalent to about 20 trillion joules per second for the entire Earth. Nearly half of the surface heat loss is thus compensated by internal nuclear energy at present.[3]

COMPARISON WITH SOLAR ENERGY

In closing this chapter, let us now compare the internal heat with solar energy, which is another important energy source for the Earth system as a whole. The solar energy received at Earth, per unit time per unit area that is perpendicular to the Sun's rays, is called the "solar constant", and is approximately 1.3 kilojoules per second per square meter. The amount of solar energy that the whole surface of the Earth receives, calculated by multiplying this constant by the cross-section of the Earth, is approximately one joule per year per kilogram if distributed within the entire Earth. This is about ten thousand times greater than the heat generated by radioactive elements. However, most of the solar energy is reflected back into space again or used up to drive circulations in the oceans and atmosphere, and has almost no effect on temperature within the Earth. So the energy released from radioactive elements through nuclear disintegration is effectively the

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sole energy source for the dynamic history of the Earth, which we will try to unfold in this book.

NOTES

1. The possibility that potassium may go into the core has been repeatedly discussed,[2–5] but such behavior by potassium would be accompanied by other elements of similar chemical nature, which is not observed.[6]
2. The latest estimate on the thermal history of Earth suggests that the planet was warming up instead of cooling down prior to about 3.5 billion years ago.[7]
3. The Earth's thermal budget is actually a controversial topic. Geophysical theories developed in the early 1980s [8,9] suggest that Earth's heat flux is predominantly supported by radiogenic heating, much more than indicated by the compositional models of Earth, and this view of a highly radioactive Earth is often considered as a standard model among geophysicists.[10] For a comprehensive review on this issue, see [11].

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2 At the time of the Earth's birth

NUCLEOSYNTHESIS IN THE GALAXY

The colorful drama of Earth's evolution begins with the formation of the Solar System. The Earth is, after all, merely one of several planets orbiting around the Sun, and the story of how the Earth formed cannot be told without describing how the entire Solar System was formed. Studying the formation of the Solar System in turn enables us to better understand the processes leading to the birth and death of stars, and the mechanisms by which all of the chemical elements in the universe were formed.

Thanks to nuclear physics, we now know how the chemical elements in the universe were made. Except for hydrogen, helium, and some lithium, which were created shortly after the Big Bang, all of the chemical elements were made by stars.[1] Stars explode to end their life and eject the old and newly created elements into interstellar space. When a cloud of interstellar materials has high enough density, it will collapse under its own gravity to form a new star as well as a dusty disk around it, from which planets will emerge. A whole new cycle of chemical element synthesis (called nucleosynthesis) starts again within the central star, until the star consumes all the nuclear fuel and ends its life cycle explosively. In doing so, the universe becomes chemically more and more enriched with heavy elements.

Deciphering the details of nucleosynthesis in the universe, in particular how all of those elements that constitute the Earth were actually formed, is quite difficult, but we have some clues from isotopes. As mentioned in Chapter 1, the isotopic ratio of uranium-238 and uranium-235 has a present value of 137.88 : 1. What does this tell us? Based on nuclear physics, we can calculate the ratio of ^{238}U to ^{235}U in an exploding supernova, and the difference between the theoretical