MASS AND ENERGY: INTERACTIONS OF THE EARTH SYSTEM

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Contents

Summary

The Earth's surface processes are predominantly controlled by the interaction between the Earth's internal heat and solar radiation. Surface heat-flow measurements reflect the increase in temperature with depth, which results in flow of the Earth's internal heat from the core, through the mantle, to the surface. Heat-flow is highest in volcanically active regions and is lowest near oceanic trenches. The source of the Earth's internal heat comes from a combination of processes, which include the formation of the planet and its internal layers and the decay of its radioactive elements, which release heat as the unstable parent element is converted to a stable daughter element. Radioactive decay is the primary agent responsible for convection in the mantle that, in turn, results in plate tectonics.

Solar radiation is the most important external energy source and this energy stimulates a variety of surface processes. The food chain is an important example of this stimulation, whereby solar energy absorbed by photosynthetic organisms is transmitted down the food chain by herbivores and carnivores. This process is highly inefficient, however, so that energy within the biosphere is lost along the food chain and the number of animals

decreases. When plants or animals die, their decomposition in air returns their stored energy to the atmosphere. Should decomposition occur in oxygen-starved environments, the energy may be stored in the form of fossil fuel deposits. Solar energy is also the primary driving mechanism of the hydrologic cycle, which, in turn, controls circulation in the atmosphere, continental erosion, drainage systems and the availability of water resources.

The interaction between internal and external energy sources results in recycling of elements within the Earth's surface layers. Elements introduced to the Earth's surface by plate tectonic activity may be transmitted into the atmosphere, the hydrosphere, and/or the biosphere. This concept is most readily evident in the recycling of carbon.

There has been a considerable debate as to whether, over geologic time, life has harnessed the Earth's internal and external energy sources so as to make its own environment more hospitable. An alternative hypothesis suggests that life has evolved on Earth primarily by interacting with, and responding to, changes in the environment, rather than by manipulating it for its own purposes.

1. Introduction

Two sources of energy interact at the Earth's surface: Earth's internal energy, which is the result of heat flowing from the Earth's mantle and molten core to its surface, and external energy, which is predominantly the result of energy output from the Sun (solar energy). External energy also includes a small amount of radiation derived from outside our solar system (cosmic energy).

The interaction between the Earth's internal and external energy sources has exerted a dominant influence on the Earth's surface processes throughout geologic time. Earthquakes and volcanic eruptions are dramatic and instantaneous expressions of the release of the Earth's internal energy at its surface. Over hundreds of millions of years, however, this energy has powered the motion of the Earth's plates at rates of up to 20 centimeters per year, resulting in the creation and destruction of oceans and mountain belts, and the growth of continents. Solar radiation is the primary driving force behind the hydrologic cycle, climate, and weather. The interaction of these energy sources is illustrated by the Himalayas, which are being uplifted by plate motion and are under attack from the monsoon rains of southern Asia. Each year, these rains erode the Himalayas, and drainage systems transport billions of tons of sediments to the Indian and Pacific oceans. This type of interaction has reduced ancient mountain belts, once the height of the Himalayas, to minor remnants of their former selves.

Although the Earth's atmosphere is bombarded by cosmic radiation as well as by solar radiation, its influence is subtle. One of the most obvious examples is the production of Carbon-14 from Nitrogen-14 in the atmosphere. Carbon-14 is then absorbed by living tissue into the biosphere, facilitating Carbon-14 dating (a method of determining an age by measuring the concentration of Carbon-14). (See *Cosmic Influences on the Earth*.)

2. The Earth's Internal Heat Source

2.1 Surface Heat-flow

Measurements of heat-flow (the flow of heat from the interior of Earth) on the Earth's surface indicate that the Earth loses more heat at its surface than it absorbs from the Sun, implying that the planet as a whole is cooling down. Heat-flow in any locality can be obtained by measuring the temperature at different depths in a drill-hole.

The average surface heat-flow rate is about 0.08 watts per square meter (W m^{-2}). A more convenient expression of heat-flow is the Heat-flow Unit (or HFU) measured in microcalories per square cm per second, where: 1 HFU = 4.2 x 10^{-2} W m^{-2}. Therefore, the Earth's average surface heat-flow is equivalent to 1.9 x 10^{-6} cal cm^{-2} s^{-2} or 1.9 HFU. Surface heat-flow measurements are the result of heat flowing to the surface from the Earth's core (which extends from the Earth's centre, 6370 km below the surface to a depth of 2900 km) through the mantle (which extends from a depth of 2900 km) and the Earth's crust (whose thickness typically varies from 6 to 40 km).

Since heat flows from warmer regions to cooler regions, it follows that the Earth's interior is warmer than its surface. As a result, the temperature of rocks in deep mines is higher than their temperature at the surface. The increase in temperature with depth in the Earth is known as the geothermal gradient. (See *The Geosphere*.)

Surface heat-flow measurements vary significantly from one region to another, and this variation primarily reflects the geological environment and the composition of the rocks. In locations where cool oceanic crust is sinking into the mantle below, a process known as subduction, the geothermal gradient may be as low as 10°C per km, with a heat-flow of about 0.75 HFU. Modern examples of this process occur adjacent to the deep ocean trenches along the western margin of the Pacific Ocean. In regions of the crust above the sites of ascending magma, the gradient can be as high as 75°C per km. Such steep geothermal gradients may be found near oceanic ridges, where new oceanic crust is generated by magma that is ascending from the mantle below. Surface heat-flow measurements near ocean ridges are typically between 2 and 5 HFU.

The highest geothermal gradient within continental crust occurs in rifting environments, where the crust is stretched and thinned. This results in upwelling of the hot mantle and, in these regions, the geothermal gradient is on the order of 30°C per km with a heat-flow of 2.5 HFU.

Regions with a high heat-flow are a source of geothermal energy, which is typically used to generate electricity or provide heat for buildings. The anomalously warm, near-surface rocks drive the circulation of water and, in regions such as Iceland, which sits astride the Mid-Atlantic Ridge, this energy source produces 75% of the country's energy requirements. In the southwestern United States, where the crust has been significantly stretched, near-surface rocks with geothermal gradients up to 30°C km^{-1} drive water circulation and 19 geothermal fields are currently in operation.

More generally, however, the heat-flow and geothermal gradient in crustal rocks is highest in active volcanic regions, and the average geothermal gradient in oceanic crust is about 25°C km^{-1}, compared to that in continental crust, which is about 20°C km^{-1}. The geothermal gradient is higher in oceanic crust because it is a better conductor of heat, a fact attributed to the abundance of iron-magnesium rich minerals in oceanic crustal rocks. These minerals (such as pyroxenes and olivine) are better conductors than the silicon-rich minerals (such as quartz and feldspars) of continental crust. This difference is expressed by the contrasting thermal conductivities of the dominant rocks in oceanic and continental crust. Basalt, the dominant rock in oceanic crust, has a thermal conductivity of 1.8 W per meter per degree Celsius (1.8 W m^{-1} $°C^{-1}$), whereas granite and diorite, the dominant rocks in the continental crust, have thermal conductivities ranging from 2.8 to 3.3 W m^{-1} $°C^{-1}$. (See *Volcanic and Magmatic Rocks*).

2.2 Heat-flow from the Earth's Interior

The flow of heat within the Earth depends on a wide number of variables. The most important of these are the current temperatures within the Earth's interior, the original temperature of the Earth, the production of heat within the Earth, the relative abilities of different materials to conduct heat, and the transfer of heat between different regions. The most efficient form of heat transfer in the Earth is accomplished by convection within the mantle. Mantle convection is a major influence in the motion of the Earth's tectonic plates. Although the mantle is solid, it is soft because temperatures in the mantle are close to melting temperatures. Just as valley glaciers move downhill under the influence of gravity while remaining solid, the mantle can move by solid state flow, a process known as creep. The principal driving mechanism of this flow is the variation in temperature within the mantle and, as a result, circulation occurs by thermal convection, in which warm buoyant mantle rises and cool dense mantle sinks.

The Earth's internal heat has three main sources. Two of these sources are related to the formation of the Earth and its internal layering (i.e. the core, mantle, and crust), the heat from which has been slowly dissipating since that time. The third source of heat is attributed to ongoing radioactive decay, which adds to the global heat budget.

The formation of the Earth is explained by the solar nebula theory, which accounts for the origin of the entire solar system. According to this theory, following a disturbance in a rotating cloud of dust and gas, the force of gravity drew particles ever closer together. Like an object falling from the table to the floor (a process that converts potential energy into kinetic energy), the gravitational accretion of interplanetary dust resulted in an increase in temperature. About 90% of the rotating cloud of dust and gas condensed into a central region, resulting in temperature increases so extreme that the material ignited, leading to the formation of the Sun. Eventually, as the region around the Sun began to cool, elements that became solid at high temperatures began to form small objects, known as planetesimals, which ranged in size from a few cm to a few km across. As they orbited the Sun, the planetesimals collided with one another and formed larger objects known as protoplanets, which eventually became the terrestrial planets (Mercury, Venus, Earth, and Mars). This process was also accomplished by gravitational accretion, such that the Earth, which formed in this manner about 4.57 billion years ago, stored and then released vast quantities of heat. (See *Early Earth*).

The accretion process released sufficient heat to cause large-scale melting, allowing the heavy elements, such as iron and nickel, to sink towards the centre of the Earth and lighter elements, such as silicon and aluminium, to rise towards the surface. This gravitational collapse (density separation) of heavy elements (predominantly iron) into the core, an event known as the iron catastrophe, generated the second source of heat. Model calculations indicate that the Earth was segregated into its three principal layers, core, mantle, and crust, within 20 million years of the planet's formation.

The third source of heat is the result of radioactive decay, which occurs when unstable radioactive elements spontaneously convert to more stable isotopes. This process is similar to making popcorn. Once the kernel has popped, the process is irreversible. As a result, the number of radioactive elements has decreased with time. Heat production from modern radioactive decay has also decreased to about 12% of its original value (see Figure 1). A significant amount of the Earth's radioactive elements occur within the mantle, which accounts for 83% of the Earth's volume, and current heat production from radioactive decay is sufficient to cause thermal convection of the mantle which, in turn, drives the motion of the Earth's surface plates. Because of the relative abundance of radioactive elements early in the Earth's history, it is speculated that mantle convection may have been more vigorous in the Earth's past than it is today.

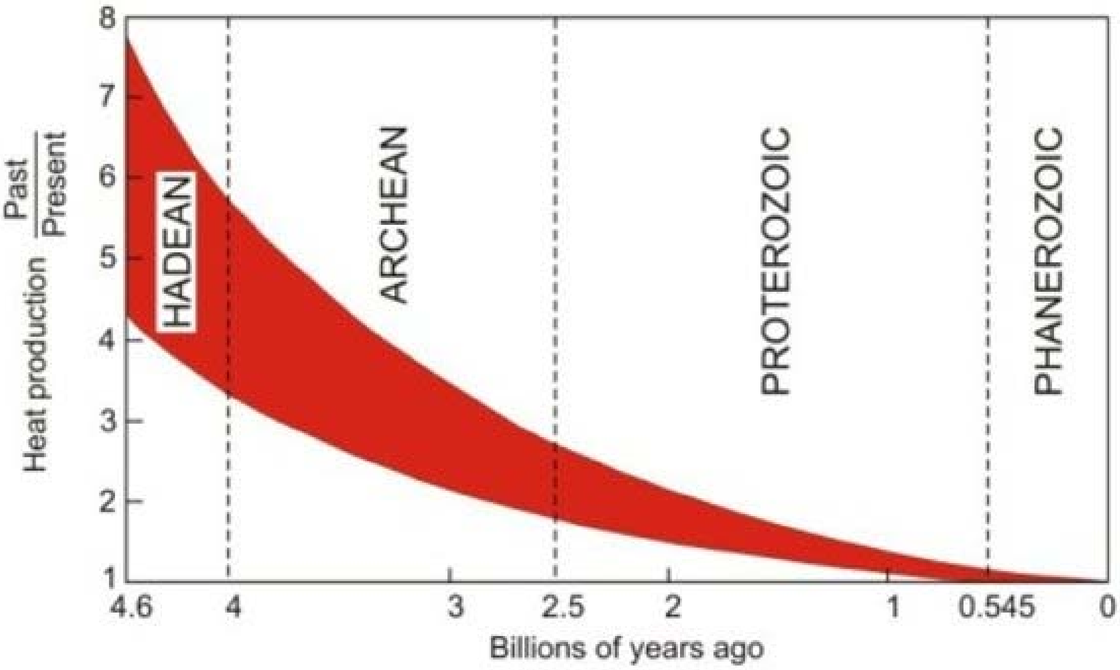

Figure 1. Variation of heat produced by radioactive decay of elements through time. The ratio of radiogenic heat produced in the past to that produced at the present time shows that the heat production has decreased exponentially through geologic time. The width of the band corresponds to the uncertainty of the data.

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Biographical Sketches

Brendan Murphy is an Irish citizen who completed high school and his B.Sc. degree in Ireland, before immigrating to Canada in 1975. He acquired his M.Sc. from Acadia University in Wolfville, Nova Scotia, in 1977 and a doctorate degree from McGill University (Montreal, Quebec) in 1982. In 1982, he joined St. Francis Xavier University, where he is now a professor of geology. He has published over 100 scientific articles in academic journals, book chapters, monographs, or geological field guidebooks, and has authored or co-authored more than 120 conference abstracts.

Jaroslav Dostal received his initial education in geology at Charles University in Prague, Czechoslovakia. He was a lecturer at that university before immigrating to Canada where he received his doctoral degree from McMaster University in Hamilton, Ontario, in 1974. After a year of postdoctoral studies at Dalhousie University, Halifax, Nova Scotia. He is now a professor of geology at Saint Mary's University in Halifax. Dr. Dostal has also worked as a researcher at the Universite de Montpellier, and the Universite dAix-Marseille, France, and the Universita di Modena, Italy. He has authored or co-authored over 150 papers in academic journals as well as more than 200 conference abstracts and other publications.

Damian Nance is from Cornwall, England, and is a citizen of both the United Kingdom and the United States. He received his education in geology in England with a B.Sc degree from the University of Leicester in 1972 and a doctoral degree from Cambridge University before emigrating to Canada in1976 to teach at St. Francis Xavier University in Nova Scotia. In 1980, he joined Ohio University where he is now a professor of geology. The focus of much of his research has centred on the early evolution of the Appalachian Mountains and on the global-scale plate tectonic processes responsible for their development. He has published over 150 scientific articles in academic journals, books and government documents, and has authored or co-authored more than 180 conference abstracts.