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PART I Earthquakes, deep time, and the population explosion

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1 Plate tectonics and why we have earthquakes

INTRODUCTION

During my lifetime, the earth sciences have undergone a scientific revolution, as significant as the discovery that matter is composed of atoms containing a nucleus and electrons, or the discovery of DNA. This is the theory of *plate tectonics*, which completely knocks the props out from what I was taught in graduate school. This theory provides an explanation of why Earth, probably unique among the inner planets, is afflicted with earthquakes. I lived through this paradigm shift, and I now regard it as one of the most thrilling scientific adventures in my own life. Some of the major discoveries in this revolution were made by graduate students who were my own age.

THE PARADIGM SHIFT TO PLATE TECTONICS

Up until World War II, most geologists had no doubt that continents and ocean basins had always been where we now find them, although Alfred Wegener, a German meteorologist, had postulated the theory of *continental drift* as early as 1912 in the first edition of his book, *The Origin of Continents and Oceans*. Wegener had observed that you could close up the Atlantic Ocean, and the continents would come back together, like fitting together the pieces of a jigsaw puzzle. In addition, after fitting the puzzle pieces back together into a supercontinent Wegener called *Pangaea*, the picture on top of the jigsaw puzzle matched. Fossil plants and shallow-water animals on one side of the puzzle were found to be similar to those on the other side, even though the two sides are now separated by thousands of miles of ocean floor. Wegener argued that these plants and animals could not have made their way from one continent across the deep ocean to the other.

Wegener's idea was rejected by the scientific establishment of Europe and North America, but it was attractive to geologists in the Union of South Africa, especially Alexander du Toit. He pointed out that the geology of mountain ranges in South Africa is very similar to the geology of mountain ranges in South America after the continents had been fitted back together.

As pointed out above, Wegener's theory was attacked by the most prominent scientists of the day, especially in the United States. The American Association of Petroleum Geologists organized a symposium in New York City in 1926 in which America's foremost geologists presented papers arguing against Wegener's theory of continental drift. Wegener gave a talk at this symposium, but the Americans weren't buying. They stated that the Earth's crust is simply too firm for the continents to "simply plow through." The correspondence of coastlines pointed out by Wegener had different explanations, and the similarity of fossils could be explained by "land bridges" between the now widely separated continents, although no clear evidence for such land bridges was ever advanced. Except for du Toit of South Africa, and his colleagues, the theory fell out of favor and was essentially abandoned.

While I was in graduate school in 1954–1958, all but one of my professors regarded the theory of continental drift as nonsense. The one professor who accepted the idea, Professor Harry Wheeler, was considered to be a bit loony. My fellow grad students used him to illustrate the point that there is a fine line separating genius from madness. Back to him later.

In 1912, Wegener himself, in the first edition of his book, had advanced the idea that answers the objections that would be raised later at the New York symposium. The floor of the Atlantic Ocean could be continually tearing apart, an idea that would later evolve into *sea-floor spreading*. However, the vehement opposition to continental drift as an explanation for the distribution of continents caused Wegener to abandon the idea of tearing apart the ocean floor in later editions of his book. Wegener's first love was exploration of the

Arctic, particularly the Greenland Icecap, and expeditions to that unknown region beginning in 1906 took priority over defending his continental drift theory. Four years after the New York symposium, in 1930, Wegener lost his life during his fourth Greenland expedition, when his team of explorers attempted to spend the winter on the icecap. His body is still buried there. But du Toit and a few others continued to support Wegener's idea of continental drift.

The debate foundered because of the lack of knowledge about the deep ocean floor, which was more poorly known than the surface of the moon. This lack of knowledge persisted despite the laying of trans-Atlantic cables in the mid-nineteenth century and the world-wide expedition of the HMS *Challenger* in 1872–1876.

This changed during World War II, when it became necessary for the Allies to map the topography of the ocean floor in their search for enemy submarines (a plot line used in the 1984 Tom Clancy novel and the movie, *The Hunt for Red October*). The US Navy developed echo sounders in which a ship would send a continuous sound signal (sonar) to the deep ocean floor, which was returned to the ship in such a way that the distance between the ocean surface and the ocean floor could be determined, and a profile of the ship's track could be plotted. (This is the same system of echo-location used by bats!)

During World War II, Professor Harry Hess of Princeton University was called to active duty, where he served as the commander of a Navy attack ship, the *Cape Johnson*. Hess used his authority to take his ship across sea-floor features that might provide insight into the origin of ocean basins, in addition to clues as to the hiding places of German submarines. The technology of echo-location improved so much that after the war it could be shown that, unlike the assumptions of the American participants at the New York symposium, the ocean floor is not a gentle landscape receiving the sediment of billions of years. It is, instead, highly complex, with undersea mountains and canyons, as shown in a new map of the Atlantic Ocean floor published after the war by Bruce Heezen and Marie Tharp of Columbia University. The most important of these mountains is the

Mid-Atlantic Ridge, which lies midway between the Americas and Africa, the longest mountain range on Earth (Figure 1.1). Another set of features, pointed out by Hess, was *deep-sea trenches*, linear deep-water zones adjacent to mountain ranges like the Andes and Aleutians (Figure 1.1). These trenches are the location of the ocean's greatest depths.

This led to a new age of discovery: a series of campaigns by major American oceanographic institutions to map the topography of the ocean floor, leading to the discovery of other mid-ocean ridges in the Indian and Pacific oceans, deep-sea trenches off the mountainous coasts of South and Central America, Mexico, Alaska, and Japan, and great faults that displace the mid-ocean ridges. One of these ridges, the Juan de Fuca Ridge, lies off the coast of the Pacific Northwest. At about this time, I realized that most of the tectonic concepts I had learned in graduate school (and had been questioned on during my PhD oral exams) were wrong. And I gained a new respect for that

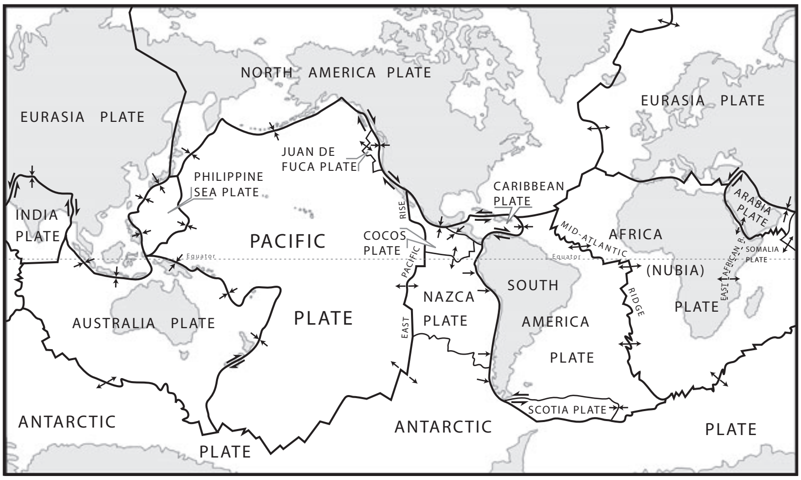

figure 1.1 Division of Earth's surface into tectonic plates, all moving with respect to one another; microplates not shown. Diverging arrows, sea-floor spreading centers; converging arrows, subduction zones, including converging ranges (Himalaya, Alps); arrows parallel to boundary indicate strike slip, like the San Andreas fault. Source: image prepared by Kristi Weber.

"crackpot" Professor Harry Wheeler, who had not been a member of my PhD examining committee. Professor Wheeler did have some weird ideas, but on continental drift he was correct and far ahead of his time.

This led to a great scientific breakthrough by geologists in the United Kingdom. Professor Arthur Holmes (1978) of the University of Edinburgh wrote a textbook, *Principles of Physical Geology*, in which he used the known rates of radioactive decay of isotopes to argue for an Earth that is billions of years old. This led him to revive Wegener's theory of continental drift with his theory of convection cells (Figure 1.2), in which the ocean crust and underlying mantle could move by horizontal convection, thereby dissipating the Earth's internal heat. Because he had already pointed out the Earth's extreme age, the convection cells could move very slowly, and continents could be transported on top of them as passengers, like ice floes in the Arctic Ocean.

PALEOMAGNETISM

At the same time, geophysicists in Great Britain were measuring the magnetic properties of minerals. Our magnetic compasses depend on the flow of magnetic lines of force in the Earth that locate the magnetic north pole and permit ships to navigate on the open ocean, out of sight of land, when the stars are not visible. Navigators had been using magnetic lines of force to steer ships, even though no one knew why the magnetic lines of force exist. The magnetic north pole is not at the same place as the true north pole, the axis of Earth's rotation, and so maps were created showing the correction that your compass has to make to allow you to calculate the direction to true north. (My Boy Scout handbook had one of these maps, and I needed to use it to earn the Map-Reading Merit Badge.)

British scientists then began to measure the orientation of magnetic lines of force in volcanic rocks (*paleomagnetism*), which gives not only the direction to the magnetic pole of rotation but also the distance: The lines of force in a rock close to the magnetic pole would

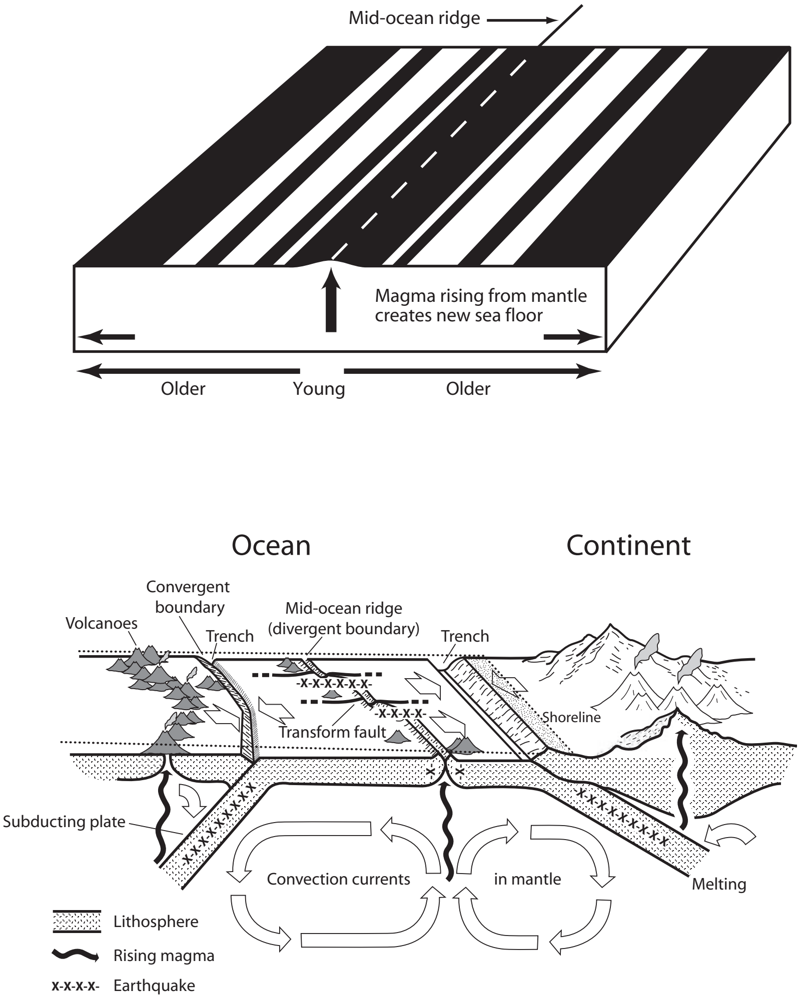

FIGURE 1.2 Top: mid-ocean ridge locates hot oceanic crust rising to the surface as older crust cools and moves away (diverging arrows). Spreading rate is dated by boundary between higher apparent magnetization of today's oceanic crust, magnetized in present magnetic field, (black; compass arrow points north) and lower apparent magnetization where the compass arrow points south (in white). This boundary is based on radiometric dating of volcanic rocks for which magnetization direction is known. Magnetic stripes make a symmetrical, mirror-image pattern. Bottom: relation of sea-floor spreading center, where oceanic crust is created, and subduction zone, where oceanic crust descends into Earth's mantle and is consumed, accompanied by great earthquakes (X). System driven by slowly moving convection currents in the mantle. Source: Ellen P. Metzger, Sea-Floor Spreading Teacher's Guide.

have a nearly vertical orientation whereas the lines of force in a rock close to the magnetic equator, one-quarter of the distance around the world, would be horizontal. These discoveries resulted in a startling discovery: The lines of force in volcanic rocks in some cases do not correspond to the lines of force of the present Earth's magnetic field. The lines of force point in other directions, and in some cases point south rather than north! (This was so bizarre that it was as if an instrument had just proven that the force of gravity in the geologic past had pointed up!) The conclusion that was reached was that the direction of the paleomagnetic lines of force could be used to tell you the latitude (north–south location with respect to the magnetic pole) the lava had been when it had cooled.

My employer at that time, Shell Oil Co., set up a paleomagnetics lab in Los Angeles to use the orientation of magnetic lines of force in drill cores to orient the cores with respect to north. This worked rather well except that some of the lines of force pointed south rather than north, exactly opposite the expected direction of the present day. Had we done something wrong? One theory was that the magnetic lines of force underwent self-reversal, changing their orientation for some unknown reason. In orienting cores, we learned to compensate by just assuming that a southward orientation could be used in the same way as the expected northward orientation. However, the lack of a rational scientific explanation was troubling.

Three young geologists at the US Geological Survey (USGS) and Stanford University collected a suite of volcanic rocks of various ages and measured their ages based on the radioactive decay of isotopes of the elements potassium and argon, ^{40}K to ^{40}Ar, following up on Arthur Holmes' discoveries. When their samples were taken from the outcrop, they were oriented in the present Earth's field, and this enabled them to determine the orientation of the magnetic lines of force in each of the samples they had dated.

The magnetic lines of force in all the volcanic rocks younger than 780,000 years behaved as one would expect – that is, they pointed north, toward the present Earth's magnetic pole. On the other hand, to the great surprise of the paleomagnetics team, the lavas dated as 780,000 to 2,600,000 years old were characterized by magnetic lines of force that pointed south! One of the three investigators, Brent Dalrymple, who is about my age, moved to Oregon State University late in his career as the dean of the College of Oceanography and became my neighbor and friend. It was obvious that this fundamental discovery had been a landmark of his career and life.

This age relationship proved to be true worldwide, meaning that it did not matter where the volcanic rocks had cooled, the only factor affecting whether they were normally magnetized or reversely magnetized was their age. This worldwide relationship meant that a geologic time scale could be established based on paleomagnetic reversals rather than on fossils. The youngest – normally magnetized – rocks are referred to the Brunhes Normal Magnetic Chron, and the older rocks – where the magnetic lines of force point south – are referred to the Matuyama Reversed Magnetic Chron, both named for pioneer investigators in the new field of paleomagnetism. There was more to come: The next epoch back in time is the Gauss Normal Magnetic Chron. In addition, there are shorter-term changes: the Jaramillo Normal Subchron in the upper part of the Matuyama and the Olduvai Normal Subchron in its lower part.

This showed that the change from normal to reverse was not part of a regular cycle like the tides or the phases of the moon. It was irregular, more like the timing of someone entering a room and turning on a light switch and someone else later turning the light switch off. Other workers extended the magnetic time scale back more than 150 million years. The conclusion from this was that in dating volcanic rocks, the Earth acts as its own magnetic tape recorder!

This changed the focus of oceanographic expeditions, and the next discoveries were made at sea in the early 1960s. Magnetic surveys over the Mid-Atlantic Ridge and the Juan de Fuca Ridge showed that the high- and low-intensity anomalies are quite linear and are parallel to the Mid-Atlantic and Juan de Fuca Ridges. North