12 Geology: Modern Science on the Rocks

I used to look down upon geology; after all, what could possibly be interesting about chipping off rock samples with a hammer. While writing this book, I have come to understand that geology is a complex and vibrant science, and that too little of its nature as a science is known to the general public. Since modern geology is of recent origin—much more so than the classical trio of physics, chemistry, and biology—I feel that it is worthwhile devoting a chapter to the nature of geology.

It is often difficult to get an intuitive feeling for the nature of science, because so much of the pioneering work was done hundreds of years ago when people lived quite differently than we do today. Even Einstein's theory of special relativity was published only in 1905, just two years after the Wright brothers' first flight and ten years after the Lumière brothers' first demonstration of cinema. But theories of modern geology are much more recent: *continental drift* was proposed by Alfred Wegener (1880–1930) in 1915, but not accepted until after the theory of *plate tectonics* was proposed by Henry Hess (1906–1969) in 1962. As in other scientific fields, we shall see the same interplay of theory and observation, of initial rejection and ultimate acceptance that we saw in other earlier theories, and we can interpret this process within our definition of a scientific theory.

Perhaps since the origin of the Earth has less personal implications for our self-esteem than the origin of life, theories in geology have evoked somewhat less conflict with religion than have theories of evolution. Many creationists are willing to forego the literal truth of creation in six days, but continue to believe in the special creation of each species. Nevertheless, the study of geology is extremely similar to the study of evolution because they are both primarily historical sciences. Even though the processes described by the theories continue to be active today, the rate of change of observable phenomena is so slow that it takes some effort to assimilate their concepts.

Furthermore, both geological theories and the theory of evolution are used primarily for retrodiction. The primary aim of the theory of evolution is to explain the origin of the vast number of species of plants and animals—both living and extinct—and the relationships among the various species, while the primary aim in geology is to explain the origin of the features of the Earth that we see—mountains, rocks, and oceans—and to investigate the composition of the interior of the Earth.

Both fields are also relevant to the future: the theory of evolution is the basis of concern about biodiversity and the development of drug-resistant microorganisms, while theories of geology can explain potential natural catastrophes like earthquakes and volcanic eruptions. During the past few decades, geologists have applied their knowledge in the exploration of space because the principles that explain the structure of the Earth are used to explain the structure of planets and their moons. Evolutionary biology has yet to find application outside the Earth, but you can never know.

The study of geology

The tools of evolutionary biology come from the study of anatomy and physiology. From a knowledge of the anatomy and physiology of modern-day reptiles and birds obtained from field work and laboratory experimentation, a scientist can deduce the anatomy and physiology of extinct dinosaurs, even though he must work from fragmentary fossilized bones. Fortunately, the basic principles of life have not changed throughout hundreds of millions of years, so the reconstructions are quite reliable. Sometimes scientists disagree, for example, on the question of whether dinosaurs were warm-blooded or cold-blooded, but the disagreement is a matter of interpretation of the meager clues that have been left in the fossil record and could be resolved if sufficient evidence becomes available.

The study of the development of the Earth is much more difficult. We don't have another Earth-like planet that can be conveniently studied in the laboratory in order to obtain results that could be used to reconstruct the origin and composition of the Earth. Geology, more so than biology, depends on the interpretation of basic observations, but since the Earth is so large, these will necessarily be sporadic. The surface area of the Earth is about 500 million square kilometers, two-thirds of which are covered by oceans, so even a couple thousand samples drilled from the Earth barely scratch the surface. Furthermore, even basic observations are hard to obtain, because the behavior of rock under the immense pressures and temperatures that exist within the Earth is not something that can be easily duplicated in the laboratory. Finally, the really interesting places that you would want to investigate—active volcanoes and the deepest trenches in the ocean floor—are not exactly vacation paradises that are easily accessible.

Geologists must work with clues obtained from four sources: investigations of the chemical and physical properties of rocks, surveys of the structure of features of the Earth's surface, indirect evidence of the composition of the interior of the earth obtained by instruments such as seismographs, and contributions from allied sciences like meteorology and oceanography. There is a fruitful positive-feedback loop between geology and evolutionary biology. If you find significant deposits of marine organisms, you can conclude that the rocks were created in the sea; similarly, if you find cold-blooded reptiles, you can be sure that the rocks were not created at the poles. In the other direction, the temporal relationships among fossils can be established by studying the geological structures within which they are found, as well as by radioisotope dating of the fossils. Once you establish a date for certain fossils, you can assign a date to any geological structure anywhere on Earth where such fossils are found. In particular, small organisms are extremely common and they change their structure quite frequently, so biological dating can be quite precise.

As early as the eighteenth century, Pierre Simon de Laplace (1749–1827) had proposed that the Sun and the planets coalesced from rotating gas and dust, gradually becoming hotter as gravitation contracted the spinning material. The result would be a more or less smooth, more or less spherical, Earth.[1] So where did all the oceans and mountains come from? The number of possible explanations is large. If the Earth cooled to form a crust and then contracted again, the crust would become wrinkled like a dried apple. If the Earth cooled, formed a crust, and then expanded, cracks would open up like they do in a less-than-perfectly-baked sponge cake. Since different types of rock have different densities, blocks of land could sink or be pushed up, especially if the interior of the Earth is liquid.

It is easy to suggest a hypothesis, but it is extremely difficult to construct a concise, coherent theory that can be used to explain and predict. As in other sciences, a circularity exists: geologists need data on the composition of the Earth in order to develop theories of its structure, and conversely, they need theories to guide observations. The composition of the interior of the Earth can only be inferred from clues obtained from the analysis of seismic data from Earthquakes and explosions, and high-quality data of this sort has become available only since the second half of the twentieth century. In particular, theories that are based on uplifting or sinking or movement of continents depend on knowledge of the structure and composition of the ocean floor, but until very recently the technology did not exist for obtaining such data. Modern geology depends not only on brute-force techniques for drilling and sampling, but also on electronics and computers that enable scientists to collect, collate, and analyze large amounts of data. Computers are also essential as surrogate geological laboratories. Since you can't run experiments to investigate predictions of alternate theories for the origins of features of the Earth, the only option is to perform mathematical modeling of alternative theories with the aid of a computer.

Wegener and the theory of continental drift

In retrospect, the decisive moment for modern geology was the publication of *The Origin of Continents and Oceans* by Alfred Wegener in 1915. Wegener proposed that all the continents were originally parts of a single landmass that broke apart; then the continents drifted until they arrived at their present locations, and in fact the drift continues to this day. Every since the "discovery" and mapping of the "new" world, people had noticed that the coastlines of the Americas could be matched with the coastlines of Europe and Africa. But Wegener was the first to marshal evidence to support a concise and coherent theory of continental drift.

The evidence comes from three sources. First, not only do the coastal outlines of the continents match, but the detailed geological formations on opposite sides of the Atlantic ocean match as well. Geologists from South Africa feel right at home in parts of Brazil, and the Appalachian mountains in the United States are geologically very similar to the mountains of Scotland and Norway. Second, an analysis of both living and extinct animals and plants shows many cases in which small pockets of similarities are found at extremely remote localities, but not in neighboring localities. Why are there lemurs in Madagascar and related *prosimian* species in locations across the Indian ocean? Why are there marsupials in Australia and America, but not in New Guinea or South East Asia (a relative stone's throw from Australia)? Findings of rare extinct animals provide even better evidence for ancient connections between continents. A remarkably ugly reptile called *Kannemeyeria* lived in both Africa and Argentina, but it was simply too large and lumbering to have crossed the Atlantic and as a cold-blooded reptile could not have walked over the frigid land bridge between Siberia and Alaska on its way from one hot climate to another.

Third, there are fossil finds that are totally inconsistent with the current geography of the Earth. The Himalayan mountains are far from any ocean, but they are primarily built of sedimentary rock filled with the skeletons of marine animals. Therefore, the mountains must have been formed of land that was originally part of the sea floor. Similarly, coal deposits and fossils found in Antarctica indicate that the continent once had a lush climate, though it is currently capable of supporting only organisms that are specially adapted for its harsh, cold climate.

Analyzing all these data, Alfred Wegener concluded that the continents had once been joined and had drifted apart. The currently accepted theory proposes that a single landmass called *Pangea* broke apart about 200 million years ago into two supercontinents: *Laurasia* comprising (present-day) Asia, Europe, and North America, and *Gondwanaland* comprising (present-day) Africa, South America, India, Australia, and Antarctica. These then split into the continents we recognize today and "drifted" apart to their current positions. In fact, the continents are still moving at the rate of a few centimeters per year, as confirmed by extremely precise measurements made with the aid of laser reflectors placed on satellites and the Moon.

The theory of continental drift has been able to explain many of the puzzling observations mentioned above. The Himalayas were formed when India was detached from Gondwanaland and moved rapidly north to crash into Asia, pushing up ocean sediments into a vast mountain range in the same way that the hood of an automobile gets crumpled in a collision. Antarctica was originally located far north of its present position when it was part of Gondwanaland for millions of years, supporting tropical plants and animals that were eventually squeezed into coal. Only about thirty million years ago did it drift to the South Pole and begin to develop its massive ice cap.

They laughed at Alfred Wegener. Well, not really and not everyone. But the majority of professional geologists regarded his theory as absurd.

Part of the reason was that he was an outsider, and part of the reason was that other geologists had their own theories that explained and predicted the same phenomena. The change in the climate of the continents reflected by the changes in the fossil record could be explained by assuming that the Earth as a whole had changed its orientation in space, that is, that the geographic North and South Poles (defined by the axis of rotation of the Earth) had moved. It would be years before internal inconsistencies and theoretical calculations were able to refute this possibility. The existence of related species far removed from each other could be explained by assuming that there were land bridges between the continents that had subsequently sunk.

But the main reason for the cool reception accorded continental drift was the lack of a plausible mechanism. The best Wegener could do was to assume that continents "plowed" their way through the oceanic crust, but that made no sense because it was known that the floor of the oceans was composed of hard rock. For several decades after its proposal, the theory of continental drift languished, both because it lacked both an explanatory mechanism and also because a large body of its predictions had alternative explanations. Not that the other theories were much more successful, but at least they did not have the disadvantage of being counterintuitive. It is easier to accept a contracting or expanding Earth than to accept that continents plow through hard rock.

Vindication by plate tectonics

Following World War II, there was a massive increase in the funding for undersea exploration as well as significant improvement in the available technology. This can be attributed to commercial and military interests. Petroleum companies wished to extend their search for offshore oil fields and navies wished to improve their ability to maneuver their own submarines and to detect enemy ones. By the 1960s, the accumulated evidence led geologist Henry Hess to propose a new model for the Earth called *plate tectonics*. According to this model, all continents originally formed a single landmass, but large cracks in the Earth's crust allowed hot lava to well up from within. The lava cooled and formed plates, which pushed apart other plates, including those upon which the continents rode. Since the continents are formed of lighter rock, eventually the ocean plates sank underneath the continents to melt again. A large upwelling coming from

the Mid-Atlantic Ridge has pushed the American continents away from the plates upon which Europe and Africa ride. Continents do not drift as Wegener supposed; rather, they are simply being pushed apart. However, Wegener's reconstruction of the movements of the continents is supported by the structure of the oceanic and the continental plates.

The evidence supporting plate tectonics is massive. All rock samples taken from the ocean floors are no older than 200–300 million years, while on the continents, rocks can be found that date from close to the origin of the Earth billions of years ago. Samples from mid-ocean ridges are relatively young, while samples taken near the deep trenches that are found close to the continents are relatively old. There is relatively little sediment near the mid-ocean ridges, while relatively deep deposits are found near the continents. The theory of plate tectonics offers a simple explanation of these data. The ocean floors consist entirely of rock that has hardened as it welled up and was then transported with its plate. Younger rock is lava that has hardened recently, while older rock has moved toward the trenches. Rocks older than about 200 million years have simply vanished into the Earth's interior as the ocean plates slide under the continental plates. There has been little time for sediment to accumulate on the younger rocks near the mid-ocean ridges, while the older rocks have been exposed to sedimentation for much longer periods.

Still, other theories can explain these observations. Sediments can be swept away by currents, or the rate of sedimentation can change with the properties of the water of the oceans. Eventually, the mass of observations became inconsistent with the other theories, while remaining consistent with plate tectonics, but before that, a new set of observations appeared that proved to be decisive in favor of plate tectonics. When new rock is formed by the hardening of molten lava, magnetic material aligns itself with the Earth's magnetic poles. For reasons that are not fully understood, the direction of the Earth's magnetic field reverses itself frequently (frequently, that is, in geological terms, every few million years). Once a rock hardens, the direction of its magnetism can no longer be changed, so such rocks form what can be called fossils of magnetism.

Paleomagnetism is the study of the ancient magnetic properties of the Earth, obtained by computations and measurements performed on samples of rocks containing magnetic material. In 1963, Frederick Vine (1939–) and Drummond Matthews (1931–1997) noted that plots of the magnetic properties of the ocean floor show an amazing property. The patterns of magnetic reversal on either side of mid-oceanic rifts are mirror images of each other. The obvious explanation is that the rocks were formed at the site of the rift and then rode opposing plates as they are pushed apart. Initially, some geologists did not accept the results from paleomagnetism as evidence for plate tectonics, because the diagrams look almost like inkblot tests used by psychologists, and it was suspected that the alleged symmetries were the product of wishful thinking. In time, careful presentation of the accumulated evidence won over almost all geologists.

Mechanism, or explain and predict

The fate of Wegener's theory of continental drift can be compared with the fate of Newton's theory of gravitation. In both cases, the theory was proposed without a mechanism, and in both cases there were flaws in the theory that had to be corrected later by plate tectonics and general relativity, respectively. Yet Alfred Wegener was laughed at, while Isaac Newton was lionized. Why were their fates so dissimilar? There are two reasons. First, gravitation is familiar and it is especially easy to observe and measure phenomena that can be explained by gravitation, such as planetary motion, pendulums, and projectiles. Second, gravitation is easily amenable to a mathematical treatment. Newton and his successors were able to give explanations and predictions that were so amazingly accurate and precise that no one seriously considered questioning the basic theory for over two hundred years. Wegener certainly marshaled evidence for continental drift, but because of the nature of the science of geology it was necessarily fragmentary and equivocal. Only after plate tectonics was proposed as a mechanism for continental drift did Wegener's theory garner support, and eventually all or almost all serious critics were won over by the preponderance of evidence in its favor.

This complete turnabout during a decade or so from the time that Hess proposed tectonics is a counterexample to Kuhn's claim that scientists do not change their minds based on new evidence, but that old theories die out only when their proponents die out. Paradoxically, Wegener's theory was not vindicated until a viable mechanism was available, but the mechanism itself, the theory of plate tectonics, has been accepted despite the fact that there is no agreement on *its* mechanism! The immense forces required to move the ocean plates almost certainly come from currents of molten rock within the Earth, but no fully satisfactory explanation exists yet. Several possibilities do exist: plates are pushed apart by the upwelling of lava in rifts; plates are pulled down by the weight of the cool, hardened rock sinking into troughs; plates are dragged along by the convection currents in the mantle; massive amounts of molten material welling up from relatively small *plumes* (100 kilometers in diameter) cause the motion of the plates.

Continental drift had to wait for a mechanism to be worked out, but plate tectonics, like the theory of gravitation, is so successful in explaining and predicting that it is accepted despite the lack of agreement on the precise mechanism that causes it.

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Historical sciences like cosmology, geology, and evolutionary biology do not fit the naive view of scientists proposing scientific theories and then carrying out experiments to confirm or falsify them. Experiments are impossible and empirical data is hard to obtain and fragmentary. However, this does not mean that these fields are not scientific, and that their theories do not need to conform to the definition of scientific theories. It does mean that predictions become retrodictions and that a long time may pass between the proposal of a theory and the availability of data to check its retrodictions. In fact, such data may never be forthcoming. For these reasons, the ability to provide a mechanism for a theory is important, not only because it makes the theory more plausible, but also because mechanisms are at a lower level of abstraction (basic physics, chemistry, or biology) and thus more firmly established. Rejecting Wegener's theory of continental drift was not unreasonable until the mechanism of plate tectonics was suggested and supported by experimental results.

Alfred Wegener: Steadfast in Science and on the Ice

If there were ever a pioneering scientist who was the total opposite of the stereotyped nerd starved for exercise and fresh air, it must have been Alfred Wegener (1880–1930). Wegener obtained his doctorate in astronomy in 1905, and a year later made a recording-breaking fifty-two-hour balloon flight. His interest shifted to meteorology and in 1913 he crossed the Greenland ice cap. (This was only two years after Roald Amundsen's [1872–1928] expedition first reached the South Pole.) In 1914, Wegener served as an infantry lieutenant in the German army and was wounded twice. The second wound was serious enough that it demanded a long period of convalescence and his release from further service. It was during this period that Wegener deepened his research into continental drift and published the first edition of *The Origin of Continents and Oceans*.

Wegener's interdisciplinary interests and research made it quite impossible for him to obtain an academic position in an age where the concept of "interdisciplinary" did not exist. It was not until 1928 that he was finally offered a position especially created for him at the University of Graz in Austria.

In 1930 he led another expedition to Greenland that was to establish a station in the middle of the ice cap to perform meteorological and geophysical observations during the winter. Two of his colleagues were already at the station, desperately in need of supplies before they were cut off by the winter weather. Despite serious delays and worsening weather, Wegener refused to abandon his friends, eventually arriving at the station with two companions, one of whom was so severely frostbitten that he had to remain. The supplies would not suffice for everyone, so the next morning, Wegener set out on the return journey with Rasmus Willumsen, a native of Greenland. Wegener apparently died of a heart attack and his body was recovered the next summer; Willumsen was never seen again.

One of the claims frequently made by opponents of science is that scientists organize themselves into closed guilds, and that outsiders with revolutionary ideas are not afforded a cordial reception. This is both true and false in the case of Wegener. It is true that since he was not a geologist (he was trained in astronomy and later made the transition to meteorology), professional geologists considered him as an interloper writing in a field that was not his. Nevertheless, Wegener was a bona fide scientist,

and he knew how to present his ideas to scientists by marshaling evidence, drawing conclusions, proposing tests, and responding to criticisms.

Like Darwin, Wegener searched for evidence wherever he could find it: geological structures on the Earth's surface, geophysical theories of the composition and movements of the interior of the Earth, studies of the distribution of flora and fauna throughout the world, and the implications of the fossil record on climate change. Also like Darwin, Wegener revised his *Origin* several times, modifying his theory in response to criticism and new evidence, and would certainly have prepared further revisions had he lived longer. Just as Darwin courageously confronted possible difficulties with the theory of evolution, Wegener was deeply conscious of the problems with his theory of continental drift, above all because of the lack of a reasonable mechanism to explain the drift. "The Newton of drift theory has not yet appeared," he wrote.[2]

Had Wegener lived to a ripe old age, he would have seen the emergence of plate tectonics as a mechanism and the beginning of the triumph of his theory.