The Behavior of the Earth

Continental and Seafloor Mobility

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Geology is a science with roots in the 16th and 17th century coming to age in the early 19th century and by the 20th century somewhat degenerate and split up in many independent and hence isolated sub disciplines pursuing rather pedestrian work. All of that would change dramatically in the middle of the last century with the so called theory of moving tectonic plates which brought about a revolution unifying all the various approaches by bringing about an awareness that they were all studying the same subject, namely the Earth.

The story begins with the German meteorologist Alfred Wegener (1880-1930) who suggested the idea of continental drift in 1912. Many of us have noticed how well the eastern coastline of South America fits with the western of Africa and our infantile instinct to see them as pieces of a jigsaw puzzle to be fitted together may lead some of us to formulate fanciful notions of drifting continents[1]. But it is one thing to merely play with an idea another to propose additional arguments to buttress it, but that was what Wegener did. He noted that the fit became even more convincing when the underling geological formations were laid bare, showing how one formation was cut off by the South Atlantic only to be continued on the other side. Then the widely separated portions showed similar faunas in past times a fact for which awkward explanations as land bridges had been proposed by the paleontologists, but would not drift constitute a far more natural one? Then there was the more crucial one, what huge forces could make the continents move? Wegener saw the continents as lighter material floating on the denser mantel, not unlike icebergs to a large extent submerged. The problem was that the mantel was solid and not a liquid the physicists of the time not having a good notion of viscosity, that a solid can act as a liquid on large time scales[2]. Although Wegener attracted some enthusiastic followers initially, especially among the geophysicists who were more liable than other geologists to appreciate the elegance of the theory and its use as a synthesizer, support for him waned over the years, partly because the strong opposition of figures of authority such as Harold Jeffreys (1891-1989) a noted mathematical geophysicist and astronomer who pounced on the inadequacy of the explanation of the mechanism for moving (and the fact that Wegener was a meteorologist and not a professional geologist certainly did not help matters). The author cannot help but heap scorn on Jeffreys and his mathematical

[1] The human propensity to detect patterns where there are indeed none has often been commented upon.

[2] The classical example is glass. When left to itself for centuries such as in a medieval church, the panes will become thicker at the bottom, as a result of the glass slowly, ever so slowly under the influence of gravity slides to the bottom.

approach, referring to the regrettable tradition of the Greeks based on rigorous deductive thinking with cause and effect at the centerpiece. Of physicists opposed to continental drift he notes that they were more rigid than rigorous. As a mathematician I concede that the author has a point to which I will return. The geological community ignored Wegener and pursued their pedestrian interests unabated. As an example of such a deadening project was to construct more and more detailed geological maps, each student being given a small patch, for no better reason than for its own sake, the professors unable to think of anything more exciting to do. And when the students grew up their early work had so stunted their imaginations that they could think of nothing better to do than more of the same. This of course conforms fairly closely with the publics caricature of science as a systematic endeavor of observation using objective methods and painstaking procedures. The breakthrough would come through oceanography mapping the seaboard starting after the war. It was discovered that the seafloor spread, starting at a ridge and then like a conveyor belt being subducted in a trench, the whole process taking some 200 million years, thus in particular the seafloor was never older than that, while on the continents rocks had been found several billion years old, close to what later would turn out to be the age of the planet itself. Continents were not destroyed, subducted into the mantle, but by virtue of their lesser density floating above. Now the interesting thing is how this was discovered?

To understand this we need to remind the reader of the Earth being a magnet. The source of this magnetism is the rotation of the iron core along with that of the earth itself. This makes for the poles of the magnet to roughly correspond to the poles of the Earth although one should be a bit careful and not be too dogmatic. Now when minerals conducive to magnetization are formed (meaning being cooled down) the magnetic orientation will be a document of the prevailing one. By angles one may gauge the latitude and one noticed that in certain locations investigated, the orientations changed with time, as if the places had moved visavi the poles. In particular while determining the changing locations of the ancient poles based on material from Europe and North America, one got two curves that only coincided in fairly recent time, suggesting strongly that a gap appeared between the two continents. In short to get the two curves to coincide one of the continents, say North America had to be rotated closing the North Atlantic gap when going back in time. One may naively think that this would have been conclusive evidence but nevertheless it met with strong opposition in the 50's. The problem is that the principle outlined may be very simple in theory but quite something else in practice, the actual measurements were difficult and subtle and the possibility of grave error could not be discounted. If you are committed to a point of view you will normally distrust putative evidence to the contrary. We do discount stories of people flying by fluxing their arms on principle no matter how insistently and passionately those are conveyed. Now what clinched matters in the 60's was the zebra like patterns on the seafloor. It had been discovered that the orientation of the earths magnetic fields at times suddenly changes direction, or at least the magnetic record left in basalt rocks indicated that. Was that just an artifact from the way the record was made or did it really correspond to a real global change? It was noticed that the changes were consistent with the age of the rocks, and hence the conclusion was drawn that it did indeed correspond to something more

solid than local accidents. The magnetic properties of the seafloor had in previous decades been mapped, mostly because it was possible to do so, not because at the time it served any useful purpose. When normal directions were encoded in black and reverse in white a pattern symmetrical around the ridges was disclosed. A black stripe along the ridge, bordered by white straps on either side which in their turn were bordered by black stripes, and so alternating. Of course only exceptionally was the picture that clear, there had been fault lines and distortions scrambling it but the underlying principle was true. As one had done a calibration earlier between age and orientation it was only to read it off and actually compute the pace of the spread, which turned out to vary between a few centimeters a year to over a decimeter. A million centimeters make up ten kilometers which gives the right order of magnitude between oceanic dimensions several hundred times that length and time intervals of up to 200 million years. The spreading in the Atlantic was slow, while the spreading in the Pacific was much faster. Now when it came to the subduction zones many of them close to continents, it was noticed that earth quakes of deep origin (700 km or so) exclusively occurred along them, and it made sense, the oceanic crust along with its sediments, the stratified layers of the debris produced by the weatherings of the continents, plunging down to its destructions being mechanically broken up, thus connecting earthquakes with other dramatic geological processes on a scale hitherto unimagined.

From now on things started to move. A plate could be seen as roughly triangular, when it moved rigidly over the sphere its movement could be given by its axis of rotation along with its angular velocity. This would produce three types of faults. At the rear plates would separate and new material emerge from the mantle, being suitably modified in the process, and corresponding to ranges; at the front there would be collision and superfluous material would be submerged referred to as trenches; and then along the remaining side, there would be movement in a small circle, where two plates would simply rub against each other. Apart from those borders of the plate there would be no tectonic activity at all. Now the small circles traced out by the fault lines would allow the location of the corresponding axis to be identified. This lead to new research projects and a number of plates were identified along there movements allowing not only extrapolation back in time but also forward.

And then what was responsible for those movements? Once you determine that movements do occur you cannot deny the fact because you cannot think of a suitable force, but such a force simply has to exist after all the plates (like the Earth) are moving. The solution was convections in the mantle behaving over time as a fluid. The convections were caused mainly by heating by the hot interior and some possible due to radioactive decay, and were strong enough to move the plates. Thus as long as there is an internal heat source the planet will be geologically active and in fact all the geological activity on the surface of he earth, its crust, which affects us most closely, is due to the dance of the plates. Thus bringing about a synthesis of all geological disciplines and making for putting interesting questions.

As an example. Wegener thought, and what else could he think, that it all started with one giant continent breaking up over time in smaller and smaller constituents. It is more likely to think of a cyclical dance during which plates as well collide and coalesce as

break apart, after all the Indian plate has in addition to separating itself from Australia and Africa also attached itself to the large Eurasian, forming the Himalayas in the process. Because this is another consequence of plate tectonics namely an explanation of orogenesis the forming of mountains[3]. Another question is whether the continents are getting larger or larger or if material is only being recycled and redistributed. New continental crust is being formed at trenches, but sedimented debris is dumped into the mantel. The idea proposed is that initially the continents grew rapidly in volume than slowed down and leveled off at the present when there is a steady state.

Now one can continue and discuss in more detail other aspects of the dynamics of the earth surface but this should suffice. The book is also statement about science, how it is done and hence its sociology, with glimpses of conferences, publications and career building, because scientists are but human and driven not only by curiosity but also ambition and one-up-man-ship. As a mathematician one is struck by the contrast between certain aspects of a science such as geology and mathematics. In mathematics we do not have the kind of controversies you have in geology. A proof can be written down for everyone to check. In practice not everyone can check but those who can usually come to a quick consensus. There is a solid body of accumulating knowledge. Reasoning can indeed be laid out logically as cause and effect. Geology is basically a historical science, abetted by various techniques, which seem rather uncontroversial, such as isotopic frequency determination and radioactive decay rates (all basically applied mathematics). In geology you want to find out what happened, There is a difference between the questions. Did the plate move? and Can the plate move? As to the latter you may have opinions but you cannot use it as an axiom, meaning that you cannot claim that a plate cannot move and hence has not moved, but you can show that a plate has moved, and hence that it can move. There is a different ordering in empirical sciences as opposed to the deductive. This is illustrated by the classical syllogism. All men are mortal. Socrates is a man. Hence Socrates is mortal. The first premise is given by God, the second observed by man. The conclusion follows in an ideal world. In the real world all we can do is to note that in addition to Socrates being a man he is also dead. This does not give the conclusion that All men are mortal although it gives evidence for it being the case. More examples can be adduced, but a deductive proof can never be supplied, only evidence. As Collingwood noted, induction does not compel, it merely allows. Everything is in principle provisional, but long established truth in science needs quite a shock to shake our beliefs. Generally this does not happen. When we want to formulate a theory, or picture a historical process, we make guesses, informed guesses to comply with what we see and touch. But there are many different theories that explain the same phenomenon, just as the traces left by the past can be interpreted in many different ways. Hence controversies. More evidence, more observation, more experiment will be needed to decide the fate between different theories, In the end one of them will win out. Not definitely but being by far the best we have. The opposition against a new idea is not such a preposterous thing as it may be thought by the benefit of hindsight. Why did not everybody at once jump on Wegeners bandwagon, he was obviously right? There is value in conservatism and inertia, one cannot change ones mind every now and then.

[3] As a child in the 50's I was told or taught that mountains formed just the way the skin of a heated apple wrinkled as it cooled off

New ideas have to prove their worth against all kinds of counterarguments, running the gauntlet of tests and attempts at falsifications. Who should do that? Not the proponents, you cannot expect that, although they have submitted their theories to severe tests in order not to make fool of themselves, they have a vested sentimental interest. After all they are but human. Hence they cannot be expected to think of all possible objections, that task should be left to their adversaries. This is pure popperism. In the case of Wegener the geological community was not ready for it. Thirty years later they were. New techniques had been developed, lots of empirical observations had been made, as noted for no good reason whatsoever besides the fact that it could be done, that came in good stead. And as Kuhn would have pointed out, focused on the sociology as he was, the old guard had died (but Jeffreys lived to a very old age).

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