Exploring the Earth from Mars

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When we teach plate tectonics to young adults with little or no training in the physical sciences, one tells the "story," but does not have enough time to cover the important details. The story is really quite incredible: rigid crustal slabs sliding thousands of kilometers (miles) across the mantle of the Earth at rates that are too slow to be observed without the aid of sophisticated instruments; seafloor spreading ridges with submarine hot springs buried by 2500 meters (1.5 miles) of ocean; deep ocean trenches where the oceanic plates of the earth literally fall into the mantle; neat orthogonal ridge/transform patterns, and a magnetic field that reverses at just the right rate to be recorded by cooling lavas at the spreading ridges (Figure 1)[1]. The only part of the system that can be seen with the naked eye are the continents, which in fact don't participate in plate recycling and usually have a long and messy geological history. While plate tectonics describes the motions of the Earth's crust, we go further to claim that it is the optimal mechanism for the Earth to shed excess radiogenic heat produced in the mantle. Diffusion of heat across a thick lithosphere is less efficient than allowing the oceanic lithosphere to radiate heat as it glides across the slippery asthenosphere and then cools the mantle during subduction.

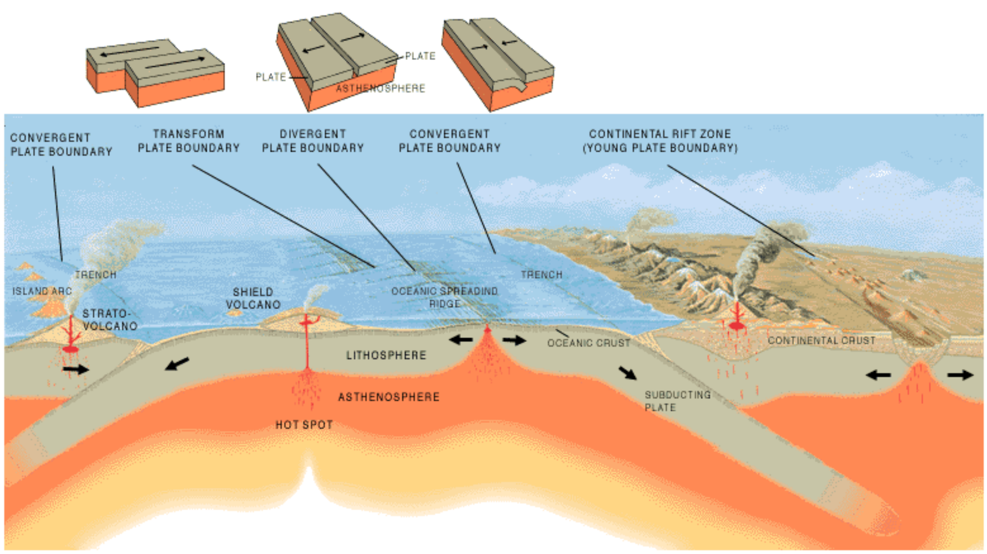

Figure 1. Artists cross section illustrating the main types of plate boundaries; divergent plate boundary, transform plate boundary, convergent plate boundary[35].

I encourage my students not to believe any of this without doing a lot more reading. There are always a few religious students who believe literally in the Bible; they question all of these ideas, especially those related to the age of the Earth. As a professor, I cannot claim that the story is true just because it is in all of the textbooks. Indeed, how do I know the story is true myself? What are the essential and totally objective confirmations of plate tectonics and how do we convey these to our students? Does the Earth really behave as described by the theory or is the theory just a qualitative description of the Earth used for instructional purposes?

One of the major difficulties in confirming the theory is that most of the evidence for plate tectonics is covered by 4000 meters (2.5 miles) of ocean water (Figure 2)[2]. The parts of the continents above sea level contain a long and rich history of multiple episodes of collision, drifting, and rifting. Still, one needs a trained geologist who believes in plate tectonic theory to properly interpret the continental geologic record. The continents offer our only means to extend the tectonics of the Earth more than about 200 million years into the past, because most of the old seafloor has been subducted. However, data from the oceans provide the primary confirmation of the theory.

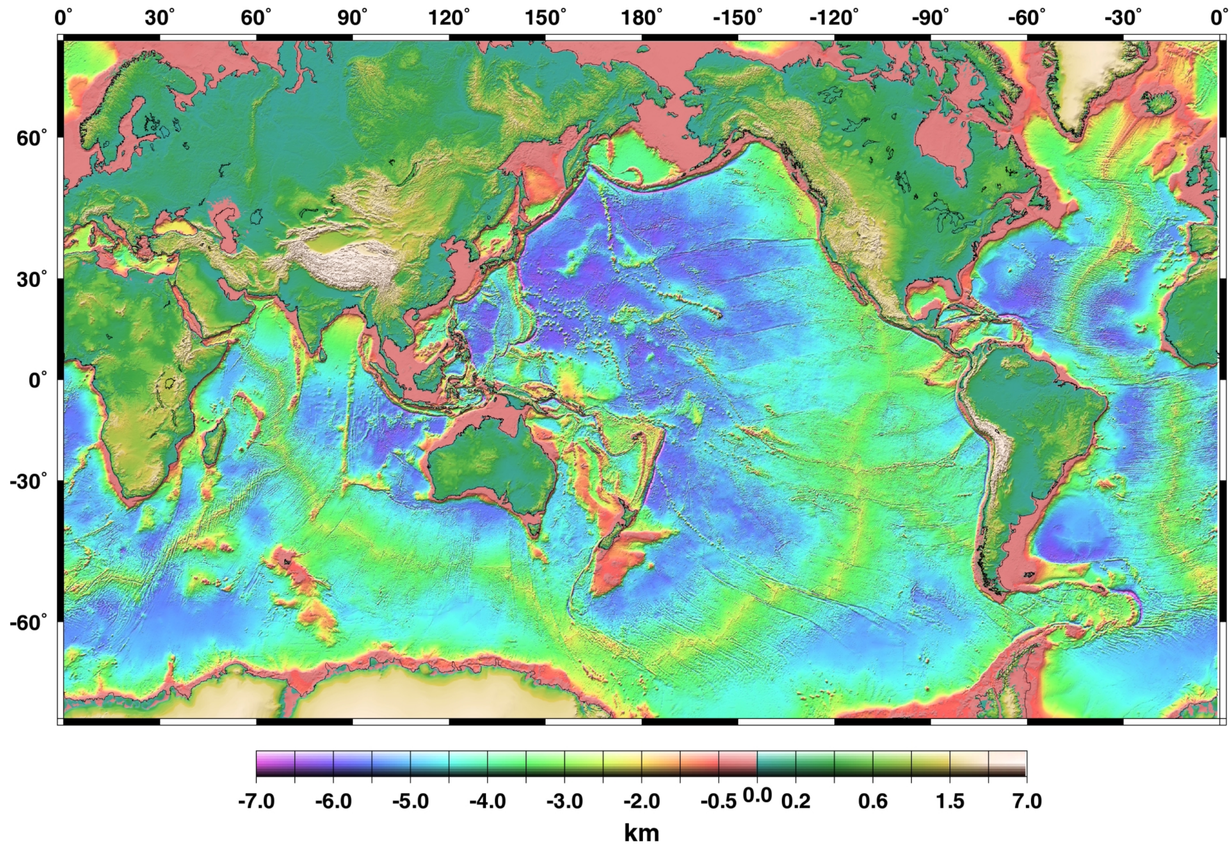

Figure 2. Topography of the earth reveals the seafloor spreading ridge system at a depth of 2500 meters (yellow). Deep ocean trenches (purple) are the sites where the cool and dense plates sink into the Earth.

Of course many textbooks, as well as this series of essays, are packed with strong evidence for the theory. Today plate tectonics is nearly universally accepted by earth scientists. However, there is always a danger that a prevailing theory will taint observations in a way to further confirm the theory. Take for the example the construction of bathymetric (ocean floor topography) charts of the southern ocean where the density of ship soundings is sparse. A reasonable mapmaker would take the available data and the known locations of the ridges and fracture zones nearby to fill in the blanks[3]. If a ship crossed a fracture zone in two locations separated by a great distance, then one could extrapolate the fracture zone along a trend predicted by plate tectonic theory. This approach of filling unknown areas using a guess based on the current understanding of the Earth, is common to many aspects of geology and geologists generally mark these areas using dashed lines. The danger of this model-based extrapolation is that it can lead to a clean and simple picture of reality. Similarly, to promote learning, most textbooks[4,5] provide an antiseptic view of plate tectonics by selecting data examples that re-enforce the theory. Is the Earth really that simple? When I was a student of plate tectonics in the late 1970's, I thought the whole theory, although basically correct, was oversimplified. Modern tools have supplied a wealth of new information about the Earth and to my surprise; the plates of the Earth behave exactly as described in the early textbooks[6]. For example, they are almost perfectly rigid, the transform faults follow the predictions of Euler's theorem, and the subducted plates penetrate deep into the mantle. Indeed much of the original evidence for the theory was collected in areas of tectonic complexity[7,8], and if one examines the bulk of the ocean basins, an amazingly simple picture emerges[9,10,11].

In this essay, I'll describe a few of the important confirmations of plate tectonic theory provided by satellites and ships; these tools were largely developed to support the cold war effort[12]. Many of these tools are labeled geodetic since they are used to make precise measurements of the size and shape of the earth as well as measurements of the spatial variations in the pull of gravity. The tools of satellite geodesy are needed for all aspects of global warfare[13]; precise satellite tracking and gravity field development are needed for precision satellite surveillance as well as for targeting ballistic missiles[14]; the Global Positioning System is used in all aspects of modern warfare; radar altimetry is used for aiming submarine-launched ballistic missiles[15] as well as for inertial navigation when submerged.

The global seismic networks were developed, in part, to monitor underground nuclear tests. Marine magnetometers were developed, in part, for detection of submarines. Multibeam seafloor mapping systems were primarily developed for surveying critical and operational areas of the northern oceans[16].

Exploring the Earth from Mars

I'll begin by claiming that the reason plate tectonics took so long to become an accepted theory is because the Earth was explored backwards. Detailed geologic structures on the continents were investigated before the entire planet was properly observed making it difficult to develop a planetary-scale model. The most efficient way to explore a planet is to start with planetary-scale observations and then design small-scale observational programs to test grand hypotheses. Indeed, this is the current NASA strategy for exploring Mars. Let's reverse the exploration scenario for the Earth.

To illustrate this point, let's come up with an Earth exploration plan that would lead to the development and confirmation of plate tectonic theory. Suppose that humans evolved on Mars rather than on the Earth. The leaders of our great nation decided that Earth may contain life or at least may be a good place to live. Moreover, telescope observations of the land areas of the Earth reveal large-scale patterns suggestive of some type of global stress field. Assume Earth actually has no life so it is easy to see the rocks and that plate tectonics does not require life. The NASA administrator gathers her best engineers and scientists to develop an exploration plan. What is the best observation strategy and at what point will the hypothesis of plate tectonics become strong enough to pursue more definitive experiments that will lead to confirmation? The exploration plan is designed as a series of hypothetical missions, and I'll highlight the ultimate contribution of each type of observation toward the understanding and confirmation of plate tectonic theory. At the end of the essay, I'll rank the observations in order of importance. Of course, my field of research will come out on top.

Mission 1 is a polar orbiting satellite that will take optical- and near-infrared- photographs of Earth at 100-meter (about 300 feet) resolution. A magnetometer is used to measure the external magnetic field and Doppler tracking of the spacecraft provides a global measure of the gravity field. A radio receiver monitors frequency of the satellite telemetry and compares this with the known carrier frequency on the satellite; a Doppler shift provides an estimate of the velocity of the spacecraft relative to the receiver. Thousands of Doppler observations can be used to establish the precise orbit of the spacecraft, and the gravity field perturbations of the planet. The satellite optical imagery reveals the mountains, river channels, and ice-covered areas in great detail. The variety of structures and morphology is overwhelming, and the scientists retire to their labs to try to digest the enormous supply of data. This will take at least 5 years and in the end, the optical data are not useful for discovering plate tectonics. However, they do reveal something important. The arcuate island chains, first observed through the Mars-based telescopes, are large volcanic structures with central caldera. Many show evidence for young lava flows and a few are actively spewing lava today. The Earth is volcanically active; in fact, much more active than Mars. A second major discovery is a prominent magnetic field with north and south poles approximately aligned with the spin axis of Earth. A third major discovery comes from the tracking of the spacecraft orbit that reveals that the core of the earth is quite dense and probably made of iron just like Mars[17]. None of these measurements are unusual for a terrestrial planet (Mercury, Venus, Earth, the Moon, and Mars) so they don't provide any hint that the Earth has global tectonics.

Scientists are frustrated since the ocean covers two thirds of the Earth's surface. A group of scientists and engineers hold a conference to develop an approach to explore the ocean. How deep is it? What does the bottom look like? Why do the coastlines of some of the continents seem to fit together? Their recommended plan will be implemented in the third mission since the second mission is ready to launch.

Mission 2 is focused on measurements land topography, ice topography, and ocean topography using a radar altimeter. There is also instrumentation for remotely examining the chemistry of the rocks, as well as a passive microwave radiometer to probe the temperatures of the atmosphere and ocean surface. The radar altimeter reveals linear topographic features on the land, which correlate with the optical imagery from Mission 1. More important, the radar data reveal broad variations in the height of the ocean surface above and below an ideal ellipsoidal shape. What causes these bumps and dips in the ocean surface? To a first approximation, the Earth has the shape of an ellipse where the equatorial radius is about 20 kilometers (12 miles) greater than the polar radius. Over time scales of millions of years, the Earth can be thought of as a rotating fluid ball where the equatorial bulge reflects centrifugal force due to rotation. Consider a supertanker full of oil steaming from the north pole to the equator. During its voyage it will move some 20 kilometers (12 miles) further from the center of the Earth. However, since water seeks its own level, the supertanker does not have to do any work to go uphill. The actual ocean surface (the geoid) does not follow the ellipsoidal shape exactly and can bulge outward on inward by up to 100 meters (300 feet). For example, the lowest point in the geoid lies just south of India while the highest point is just north of Australia. These global-scale variations in geoid height reflect the variations in mass inside the Earth and are expected. Although this radar has only a 10 centimeter (4 inch) precision, it shows some prominent lows offshore of the arcuate island chains. These are dominant features of the geoid but what are they? Based on these initial findings of ocean height, an improved radar altimeter is planned for the third mission.

Mission 3 carries a second radar altimeter, an improved camera, and magnetometer. After about 1.5 years of collecting altimeter profiles, it becomes clear that variations in the height of the ocean surface reflect the features on the bottom of the ocean. Researchers[18] present some color-coded maps at scientific meetings that provide direct evidence for the coastline match across the Atlantic Ocean (Figure 3). In the equatorial Atlantic, linear anomalies extend across the ocean basin and seem to connect points on Africa and South America. Moreover, the center of the ocean contains gravity ridges and troughs that are exactly perpendicular to the fracture zones. This planet has some clear and organized surface structures and the scientists are now working day and night to digest data and formulate hypotheses. Many puzzles remain until instruments are sent to the surface of the planet.

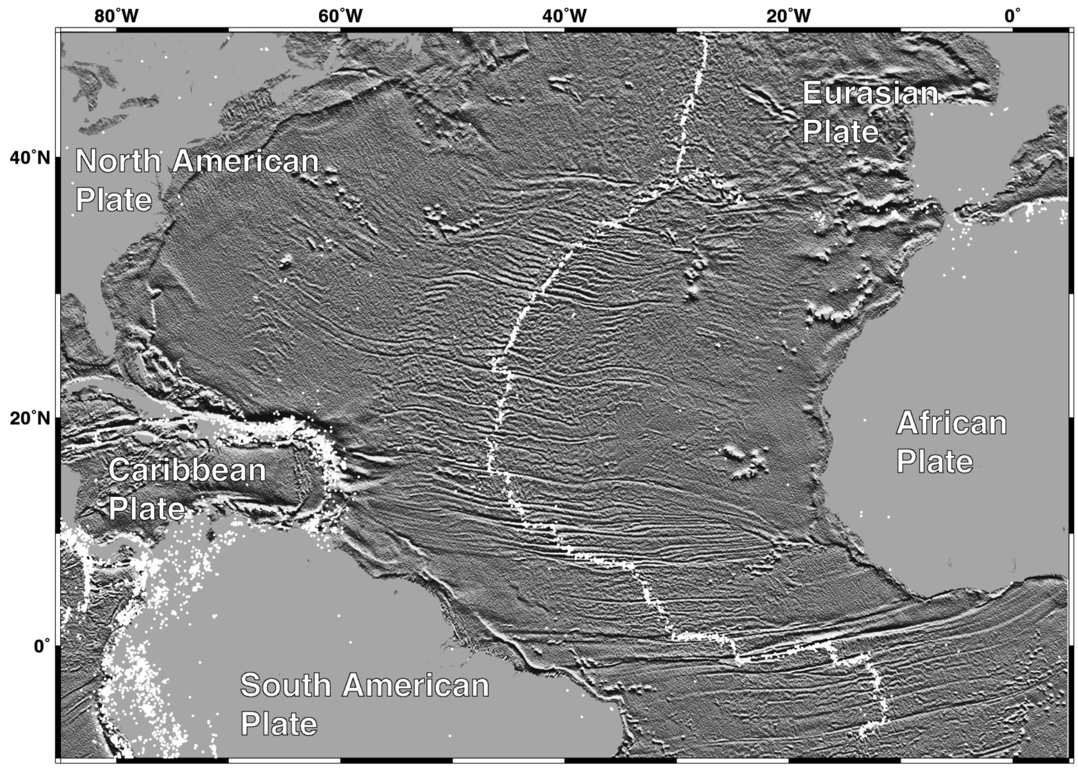

Figure 3. Topography of the ocean surface derived from Geosat (US Navy) and ERS-1 (European Space Agency) satellite altimeter measurements[36]. Fracture zone traces clearly record the opening of the Atlantic ocean basin. Earthquakes (white dots) mark the plate boundaries.

Mission 4 carries seismometers that are deployed by parachute to the surface of the continents at 6 locations. Of course, a similar but much larger set of seismometers was used to locate shallow crustal quakes on Mars. Moreover, the travel times and shapes of the recorded waves was used to infer the internal structure of Mars in great detail. The mission plan is to monitor the Earth in the same fashion. There were two important discoveries derived from the patterns of earthquake locations. First, the earthquakes are not randomly distributed over the planet but are concentrated along discrete zones at the ridges in the center of the oceans and also beneath the island arcs (Figure 4a)[19,20].   The biggest surprise is that some of the earthquakes occur up to 650 kilometers (400 miles) beneath the surface of the Earth (Figure 4b)[21,22]. This was completely unexpected. Earthquakes should occur only in brittle material, and since the Earth is larger than Mars, it was expected that its interior should be hotter, and grow ductile at a shallower depth - about 50 kilometers or 33 miles. The reason that earthquakes can occur at depths greater than this is still not completely understood[23]. These earthquakes occur in the transition zone (325-690 kilometers or 200-430 miles deep) of rapidly increasing seismic velocity that also corresponds to phase transitions in the mantle. In particular, the olivine to spinel mineral phase transformation is associated with a significant volume decrease. As the relatively cold slab falls through this phase transition depth, the phase transformation is delayed in a triangular wedge between the still cold interior of the slab and the outer edges of the slab. This difference in contraction results in a large stress. Why this stress is relieved in sudden events – earthquakes - is not well understood. A third major observation is that shallow earthquakes occur precisely on the mid-Atlantic ridge and virtually no earthquakes occur off the ridge (Figure 2).

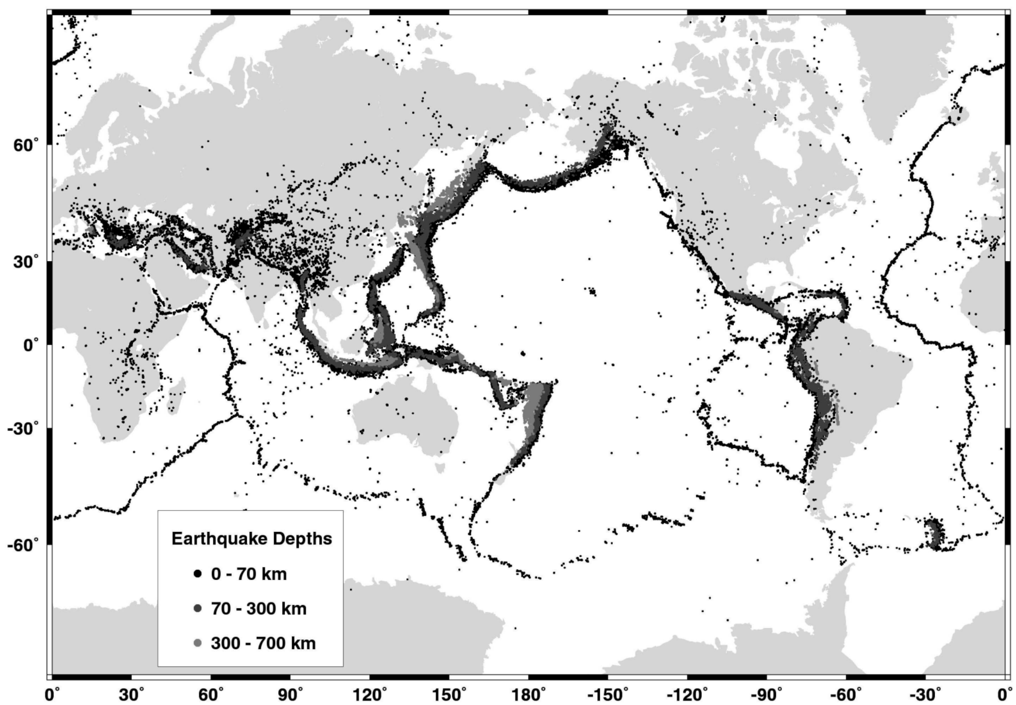

Figure 4. (a) Locations of shallow (black < 70 km deep), intermediate (medium gray between 70 and 300 km deep) and deep (light gray > 300 km deep)[20]. Shallow earthquakes occur on the seafloor spreading.

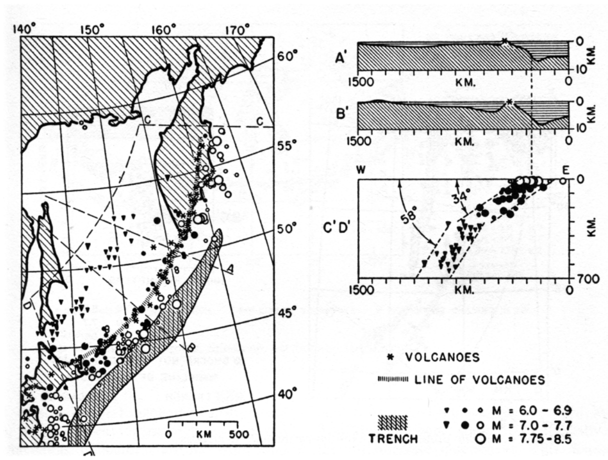

Figure 4. (b) Depth section of earthquakes at the Kurile Trench provides an image of the subducting slab that confirms deep subduction of the lithosphere at ocean trenches [figure from *Benioff*, 1954]

At this point, all of the elements of plate tectonics are apparent: the altimeter data reveal the opening of the Atlantic ocean as well as the deep ocean trenches. The seismic data reveal the active plate boundaries, and the deep earthquakes prove that cold slabs plunge into the mantle. The evidence that is still missing is the rate of the tectonic activity and direct measurements of the moving plates.

Mission 5 deploys a robot survey ship to carry out two important experiments. Scientists select a survey site at the Pacific-Antarctic ridge just north of the Eltanin Fracture Zone in the South Pacific Ocean[24], because this is the simplest structure apparent in the radar altimeter measurements. The basic shipboard instruments are a sonar to measure depth, devices to sample the properties and chemistry of the ocean, and a magnetometer to measure small variations in the magnetic field. The mapping of the magnetic field on the previous missions at satellite altitude did not reveal any unusual crustal anomalies, so the role of the shipboard magnetometer is unclear. Note that the lack of a crustal signal at the altitude of an orbiting satellite is purely a geometric smoothing effect that can only be overcome by moving closer to the surface of the earth. Two shipboard experiments are proposed. Experment 1 is a survey of the spreading ridge axis as identified in both the prior altimeter measurements and the earthquake locations. Scientists find a narrow axial ridge 250 to 500 meters (750 – 1500 feet) tall that is superimposed on a broad rise where the average depth is 2500 meters[25] (1.5 miles). The second experiment is a trackline perpendicular to the ridge axis. The sonar readings show a symmetric deepening of the ridge axis as a function of distance from the axial high (Figure 2). The survey is extended far on either side of the ridge to examine this symmetric depth observation. Today, we understand this observation as the signature of the thermal contraction of the oceanic plates as they slide away from the spreading sidges[26]. This cooling of the oceanic plate (the lithosphere) is the primary mechanism for the Earth to shed its excess radiogenic heat so the symmetric deepening of the seafloor as it ages is the primary geodynamic and tectonic signature of the Earth.

The most surprising result comes from the magnetometer that shows a square-wave pattern of magnetic highs and lows. A more complete survey reveals that these magnetic anomalies form long stripes parallel to the ridge axis, but most important, the stripes have spacings that are symmetric on either side of the ridge axis. As will be discussed, this observation of symmetric marine magnetic anomalies not only provides direct evidence for symmetric seafloor spreading, but also proves that the global magnetic field of the Earth reverses polarity on a time scale that is perfectly recorded in the cooling lava at the seafloor spreading ridges.

Some Relevant Aspects of the Real Story

From this point on, it is impossible to predict when the grand hypothesis of plate tectonics will be proposed. Moreover, the proposition must be forceful enough to prompt further confirmation. At this point, I'll abandon the hypothetical exploration of the Earth. There are three issues worth further discussion. First, for the record, I'll provide a brief history of satellite altimetry and the events leading to the declassification of Geosat radar altimeter measurements. Then I'll discuss the two remaining important observations of plate tectonics - paleomagnetic intensity variations in sequences of lava flows, and direct measurement of present-day plate motion.

Notes on the History of Satellite Altimetry

The original altimeters (as in those aboard NASA’s SkyLab and Defense Mapping Agency’s GEOS-3) were launched to measure global-scale geoid height variations but what they discovered were much smaller-scale geoid height variations (10- 50 kilometer or 6-33 mile horizontal scale and 2-10 centimeter or 1-4 inch vertical scale). The smaller-scale bumps and dips in the ocean surface reflect the gravitational attractions of structures on the ocean floor (spreading ridges, fracture zones, trenches, and volcanoes). When the GEOS-3 results were first published[27], it was obvious that radar altimetry was the optimal tool for global mapping of the seafloor. Ship soundings were too sparse to provide a global perspective. What was needed was an improved altimeter to achieve a 2-centimeter (one inch) range precision as well as to achieve dense track coverage. The Seasat altimeter launched in 1978 achieved the range precision, but did not achieve dense track coverage because it failed after only three months in orbit. Using data from the Seasat altimeter (NASA Jet Propulsion Laboratory)[28], William Haxby and others at Lamont-Doherty Geological Observatory compiled the first completely objective map of the ocean basins in 1983. Unlike other maps of the ocean where scientists decide where to collect data, how to eliminate bad data, and how to fill in the blank areas, Haxby's map was based on a uniform coverage of the oceans and the data were all treated equally by a single computer algorithm. Most important, another scientists using the same data and the same algorithm could obtain exactly the same answer. This first map had only moderate detail due to the short 3-month lifetime of the Seasat altimeter. Nevertheless, this map, plus similar maps prepared in our lab (National Geodetic Survey), convinced me that plate tectonics was a fair and accurate description of planet Earth. In addition to confirming plate tectonic theory, these maps revealed many important geological structures and also guided seagoing expeditions for the next 15 years.

It took until July of 1995 before better altimeter coverage became available from the ERS-1 satellite altimeter (European Space Agency) and the Geosat altimeter. The Geosat satellite built by the Johns Hopkins University's Applied Physics Laboratory (JHUAPL) and launched in 1985 by the US Navy[29], collected high-precision sea surface height measurements in a non-repeat orbit for 1.5 years and continued in a repeating, unclassified mode for another 3 years. These data were processed and archived in two locations, the Naval Oceanographic Office (NOO), Stennis Space Center, Mississippi and the JHUAPL, Maryland. The Navy used the Geosat-derived gravity field information to improve the accuracy of sea-launched ballistic missiles for the Trident Submarine Program[15]. The research activities in the classified NOO lab are not yet declassified. The main activity at the JHUAPL and the National Geodetic Survey (NGS) (including Bruce Douglas, Robert Cheney, Dave Porter, Dave McAdoo, Laury Miller, Russel Agreen and David Sandwell) was to extract unclassified altimeter products from the Geosat data using a facility at JHUAPL. David McAdoo (NGS) and I (NGS, now at Scripps Institution of Oceanography - SIO) did not have access to the classified data - only the unclassified products. The first unclassified oceanographic data were selected to follow the old Seasat tracklines so that no significant new gravity information would be revealed. Understanding the extreme scientific value of these Geosat data, Bruce Douglas, Karen Marks, Dave McAdoo (all of NGS), Bernard Minster (SIO), Walter H. F. Smith (SIO and NGS), many others and I sent several requests to The Oceanographer of the Navy asking for release of subsets of data. The declassification of Geosat data came in three installments. First in 1987, the Navy agreed to not classify all Geosat altimeter data in Antarctic waters south of 60˚S latitude. Second, at the request of the National Research Council Committee on Geodesy, (Minster, McAdoo, Sandwell and others)[30], Rear Admiral Chesbrough, The Oceanographer of the Navy, agreed to declassify all data south of 30˚S latitude on June 10, 1992[31]. Finally, at the request of the Medea Committee[16] as well as a request from the American Geophysical Union, Admiral Boorda, The Chief of Naval Operations, authorized declassification of all Geosat data on July 19, 1995. The most relevant aspect of this final declassification was that the ERS-1 altimeter had just completed a 1-year altimeter mapping mission that basically duplicated the still classified Geosat data, so there was no longer a reason to keep the Geosat data classified.

On a related matter, the Medea Committee[16] assessed the scientific utility of all types of geophysical data collected by the US Navy. The report states:

"During the past 30 years, the Navy's ocean surveys have systematically collected bathymetry, gravity, magnetics, and salinity/temperature data on a global basis. In particular these surveys encompass almost all of the Northern Hemisphere. All together more than 100 ship-years of data acquisitions have been devoted to this effort, making this the most comprehensive surveying activity ever undertaken. **It is highly unlikely that such an effort will be repeated, and it is certain that civilian environmental scientific resources could not aspire to an ocean survey program of this magnitude during the next 20 years.** "

While the Geosat altimeter data and the arctic sea ice thickness data were declassified in 1995, the remaining 100-ship years of bathymetry, gravity, and magnetics data remain classified and discussions of possible declassification have not continued. The main barrier to declassifying the ship data is that the uneven track coverage could reveal zones of interest to the Navy. In contrast the altimeter mapping of the ocean is uniform and unbiased.

Magnetic Reversals and Direct Measurement of Plate Motion

According to the textbooks and historical accounts, magnetic reversals at sea, coupled with dated magnetic polarities of lava flows on the continents worldwide, provided the turning point in the real story of plate tectonic acceptance. However, in the scenario just outlined, the magnetic evidence is not absolutely necessary. Indeed, the ability to observe magnetic reversals from a magnetometer towed behind a ship relies on some rather incredible coincidences related to reversal rate, spreading rate, ocean depth, and Earth temperatures.

In the case of marine magnetic anomalies, 4 scales must match. First, the temperature at which cooling lava first records the direction of the global magnetic field must lie between the hot temperature of the mantle and the cold temperature of the seafloor. This may not seem that remarkable until one considers that the surface temperature of our sister planet Venus is too high for this to occur. Most of this magnetic field is recorded in the upper 2 kilometers (1.3 miles) of the oceanic crust. If the thickness of this layer was too great, then as the plate cools while it moves off the spreading ridge axis, the positive and negative reversals would be juxtaposed in dipping layers; this superposition would smear the pattern observed by a ship. On Earth, the temperatures are just right for creating a thin magnetized layer. The second scale is related to ocean depth. Consider recording the magnetic field along a track perpendicular to the ridge axis. If the magnetometer is towed close to the bottom of the ocean - just above the magnetized layer - then the square-wave reversal pattern will be sharp and clear. However, most magnetometer measurements are made at the surface of the ocean which is on average 4 kilometers (2.5 miles) above the magnetized layer. At this distance, the reversal pattern becomes attenuated and smooth. The result is that anomalies having a spacing of about 2π times the ocean depth will have the strongest signal. As just noted, the crustal anomalies are invisible at the altitude of an orbiting satellite because of the geometric smoothing effect with distance. The third and fourth scales that must match are the reversal rate and the seafloor-spreading rate. Half-spreading rates on the Earth vary from 10 to 80 kilometers (6-50 mile) per million years. This suggests that for the magnetic anomalies to be most visible on the ocean surface, the reversal rate should be between 2.5 and 0.3 million years. It is astonishing that this is the typical reversal rate observed in sequences of lava flows on land. While most ocean basins display clear reversal patterns, there was a period between 85 and 120 million years ago when the magnetic field polarity of the Earth remained positive so the ocean surface anomaly is too far from the reversal boundaries to provide timing information. This period of time is called the Cretaceous Quiet Zone and it introduces a large uncertainty in the Cretaceous reconstruction of the plate motions. This lucky convergence of length and time scales makes it very unlikely that magnetic anomalies, due to crustal spreading, will ever be observed on the other planet. This is the main reason that I do not believe the recent publication that interprets the Martian field as ancient spreading anomalies[32] - one cannot be this lucky twice.

The final nail in the coffin related to the confirmation of plate tectonics is the direct measurements of plate motion using space-geodetic methods. Because atmospheric refraction reduces the speed of light in unpredictable ways and because the plate motions need to be measured between points on opposite sides of the Earth, one must use space objects as stable reference points. The typical rate of separation between continents due to plate tectonics is tiny (only 10 centimeter or 4 inch per decade), so a variety of methods need to be deployed to double check the results[33]. Very Long Baseline Interferometry (VLBI) uses coordinated radio-telescope observations to record microwave emissions from quasi-stellar objects (quasar). Precisely timed tape recordings from two or more VLBI antennas are brought together and correlated in a computer to determine the time delay of signal from the quasar. Because the VLBI antennas are moving on separate plates, this time delay will change over a period of many years. For example, several years of VLBI measurements between Haystack, Massachusetts and Onsala, Sweeden recorded a plate motion of 1.7 centimeters per year (0.7 inch per year) which agrees remarkably well with the rate determined from marine magnetic anomalies[34]. Similarly, spacecraft can be simultaneously tracked by a network of lasers (Satellite Laser Ranging - SLR) or a network of antennas (Global Positioning System - GPS) to establish the relative motions of the plates. The outcome of two decades of these space geodetic measurements is, that to first order, the present-day plate motions agree with a 2-million year average. There are small differences related to deformation of the interiors of the continental plates, but taken as a whole, these measurements confirm plate tectonic theory.

In conclusion, the actual path to discovery and confirmation of plate tectonics was slow and painful because many of the Cold War tools were not available. Continental drift theory was based on the fit of the continental shorelines, the evidence for matching fossils on dispersed continents, and the evidence for glacial striations on continents which are now at low latitudes where there is no ice. Paleomagnetic evidence and mapping of the seafloor magnetic anomalies came much later. This evidence convinced most scientists that plate tectonics is an accurate description of the Earth. As discussed here, we are fortunate to live on a planet where seafloor spreading is nicely recorded in the magnetic field of the crustal rocks. Earthquake seismology delineates both the shallow plate boundaries and the deep subducted slabs. Finally, the space-age tools provided further confirmation the theory. The path to discovery and confirmation of plate tectonics would have been smoother if we only had the advantage of exploring the Earth from another nearby planet. Nevertheless, the outcome would be the same. With modern tools and 20-20 hindsight, today, the most important observations related to plate tectonics are provided by space geodesy, seismology, ship surveys, and geological investigations and I would rank them as follows:

1) radar altimeter measurements of marine gravity, fit of the continents
2) space geodetic measurements of plate motion
3) shallow earthquakes to define plate boundaries
4) deep earthquakes prove slabs penetrate into the deep mantle
5) magnetic reversals at sea to provide plate speed
6) mid0ocean ridge axis topography and symmetric deepening about the ridge
7) dating of reversals on land
8) fossil evidence
9) glacial striations
10) matching of rock types on conjugate continental margins

You see: this is exactly the reverse of the order in which things actually occurred

References

1. Kious, W. J. and R. I. Tilling. 1997. *This Dynamic Earth: The Story of Plate Tectonics*. Washington, DC: U. S. Geological Survey, U. S. Government Printing Office. http://pubs.usgs.gov/publications/text/dynamic.html
2. Smith, W. H. F. and D. T. Sandwell. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277:1956-1961.
3. Mammerickx, J., S. M. Smith, I. L. Taylor and T. E. Chase. 1975. *Topography of the South Pacific*. La Jolla, CA: Institute of Marine Resources, University of California at San Diego.
4. Turcotte, D. L. and G. Schubert. 1982. *Geodynamics: Applications of Continuum Physics to Geological Problems*. New York: John Wiley & Sons.
5. Press, F. and R. Siever. 1994. *Understanding Earth.* San Francisco, CA: W. H. Freeman and Company.
6. Cox, A. 1973. *Plate Tectonics and Geomagnetic Reversals*. San Francisco, CA: W. H. Freeman and Company.
7. Raff, A. D. and R. G. Mason. 1961. Magnetic survey off the west coast of North America, 40N latitude to 50N latitude. *Geol. Soc. Am. Bull*. 72:1267-1270.
8. Vine, F. J. 1966. Spreading of the ocean floor: New evidence. *Science* 154:1405-1415.
9. Heirtzler, J. R., G. O. Dickson, E. M. Herron, W. C. Pitman and X. Le Pichon. 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. *J. Geophys. Res*. 73:2119-2136.
10. Atwater, T. and J. Severinghaus. 1989. *Tectonic Map of the Northeast Pacific Ocean*. Boulder, CO: The Geological Society of America, Inc.
11. Cande, S. C., J. L. LaBrecque, R. L. Larson, W. C. Pitman, X. Golovchenko and W. F. Haxby. 1989. *Magnetic Lineations of the World's Ocean Basins*. Tulsa, OK.
12. Foster, J. S. and L. D. Welch. 2000. The evolving battlefield. *Physics Today* December, pp. 31-35.

13. Cloud, J. 2000. Crossing the Olentangy River: The figure of the Earth and Military-Industrial-Academic Complex, 1947-1972. *Stud. Hist. Phil. Mod. Phys*. 31:371-404.
14. Day, D. A., J. M. Logsdon and B. Latell. 1998. Eye in the Sky: The Story of the CORONA Spy Satellites. Washington, DC: Smithsonian.
15. Chesbrough, G. L. 1991. Letter from Oceanographer of the Navy to David Sandwell acknowledging the request for declassification and noting the reasons for classification of Geosat altimeter data, 23 December.
16. Medea. 1995. *Scientific Utility of Naval Environmental Data*. McClean, VA: MEDEA Office.
17. Kaula, W. M. 1963. Determination of the Earth's gravitational field. *Rev. Geophysics* 1:507-551.
18. Haxby, W. F. 1987. *Gravity Field of the World's Oceans*. Boulder, CO: National Geophysical Data Center, NOAA.
19. Barazangi, M. and J. Dorman. 1969. World seismicity map compiled from ESSA Coast and Geodetic Survey epicenter data, 1961-1977. *Seismol. Soc. Amer. Bull*. 59:369-380.
20. Engdahl, E. R., R. vanderHilst and R. Buland. 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. Seismological Soc. Am*. 88:722-743.
21. Wadati, K. 1928. Shallow and deep earthquakes. *Geophys. Mag*. 1:162-202.
22. Benioff, H. 1954. Orogenesis and deep crustal structure: Additional evidence from seismology. *Geol. Soc. Amer. Bull., Spec. Papers* 62:61-75.
23. Kirby, S. H., S. Stein, E. A. Okal, and D. C. Rubie. 1996. Metastable mantle phase transformations and deep earthquakes in subducting oceanic lithosphere. *Rev. Geophysics* 34:261-306.
24. Pitman, W. C. and J. R. Heirtzler. 1966. Magnetic anomalies over the Pacific-Antarctic ridge. *Science* 154:1164-1171.
25. Menard, H. W. 1986. *The Ocean of Truth*. Princeton: Princeton University Press.
26. Parsons, B. and J. G. Sclater. 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. *J. Geophys. Res*. 82: 803-827.
27. Brace, K.L. 1977. *Preliminary ocean-area geoid from GEOS-III satellite radar altimetry*. St. Louis, MO: Defense Mapping Agency.
28. Tapley, B. D., G. H. Born and M. E. Parke. 1982. The SEASAT altimeter data and its accuracy assessment. *J. Geophys. Res*. 87:3179-3188.
29. Apel, J. 1987. *The Navy Geosat Mission*. Laurel, MD: The Johns Hopkins Applied Physics Laboratory.
30. Minster, J.-B., D. Sandwell and D. McAdoo. 1991. *Scientific Rationale for Declassification of Geosat Altimeter Data*, unpublished white paper.
31. Chesbrough, G. L. 1992. Letter from Oceanographer of the Navy to David Sandwell acknowledging the declassification of all Geosat data south of 30˚ south latitude, 10 June.
32. Connerney, J. E. P., M. H. Acuna, P. J. Wasilewski, N. F. Ness, H. Reme, C. Mazelle, D. Vignes, R. P. Lin, D. L. Mitchell and P. A. Cloutier. 1999. Magnetic lineations in the ancient crust of Mars. *Science* 284 (April 30): 794-798.
33. Jordan, T. H. and J.-B. Minster. 1988. Beyond plate tectonics: Looking at plate deformation with space geodesy. In M. J. Ried and J. M. Moran, eds., *The Impact of VLBI on Astrophysics and Geophysics: Proceedings of the 129th Symposium of the International Astronomical Union held in Cambridge*, pp. 341-350. Boston, MA: Kluwer Academic.
34. Herring, T. A., et al. 1986. Geodesy by radio interferometry: Evidence for contemporary plate motion. *J. Geophys. Res*. 91:8341-8347.
35. Simkin, T., J. D. Unger, R. I. Tilling, P. R. Vogt and H. Spall. 1994. *This Dynamic Planet - World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics*. Denver, CO: U. S. Geological Survey.
36. Sandwell, D. T. and W. H. F. Smith. 1997. Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. *J. Geophys. Res*., 102:10,039-10,054.