PLATE TECTONICS

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CONTENTS

The Earth's solid surface behaves in most places as if it were divided into a number of almost rigid "plates". Any horizontal motion of a rigid plate on a spherical Earth is necessarily a rotation about an axis through the center. This axis cuts the surface at the "pole of rotation". The plates move relative to one another over the asthenosphere (q.v.) at speeds of the order of 10–100 millimetres per year. Two good modern textbooks on the subject are Cox and Hart (1986) and Fowler (1990).

Figure 1 is a map of shallow earthquakes, which mark the plate boundaries well in the oceans, but less so in continental areas. At mid-ocean ridges (see Figure 2), the ocean is typically 2.5 km shallower than average, the plates are moving apart, hot soft asthenosphere rises and turns into hard cold sea-floor, and there are only shallow earthquakes. The opposite sides of oceanic plates usually have "subduction zones" where the plates bend and go down into the mantle. These zones are marked by trenches several kilometres deeper than normal ocean nearby, by earthquakes which are shallow near the trenches, and become deeper with distance away from them, and by lines of andesitic volcanoes above the earthquakes 100–200 km deep.

Continental plate collision zones are marked in the same way as subduction zones in Figure 2; the difference is that ocean plates subduct, to depths of at least several hundred kilometres, whereas continental plates do not. They normally pile up in a mountain range instead; the largest example is the Himalayas. At transform faults, the remaining type of plate boundary, one plate slides horizontally past the other, with little or no rising or sinking of crustal material.

All plate boundaries are seismically active: subduction zones the most, transform faults less so (there may even be continuously creeping segments with no earthquakes, as in parts of the San Andreas fault in California), and ridges least of all.

Figure 3 is a schematic, true-scale, cross-section of a typical region of the Earth, showing a subduction zone, a ridge, and parts of three plates. On this scale oceans and mountains are invisible, and only the most violent volcanic eruptions throw ash high enough to be seen.

No two experts in the field would be likely to show exactly the same map of the plates. For example, DeMets et al. (1990) separate the Indian and Australian plates along a nearly east-west line between the Carlsberg and Central Indian ridges, and do not show the Scotia or Sandwich plates as separate from the Antarctic. (The Sandwich plate is the small D-shaped area just east of the Scotia plate in Figure 2.) Other authors show more "microplates", e.g., separating an Adriatic plate from the African and Eurasian plates (Anderson 1987), or the Caroline basin from the Pacific plate (Weissel and Anderson 1978), or inserting Easter and Juan Fernandez microplates on the Nazca-Pacific plate boundary (Hey et al. 1985). The location of both dotted boundaries in Figure 2 is controversial.

In continental regions being compressed by plate motion, the deformation may be so widespread that it is doubtful whether the concept of plate behavior is useful at all. Molnar and Tapponnier (1975) suggested that the eastward motion of Tibet and nearby areas is better explained in terms of plastic flow throughout the region, as India continues to be pushed north into it. For people trying to understand the Earth as a whole, plate tectonics is a useful large-scale model. Even for those concentrating on a deforming region like Tibet or New Zealand, plate tectonics provides at least the boundary conditions at a large distance, and helps to explain why the deformation occurs.

HISTORY

Plate tectonics appeared during the 1960s as a synthesis of much previous work. The history is well described by Cox (1973) and Emiliani (1981). References for this section not listed below can be found in one or other of those books. Both show the subject as a fine example of how major changes occur in scientific understanding.

The general idea of currents inside the Earth leading to surface displacements dates back to the nineteenth century. In the early 20th century Wegener introduced the concept of drifting continents, which neatly explained a variety of topographic, sedimentological, paleontological, botanical and zoological observations. Wegener had no convincing driving mechanism, however, and so failed to convince many people (except in the Southern Hemisphere, where the field evidence for former connections of continents now separated was much stronger than in the Northern Hemisphere).

Hills (1934) drew the analogy between froth floating on boiling jam and moving continents floating on the mantle of the Earth, in each case the driving mechanism being thermal convection. Jeffreys (1934) admitted that this sort of driving mechanism would avoid his earlier objection (on mechanical grounds) to continents ploughing their way across basaltic ocean floors. Both authors thought that such movements had stopped early in the history of the Earth.

The seismological results of Gutenberg and Richter (1949) did not immediately lead to the emergence of plate tectonics, in spite of their maps which were very like Figures 1 and 2, mainly because oceanic geology was too little known at the time. Neither did the work of Runcorn in 1962 on paleomagnetism (q.v.). He and many others deduced polar wander paths from observations of the direction (in three dimensions) in which dated rocks in different parts of the world are found to be magnetised. From land-based paleomagnetic work the major conclusion was that about 200 million years ago the former supercontinent Pangaea began to split, first to Laurasia and Gondwana, then to the present collection of continents and fragments. Some, like India, have since reunited with larger blocks. It should be mentioned that Pangaea was not primordial: Laurasia was assembled from separate parts during the Palaeozoic, Gondwana probably earlier.

The evidence that finally convinced Earth scientists of plate tectonics was the pattern of magnetic anomalies in the ocean floors, confirming the seismological conclusions. The Earth's magnetic field reverses itself at irregular intervals, and mid-ocean ridge rocks everywhere are magnetised in the direction of the field prevailing when they cool through the Curie point. As they move away from the ridges, at a speed which is nearly the same on each side, a pattern of normal and reversed magnetism develops which has its own mirror image across the ridge. The irregularities in timing of reversals become irregularities in spacing of the magnetic anomalies which, since the work of Hess (1962), Morley (first published by Emiliani, 1981) and Vine and Matthews (1963), have been identified and correlated over most of the oceanic crust.

The plate tectonic synthesis was expressed by Morgan (1968), Le Pichon (1968), and Isacks, Oliver and Sykes (1968). The theory was triumphantly confirmed by the first few Deep Sea Drilling Project cruises in the late 1960s. These found ages of fossils from the bottom of the ocean sedimentary layer steadily increasing with distance from mid-ocean ridges; the magnetic and paleontological time scales could then be calibrated against each other. The latter scale had already been calibrated radiometrically.

The driving mechanism remained in dispute much longer. Gilluly (1971) began a paper with "So far as I know, no one has yet suggested a model for the generation of plate motion that is acceptable to anyone else", but by now there seems to be a consensus, largely based on work of Turcotte and Oxburgh in 1967 and McKenzie and Elsasser (independently) in 1969, that thermal convection in an Earth hotter inside than at the surface will give rise to plate motions, given that both the surface layers and the mantle below 700 km are much stiffer than the asthenosphere.

MODERN DEVELOPMENTS

Kinematics

Work far too voluminous to list here (but see Fowler, 1990, Chapter 3; DeMets et al. 1990, and DeMets 1992) shows both how the plates are moving now and how the system behaved in the past. As ocean floors are eventually subducted, oceanic reconstructions become more conjectural as one goes backwards in time. One can be fairly sure of the pattern of plate motions in the Cenozoic, but information for periods before the Jurassic has disappeared. Continents, however, can be followed paleomagnetically back through the Paleozoic, except in regions with many subduction zones, such as Indonesia and the Philippines. The work is still unfinished, and the time scale is still being refined (Harland et al. 1989).

Dynamics

Many different physical plate-driving mechanisms have been proposed (Harper 1989; Harper 1990). The most plausible is thermal convection caused by radioactive heat generation in the interior of the Earth, but that statement does not explain how plates form and why no other planet seems to have plate tectonics like ours, even though they are all hot inside. The key considerations appear to be as follows.

(1) The asthenosphere (q.v.), when pushed in the same direction for thousands of years, behaves like a viscous fluid (attested by studies of the

rate of uplift of Canada and Fennoscandia after their Pleistocene ice sheets melted), and the lower mantle like a more viscous one. It is still controversial how much more. Peltier (1989) suggested a factor of 2 (upper mantle viscosity 10^{21} Pa s, lower mantle 2×10^{21}); James and Morgan (1990) suggested factors of 20 or 200 (upper mantle 10^{21} or 5×10^{20}, lower mantle 2×10^{22} or 10^{23}).

(2) The lithosphere above is strong enough not to deform significantly under forces large enough to push the asthenosphere at typical plate speeds, but it is not perfectly rigid. Oceanic lithosphere for instance bends and then sinks at subduction zones.

(3) Oceanic lithosphere is essentially cold asthenosphere rock. Being cold, it is dense, but it still floats on the asthenosphere, as ships made of steel float on water. The lithosphere thickness increases due to thermal diffusion as $\sqrt{T}$ where T is its age (i.e. the time since it appeared at a midocean ridge), at least up to 70 Ma. The ocean depth also increases, being roughly given by $d = 2.5 + 0.35\sqrt{T}$ if d is measured in km and T in Ma. (This does not hold precisely above ridges, where there is often an axial valley due to resistance to upward flow, nor for $T > 70$ Ma, where d increases more slowly with age, for reasons which are not yet clear.)

(4) In a system convecting under gravity, the major driving forces act where the major horizontal density differences occur, at the top and bottom thermal boundary layers. In the Earth, these are the plates and the mantle-core boundary, but hydrodynamic image effects (Harper 1990) imply

that the latter will have a much smaller effect on plate motions. In oceanic plates, the thickening with age implies a horizontal force per unit area proportional to ∇T away from the ridges (ridge push).

(5) When a plate subducts, it is pulled down by its own weight. This "slab pull" is the strongest plate-driving force: the fastest-moving plates all have slabs attached.

(6) New subduction zones are presumably generated if large amounts of rock break through oceanic lithosphere (like a plateau basalt, but at sea), weigh it down and cause it to founder (Turcotte 1977).

(7) Other forces also help to move plates about, such as the reaction to slab pull, which must be applied by either the asthenosphere, the non-subducting plate, or the mantle under the asthenosphere. Some authors have advocated friction at the bottoms of slabs where they attempt to push into the higher-viscosity mantle; others have included the essentially hydrostatic push that each plate exerts on the other at a continental collision zone; others have suggested that the upflow from a hotspot, spreading out in all directions under the lithosphere, will push it outwards. If a plate boundary is nearby, the result is a force on each plate away from the other.

Hotspots

The Hawaiian islands have long been known to be a line of volcanoes becoming younger to the ESE, and there are several parallel lines of seamounts and islands in various parts of the Pacific plate. They appear to be due to "hotspots" which remain nearly fixed in the mantle and which send up plumes of magma, which punch through as a volcano. Hotspots also occur on other plates, and in each case their volcanic lines are nearly anti-parallel to the local plate motion relative to the mantle; the hotspots themselves move relative to one another much more slowly than plates do. They can thus be used, along with magnetic anomalies, to elucidate past plate motions.

Back-Arc Spreading and Marginal Basins

In many places, especially the Western Pacific, sea-floor spreading occurs above a subduction zone which is generating a new, young, marginal ocean basin behind the volcanic arc. Examples are the Lau-Havre Basin west of the Tonga-Kermadec arc and the Mariana Trough west of the Mariana Islands (not to be confused with the Mariana Trench east of them). There are also inactive marginal basins (e.g., the Sea of Japan) and other marginal basins which are generated without subduction nearby (e.g., the Cayman Trough in the Caribbean Sea, which is generated by E-W movement between the North American and Caribbean plates on a short N-S ridge segment on their boundary). Wherever back-arc spreading occurs above a subduction zone, the speed of subduction is faster than the speed of approach of the major plates. It can be much faster, as at the South Sandwich Islands (if the Sandwich-Scotia spreading is treated as back-arc spreading; see Pelayo and Wiens, 1989). Several possible dynamical reasons have been advanced for such spreading (Figure 4), ranging from upwelling due to heat generation in the subducting slab (Model 1) or mantle beneath (Model 2), to the purely kinematic (Model 3: the back-arc plate retreating for other reasons), to asthenosphere flow from elsewhere pushing the slab aside (Model 4), or the slab sinking under its own weight and pushing the asthenosphere aside (Model 5).

Other Planets

The Earth is the only planet known to have plate tectonics. Mercury, Venus, the Moon and Mars seem to be one-plate planets (Solomon 1978; Kiefer and Hager 1991; Herrick and Phillips 1992). Though Venus has active mantle convection, and even subduction zones if Sandwell and Schubert (1992) are right, it seems to lack a midocean ridge system.

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FIGURE CAPTIONS

Figure 1. Earthquakes over magnitude 5.5 and shallower than 20 km, from the USGS Global Hypocenter Data Base. Larger + marks indicate larger earthquakes.

Figure 2. The world system of plates, from Fowler, C.M.R. (1990). With permission of the author and Cambridge University Press. Double lines: midocean ridges. Single lines: transform faults. Dashed lines: uncertain plate boundaries. Lines of triangles: subduction zones and continental collision regions, the triangles being on the upper plate.

Figure 3. A schematic cross-section of the Earth at true scale. Solid regions: oceanic plates (whose thickness increases with square root of age). Shaded region: a continental plate (thickness assumed constant at 100 km). Dashed circle: the 700 km discontinuity, which may be the bottom of the asthenospheric convection cells. Solid circle: the mantle-core boundary.

Figure 4. Five possible models of back-arc spreading, from Tamaki and Honza (1991). With permission of the International Union of Geological Sciences.