Mid-plate Tectonics

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There are many examples of mid-plate tectonics which require an explanation. Oceanic island chains, continental graben and rift valleys, and features which pass from continental areas into oceanic parts of the same plate, are particularly important. We argue that these are the result of crustal extension due to tensional stresses — thermal stresses due to the cooling of the lithosphere, membrane stresses due to changes in the radii of curvature or a complicated combination of both.

THE theory of plate tectonics has explained the location and cause of most seismicity, volcanism and active mountain building[1], all of which are associated with plate margins: ocean ridges where plates are created, ocean trenches where plates descend into the mantle, zones of continental collision, and great faults where lateral motion between plates takes place.

There are, however, several striking exceptions where such tectonic activities occur away from plate margins, for example, the Hawaiian Islands where extensive volcanism has created a mountain range near the centre of one of the largest plates. It also seems that the age of volcanism in the Hawaiian chain increases systematically away from the present volcanism. Such "mid-plate" tectonic phenomena can also occur in continental regions, such as the highly active seismic zone centred near New Madrid, Missouri. This seems to be the termination of a belt of seismicity and tectonic activity which extends from eastern Quebec and is associated with the development of the St Lawrence River Valley[2].

Hot Spots and Plumes

Wilson[3] attributed the island volcanicity of Hawaii to the rise of magmas from a nearly stationary "hot spot" in the upper mantle. The motion of the Pacific plate over the magma source resulted in the formation of the island chain. A modification of this theory has been given by McDougall[4].

Morgan[5,6] has further developed the hot spot theory; he identified a large number of apparent hot spots and attributed the magma source to solid state convective plumes rising from the lower mantle. Assuming that the plumes are fixed with respect to the rotational axis of the Earth, he has used the location and age of the island chains to establish the absolute motion of the Pacific plate. The only real test that has been proposed for the hypothesis is a demonstration that the hot spots or plumes are fixed relative to the rotational axis. Morgan[7] found that this could not be done without allowing the plumes to migrate at velocities between 0.5 and 1 cm yr^{-1}. McElhinny[8] has also questioned the validity of the fixed hot spot hypothesis.

Yield and Fracture

An alternative hypothesis for the origin of the Hawaiian chain is a propagating tensional fracture in the lithosphere which causes volcanic activity as it propagates[9–11]. The Hawaiian Islands exhibit tensional features; the shield volcanoes seem to be spaced along en-echelon fractures[12] (Fig. 1*a*). In order to examine this structure in terms of the theory for plastic yielding and fracture of elastic solids we consider the mode of failure of the lithosphere under tension. We assume that brittle fracture will occur near the Earth's surface where the hydrostatic pressure is low but that plastic yielding will occur at depths where the hydrostatic pressure is large compared with the yield stress. The plastic yielding must take place concurrently with the surface fracture to maintain the integrity of the plate. The conditions under which a lithosphere will yield plastically have been derived by Bijlaard[13] (see also Nadai[14]). Assuming that the Mises–Hencky–Huber criterion for yield strength is applicable, Bijlaard showed that a plate under tension would yield plastically at an angle $\beta_y = 35°$ (Fig. 1*b*).

The near-surface pattern of brittle fracture cannot be predicted theoretically. In continental regions there is evidence that the result of a tensional fracture is a graben structure. Studies of the Rhine graben[15] show that the sunken central block is bounded by normal faults with an inclination of 60°–65°. This result is in agreement with the Coulomb–Navier theory for fracture if the coefficient of internal friction is taken to be 0.58 to 0.84.

Clearly the mode of tensional fracture in ocean areas differs from that in continental areas. There is little evidence of graben structures in the Hawaiian Islands. Instead the shield volcanoes seem to lie along en-echelon fractures which have opened and have been filled with magma. The difference may be due to a greater availability of magmas from the asthenosphere in ocean areas. We assume that the oceanic lithosphere fractures under tension in the direction of maximum shear stress, at an angle $\beta_f = 45°$ (Fig. 1*b*). In terms of the Coulomb–Navier theory this corresponds to zero internal friction. When finite deformation takes place these fractures open and fill with magma. The resulting pattern of brittle fractures inclined at 45° and a zone of plastic flow inclined at 35° is similar to the structure of the Hawaiian Islands (Fig. 1*a*). Because the principal trend of the Hawaiian Islands is at 22° to lines of latitude, the predicted direction of the tensional stress is 13° to the west of north and 13° to the east of south.

It is not easy to see how a mantle hot spot or source of magma would result in regular tensional fractures. Localized heating would cause thermal expansion of the lithosphere which would lead to compression. It is possible that shear stresses associated with a plume could operate on the base of the lithosphere but it is not clear how they could produce the observed features. What are the alternative sources for the

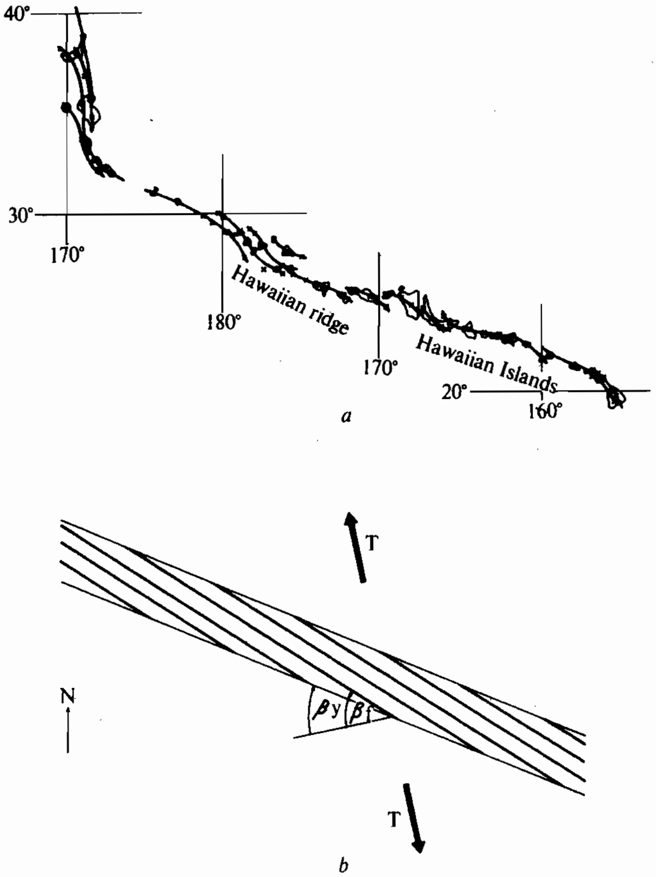

Fig. 1 *a*, Structure of the Hawaiian Islands after Jackson *et al.*[12]. Apparent shield volcanoes (×) seem to lie along en-echelon fractions (——). *b*, Predicted pattern of plastic yielding at an angle $\beta_y = 35°$ and brittle fractures at an angle $\beta_f = 45°$ due to a tensional stress shown by the vectors **T**.

tensional stresses that seem to be responsible for the Hawaiian Islands?

Thermal Stresses

The lithosphere is created in the vicinity of an ocean ridge by the cooling of mantle rock. As the lithosphere convects away from the ridge further cooling takes place and its thickness increases. The lower boundary of the lithosphere can be defined as the isotherm T_y; at temperatures less than T_y there are no significant deformations of the mantle rock on geological time scales at stresses below the yield stress.

An elastic plate which is cooled non-uniformly is subject to thermal stresses. We consider a lithosphere which is cooling as it moves away from an ocean ridge. We take the direction parallel to the ridge axis to be the y direction, the direction perpendicular to the ridge axis to be the x direction, and the normal to the surface to be the z direction as shown in Fig. 2. We assume that deformation in the y direction is zero so that the thermal stress is given by[16]

$$(\sigma_{yy})_{\rm th} = \alpha E(T_y - T_0) \qquad (1)$$

where α is the coefficient of thermal expansion, E is Young's modulus, and T_0 is the temperature to which the plate is cooled. The resultant stress is a tension parallel to the ridge axis. Taking $\alpha = 3 \times 10^{-5}$ °C^{-1}, $E = 1.7 \times 10^{12}$ dyne cm^{-2}, $T_y = 800°$ C, and $T_0 = 0°$ C as typical properties for a lithosphere we find that $(\sigma_{yy})_{\rm th} = 4 \times 10^{10}$ dyne cm^{-2}. This thermal stress is sufficient to fracture the lithosphere.

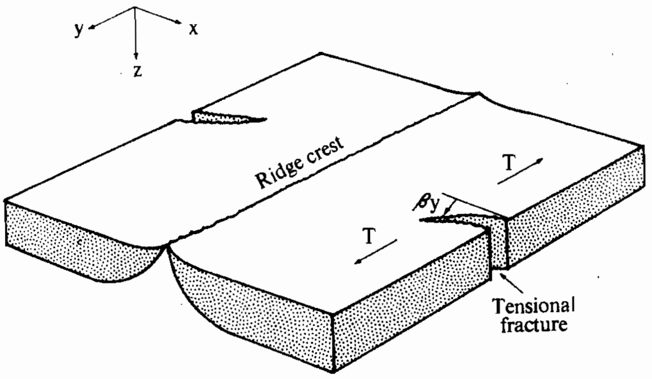

Fig. 2 Illustration of fractures due to thermal stresses in spreading plates. Tensions indicated by vectors **T**.

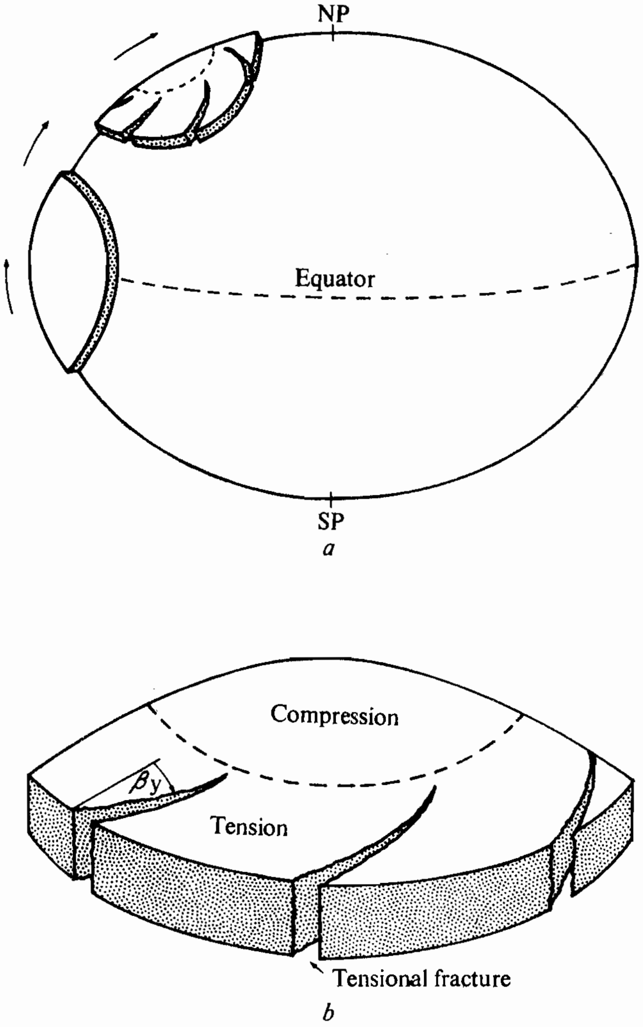

Fig. 3 Illustration of fractures due to non-spherical plate tectonics. *a*, Movement of a plate northwards from the equator showing edge fractures due to an increase in radii of curvature. *b*, Distribution of stresses and fractures due to an increase in radii of curvature in a circular plate.

Thermal stresses due to the cooling of an oceanic lithosphere will be tensions parallel to the ridge where the plate was created. Therefore, the stresses will be aligned with the magnetic anomalies in the ocean floor and will be normal to fracture zones. From the trends of the Murray and Molokai fracture zones and adjacent magnetic anomalies, the direction of the tensional thermal stresses near Hawaii should be 14° west of north and east of south. This is within one degree of the direction predicted in the previous section from the trend of the island chain.

Non-spherical Plate Tectonics

Tensional stresses in a lithosphere may also be caused by membrane stresses due to non-spherical plate tectonics. If the Earth was a perfect sphere the spherical surface plates would be free to move about without deformation. But to a good approximation the Earth is an oblate spheroid with an ellipticity of 0.00335. The principal radii of curvature at the equator are 6,378 and 6,335 km; at the poles the radii of curvature are equal, 6,400 km. If a lithosphere is created on one part of the spheroid it must deform when its latitude changes, for its radii of curvature must change. A plate which is created in the vicinity of the equator must have its radii of curvature increased if the latitude of the plate changes (Fig. 3*a*).

Bending moments are associated with changes in radii of curvature. But for a shell the thickness of which is small compared with its radii of curvature, the stresses associated with bending are small compared with the membrane stresses in the shell. The membrane stresses are simply the result of stretching the plate to different radii of curvature.

According to membrane theory[17] the magnitude of the stresses required to stretch a segment of a shell from one radius of curvature to a slightly different radius of curvature is given by

$$\sigma_M = C_1 E \, \Delta R / R \qquad (2)$$

where R is the initial radius of curvature, ΔR is the change of radius of curvature, and C_1 is a constant of order 1. If the radius of curvature of a circular segment of a spherical shell is increased, the edge of the shell will experience a tangential tensional stress and the centre of the shell will be in compression (Fig. 3*b*).

Assuming that ΔR is the difference between the radii of curvature at two locations on the Earth the ratio $\Delta R/R$ is related to the ellipticity of the Earth ε by

$$\Delta R / R = C_2 \varepsilon \qquad (3)$$

where C_2 is a function of the difference in latitude between the two points on the Earth. If this difference is a significant fraction of 90° then the constant C_2 will be of order 1. Combining equations (2) and (3) gives

$$\sigma_M = C_1 C_2 E \varepsilon \qquad (4)$$

With $\varepsilon = 0.00335$, $E = 1.7 \times 10^{12}$ dyne cm^{-2}, and setting $C_1 C_2 = 1$ we find that $\sigma_M = 5.7 \times 10^9$ dyne cm^{-2}. The membrane stresses due to the movement of the lithosphere over the surface of the non-spherical Earth are sufficient to fracture the lithosphere.

Fractures due to membrane stresses would be expected to appear in mid-latitudes because the change in the radii of curvature of the Earth with latitude is a maximum at a latitude of 45°. The point of generation of such fractures would be nearly fixed in latitude. For northward moving plates in the northern hemisphere such as the Pacific plate and the Americas plate the crack should be propagating southwards. This is the case for both the Hawaiian Islands and the New Madrid, Missouri–St Lawrence Valley tectonic zone.

Non-spherical plate tectonics requires a finite extension to relieve the membrane stresses. This is observed in rift valleys and graben structures. The Rhine graben has a mean width of 36 km and the extension across the valley is estimated to be 4.8 km (ref. 15). Other rift and graben structures have widths and crustal extensions of the same order. Burke *et al.*[18] associate the Rhine graben with a hot spot. It is, however, not clear how a hot spot or plume could lead to the known unidirectional crustal extension across the Rhine Valley. Non-spherical plate tectonics provides an explanation for a permanent extension of the crust of this magnitude.

There may be further implications of both thermal stresses and membrane stresses. For example, the fractures caused by these stresses may initiate the breakup of continents, for example, for the formation of the Atlantic Ocean. Also, the additional force required to change the latitude of a plate due to the membrane stresses would favour east–west seafloor spreading over north–south seafloor spreading.

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LETTERS TO NATURE

PHYSICAL SCIENCES

Subsidence of the Venice Area during the Past 40,000 yr

THE present day subsidence of the Quaternary deposits of the plain of Venice can be considered to be the result of either geological factors—the plain is situated on the northern margin of the subsident area of the Po valley—or of human activity over several centuries, such as overexploitation in the confined aquifers of low turnover[1], urban and industrial development on unconsolidated sediments.

The respective contribution of the different factors affecting subsidence may vary from place to place. Drillings, continuous corings[2,3] and seismic profiles[4] can provide average sedimentation rates of about 0.5 to 1.0 mm yr^{-1} since the Upper Pliocene from north to south of the lagoon of Venice. Geodesic studies[5], available since the early 1900s, have shown that in some places, Lido di Venezia for instance, the soil is now sinking at a velocity close to 8 mm yr^{-1}.

In order to study the geological component of subsidence at an intermediary time scale, systematic analysis of the chronology of the upper Quaternary deposits has been undertaken using ^{14}C measurements. This study is designed to determine whether or not "geological" subsidence for the past 40,000 yr