PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Forces Driving the Plates: Constraints from Kinematics and Stress Observations [and Discussion]

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The forces driving the plates: constraints from kinematics and stress observations

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Plate kinematics and stress observations are used to assess the nature and relative magnitudes of the forces driving the plates. Dynamical equilibrium for a purely oceanic plate determines the relative magnitudes of the active and responding forces, largely balancing drag against slab-pull. Continental plates, moving more slowly, have errors of about 30% of the estimated motions. A torque balance model is used to describe the evolution of plate dynamics over the Cenozoic Era for reconstructions of plate geometry and velocities. Torques have been fairly stable for the past 64 Ma; the misfit to the model systematically increases for earlier times, most likely due to errors in the locations of past convergent plate boundaries and velocities. Unlike kinematics, which integrates the forces acting on a plate, the stress field responds locally and can differentiate between models for forces. Stress models which incorporate the forces are compared with stress orientations for the North and South American plates.

1. Introduction

What drives the plates? Do they drive themselves by subsidence and subduction of cooling oceanic lithosphere, or are they passively carried by mantle convection? The most direct evidence is kinematics, the plate motions themselves. We begin by looking at present kinematics realizing that, though this will give insight into dynamics, the insight fails in details. Starting with the present-day motions we define their characteristics, then discuss plate reconstructions over the Cenozoic Era. These snapshots of past plate geometries and velocities are important in testing hypotheses and models derived to explain present-day kinematics. In the next section we describe a general model to balance the forces on individual oceanic plates, and present an approach to convert to torques geometrically. The torque-balance model is applied to plate reconstructions using the reconstructed velocities at subduction zones to infer ages, and, consequently, the forces acting on individual plates. The torques are fairly stable and the global fit suggests that the model is generally valid. The difficulty with inferences about driving forces from kinematics is that the motion of a rigid plate represents an integrated effect of the torques acting on the plate. Different combinations of forces can give the same net motion. Furthermore, there is considerable variation among plate-motion models, particularly for the slower-moving continental plates. On the other hand, stress observations have the potential to give detailed information about the forces driving the plates, in that sets of forces with the same net torque can produce quite different stress patterns. For specified

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force models the predicted stress fields can be determined and compared with observations of the World Stress Map (Zoback *et al.* 1989), even if the observations are only directional. Of course, stress magnitudes would further constrain models. In the final section we discuss stress observations and their utility as a test of dynamical models. The South American and North American plates are used as examples, because these plates are not dominated by long attached slabs.

2. Kinematics

Plate tectonics describes the relative motions of the plates on a global scale. Relative plate motions averaged over the past few million years, referred to as 'current' or 'present', are accurately known; locations and azimuths of transform faults and lineated magnetic anomalies, as well as slip vectors determined from analysis of earthquake focal mechanisms, give information about the relative motion of each of two adjacent plates. Data from all plate pairs can be combined to yield a self-consistent set of globally best-fitting angular-velocity vectors (Chase 1978*a*; Minster & Jordan 1978; DeMets *et al.* 1990). These relative motions are interpreted as 'absolute' motions with the assumption of a reference frame, such as hotspots assumed fixed relative to the mantle, or one in which there is 'no-net-rotation' of the set of motions. Investigations of present-day absolute plate motions have revealed certain patterns: the speed of a plate varies inversely with its continental area (every large oceanic plate moves faster than every large continental plate except for the Indian plate) (Minster *et al.* 1974; Forsyth & Uyeda 1975; Chapple & Tullis 1977), the speed of a plate increases with the fraction of its boundary that is being subducted (Forsyth & Uyeda 1975), speeds in equatorial regions tend to be greater than speeds in polar regions (Solomon *et al.* 1975), and overthrust plates at subduction zones all have a trenchward component of absolute motion, when behind-arc spreading is taken into account (Chase 1978*b*).

Reconstructions of plate velocities for earlier times are necessary to test these observations derived for the present. Global reconstructions of plate velocities in the past can be made using only seafloor-spreading data, and thus are not overdetermined as is the present. These reconstructions are made in a circuit in which relative motions are determined for two plates separated by a ridge, and then one or both of these plates is similarly linked to other plates until all plates are related. For Cenozoic time global plate reconstructions (Gordon & Jurdy 1986) relate the Pacific-basin plates using seafloor spreading data and position them relative to the Pacific hotspots; similarly, the Atlantic plates are related and then fixed relative to the African hotspots. The assumption that the African and Pacific hotspots are fixed relative to each other requires motion along an arbitrary boundary in the Pacific plate. A reconstruction for the interval from 10 Ma to the present is shown in figure 1; the reconstruction for 64–56 Ma is shown in figure 2. This reconstruction and analysis of Cenozoic plate motions, relative to the hotspot and the mean-lithosphere reference frames, shows that several simple generalizations based on present plate motions have been valid over Cenozoic time. The tendency for plates to move faster near the equator than near the poles has persisted, with only slight variation, throughout the era. However, during the Early Cenozoic the Kula and Farallon plates – both at high latitudes – moved at speeds in excess of 120 mm a^{-1}. The inverse correlation between absolute velocity and continentality, characteristic of the present and the Palaeocene, holds in the intervening intervals. Generally plates

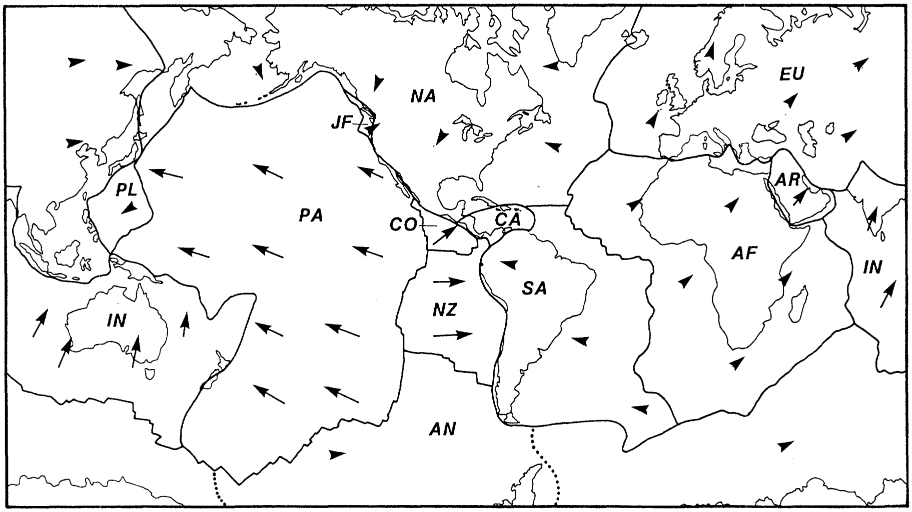

Figure 1. Cenozoic plate reconstruction, interval 10–0 Ma with present plate boundaries (from Gordon & Jurdy 1986). The arrow lengths at grid points are scaled for a constant time interval of 15 Ma. Mercator projection with top border at 70° N, bottom border at 70° S, and left and right borders at 90° E. Plate codes: AF, African; AN, Antarctic (East); AR, Arabia; AU, Australia; CA, Caribbean; CO, Cocos; CR, Chatham Rise (South Pacific); EU, Eurasian; FA, Farallon; IN, Indian; JF, Juan de Fuca; KU, Kula; LH, Lord Howe; NA, North American; NZ, Nazca; PA, (North) Pacific; PL, Philippine; PH, Phoenix (Aluk); and SA, South American.

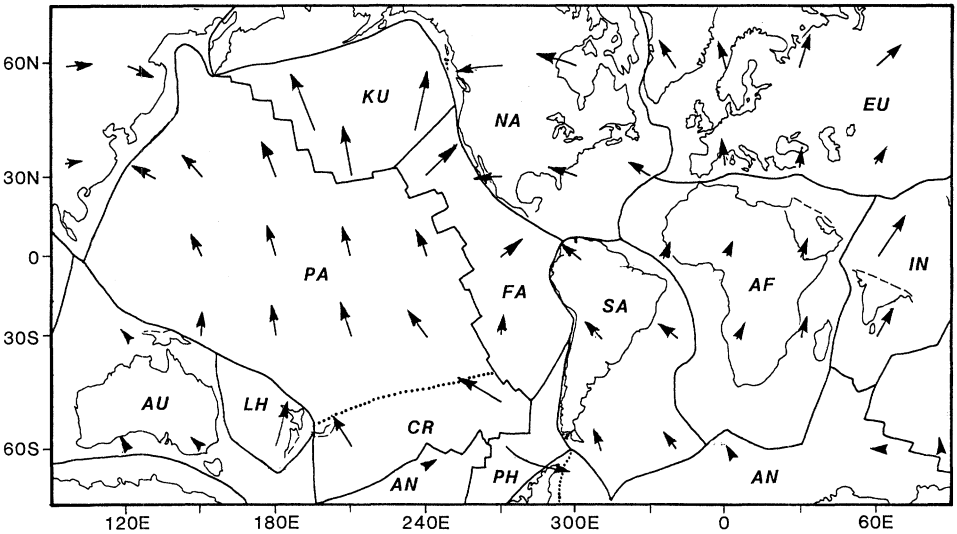

Figure 2. Cenozoic plate reconstruction, interval 64–56 Ma shown at chron 27 (61 Ma) (from Gordon & Jurdy 1986). The map parameters, arrow lengths and plate codes are as in figure 1.

moved rapidly toward their subduction zone. From this we conclude that the force of slab-pull is very important in driving the plates.

3. Dynamics

(*a*) *Dynamical equilibrium*

Plate motions themselves provide some information about the relative magnitudes of the forces and, as soon as motions were defined globally, dynamical models were attempted. Several authors found that pull on the downgoing slabs and total drag resistance dominate the balance (Harper 1975; Forsyth & Uyeda 1975; Chapple & Tullis 1977). Forsyth & Uyeda found that no other forces could be resolved from present plate motions; however, others (e.g. Elsasser 1971; Chapple & Tullis 1977; Chase 1978*a*) concluded that a net trenchward pull on overthrust plates may be significant at subduction zones. Also, Forsyth & Uyeda as well as Chapple & Tullis found that drag beneath the continents may be considerably stronger than drag beneath the oceans, though Harper's models (1975, 1986) show no such difference. Thus these early studies from kinematics come to a variety of conclusions about the relative importance of the forces driving the plates, but the studies are all based on a dynamical equilibrium between active and passive forces.

(*b*) *Two-dimensional model for oceanic plates*

A more recent simple dynamical model for oceanic plates (Carlson *et al*. 1983*a*, *b*; Carlson 1983) uses slab pull and ridge push as active forces to balance plate drag and slab resistance as response forces, ignoring other forces. Each force component is expressed as a function of age, speed, and length; a reasonable set of assumptions leads to a single equation with two parameters relating age and speed. From the relation for the age and speed, and then balancing plate drag against the slab pull and ridge push (Carlson *et al*. 1983*a*, *b*; Carlson 1983):

$$v^2 t = S v t^{\frac{3}{2}} + R t, \tag{1}$$

where v and t are the velocity and age, respectively, at the trench and S and R are coefficients fitted to 15 trenches around the world. Speeds and ages from the trenches are used to estimate the parameters, with the result that the ridge-push force is much smaller than the slab-pull force and may actually be zero within the errors (figure 3*a*). For a two-dimensional model of a plate there are three conditions for dynamical equilibrium; the net forces and the net torque about any point must all be zero. We used these conditions (Stefanick & Jurdy 1991) to estimate the magnitudes of forces as a function of age, with ridge push and slab pull as active forces, and plate drag and slab resistance as passive forces (figure 3*b*). The balance refers to purely oceanic plates where slab pull dominates. For continental plates, such as the case of South America to be discussed below, slab pull is less than ridge push.

(*c*) *Three-dimensional models for forces and torques*

The motion of a rigid plate over the Earth's surface has three degrees of freedom, rather than six degrees of freedom if it were free to move through space. Rigid-plate motion is completely described by its angular velocity vector $\boldsymbol{\omega}$. It seems reasonable to assume that we have a nearly perfect dynamical equilibrium with the passive torques (e.g. plate drag, slab resistance, collision) adjusting to balance the active torques (e.g. slab pull, ridge push, trench suction).

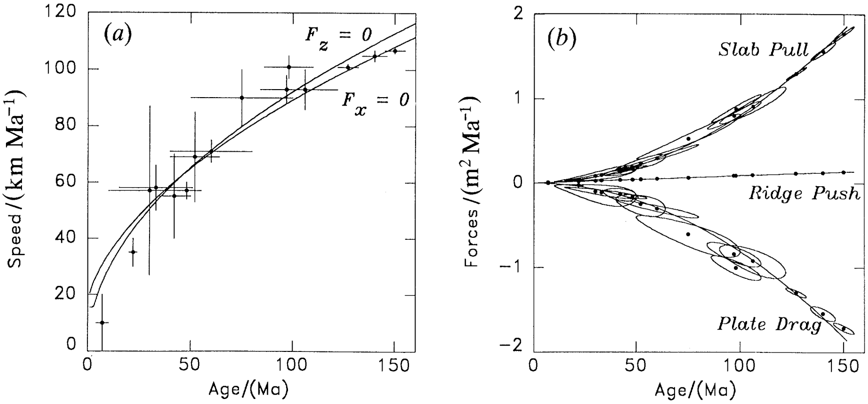

Figure 3. (*a*) Velocity–age relation for the plates at present and (*b*) force budget, with values shown for 15 trenches (from Stefanick & Jurdy 1991). (*a*) Median rate of motion against median age at 15 trenches and ranges of values (after Carlson *et al.* 1983*a*, fig. 2). The two curves correspond to the net vertical force equals zero and the net horizontal force equals zero. (*b*) Force balance against age showing slab pull, ridge push and plate drag, together with the error regions corresponding to the error bars in *a*. (Data points from Carlson *et al.* 1983*a*, fig. 3.)

The plate-drag torque $\boldsymbol{\tau}_{\mathrm{D}}$ is assumed proportional to the angular momentum of the plate:

$$\boldsymbol{\tau}_{\mathrm{D}} = -C_{\mathrm{D}} \boldsymbol{I}_{\mathrm{p}} \boldsymbol{\omega}_{\mathrm{p}}, \tag{2}$$

where $\boldsymbol{I}_{\mathrm{p}}$ is the moment of inertia tensor of the plate, $\boldsymbol{\omega}_{\mathrm{p}}$ is the plate's angular velocity, and C_{D} is the constant of proportionality. The drag model is the simplest one possible, ignoring any counterflow beneath the plate. The remaining torques are all along plate boundaries, and if the force is locally normal to the boundary and proportional to the element length,

$$\boldsymbol{\tau} = \int \boldsymbol{r} \times \mathrm{d}\boldsymbol{F} = C \int \boldsymbol{r} \times \left[\frac{-\boldsymbol{r} \times \mathrm{d}\boldsymbol{r}}{r_{\mathrm{E}}}\right] = C r_{\mathrm{E}} \int \mathrm{d}\boldsymbol{r} = C r_{\mathrm{E}} \boldsymbol{r}_{\mathrm{c}}, \tag{3}$$

where r_{E} is the radius of the Earth, $\boldsymbol{r}_{\mathrm{c}}$ is the vector from the initial to the final point on the boundary segment (chord vector), and C is a constant of proportionality.

The slab-pull torque is proportional to the chord vector of the boundary and also depends on the age of the slab and the subduction rate (Carlson *et al.* 1983*a*, *b*; Harper 1975, 1986):

$$\boldsymbol{\tau}_{\mathrm{SP}} = C_{\mathrm{S}} |v_{\mathrm{n}}| \, t^{\frac{3}{2}} \boldsymbol{r}_{\mathrm{c}}, \tag{4}$$

where C_{S} is the constant of proportionality, v_{n} is the velocity component normal to the boundary, $\boldsymbol{r}_{\mathrm{c}}$ is the chord vector, and t is the age at the trench at the midpoint of the chord. The ridge-push torque is simply proportional to the age:

$$\boldsymbol{\tau}_{\mathrm{RP}} = C_{\mathrm{R}} t \, \boldsymbol{r}_{\mathrm{c}}. \tag{5}$$

At a convergent boundary it seems physically reasonable and necessary to include collision forces which will act outward from the boundary. These collision forces would assume whatever values are necessary to achieve a torque balance but must be equal in magnitude and opposite in direction, much as internal forces inside a plate adjust in such a way that the plate moves rigidly. How should we model these?

Table 1

NA	latitude	longitude	rate (deg Ma^{-1})	SA	latitude	longitude	rate (deg Ma^{-1})
MJ	−58.3	−40.7	0.247	MJ	−82.3	75.7	0.285
C	−36.8	−70.7	0.251	C	−70.7	−131.3	0.232
GG	−67.2	−11.1	0.280	GG	−70.3	74.7	0.320
DM	−39.8	−61.4	0.246	DM	−81.6	24.9	0.293

Using equation (1) we obtain the vector form:

$$I_{\mathrm{p}}\,\boldsymbol{\omega} = (S|v_{\mathrm{n}}|\,t^{\frac{3}{2}}/r_{\mathrm{E}}^{2})\,\Delta\boldsymbol{r} + R(t/r_{\mathrm{E}}^{2})\,\Delta\boldsymbol{r}. \tag{6}$$

The simplest dynamical model for a continental plate without a large subduction zone is one that would balance plate drag against ridge push alone (and so in equation (6) the first term on the right would be dropped). In table 1 the absolute motions computed by using this model are compared with the estimates of Minster & Jordan (1978), Chase (1978*a*), Gripp & Gordon (1990), who computed absolute motions for NUVEL (DeMets *et al.* 1990), (abbreviated MJ, C, and GG, respectively) for North America and South America.

DM is a dynamical model that balances plate drag against ridge push alone and the rough agreement suggests that ridge push alone makes the major contribution to the active forces on these two plates. The link between relative and absolute plate motions is often based on hotspots and the assumption that they represent components of a single fixed set. However, hotspots may be deflected by the plate motions (Petronotis & Jurdy 1990) and in this respect dynamical model estimates may prove to be useful in defining an ‘absolute’ framework.

4. Cenozoic evolution of torques

For our previous study (Jurdy & Stefanick 1988) of driving forces over the Cenozoic, we used the reconstructions of Gordon & Jurdy (1986). In their analysis the Cenozoic Era is divided into six intervals; instead of regularly spaced time divisions, the times of major plate reorganizations were used as natural temporal boundaries: 64–56 Ma, 56–48 Ma, 48–43 Ma, 43–25 Ma, 25–10 Ma, and 10 Ma–present. The chron numbering convention and age assignments in millions of years of Harland *et al.* (1982) are followed. The absolute angular velocities of each plate relate to the hotspots for the six time intervals and the geometric factors characterizing the individual plates for each reconstruction were tabulated (Gordon & Jurdy 1986, tables 3 and 4). We used these in our computations of the torques acting on the plates (Jurdy & Stefanick 1988). Drag torque is found from the product of the moment of inertia tensor and the observed angular rotation vector. Balanced torque is found from an angular velocity vector which would exactly balance drag with active torques. These two torques are compared plate by plate and a global comparison is made by summing over the plates. (A full description is given by Jurdy & Stefanick (1988), eqs 12–15.) The global torque balance is shown for the interval 10 Ma to the present in figure 4 and for 64–56 Ma in figure 5. The misfit in torque, almost constant

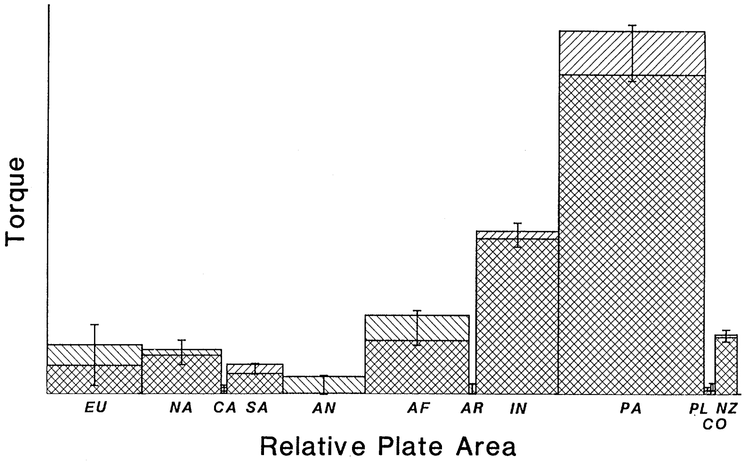

Figure 4. Torque comparison for individual plates between balanced torque and drag torque for the interval 10 Ma to present shown in figure 1. Plate velocities are in the hotspot framework (Gordon & Jurdy 1986, table 3). Torques obtained by solving the balancing equation (6) are shown by positively sloped lines, and the drag torque by negatively sloped lines. The misfit between the two torques is indicated as error bars about the mean. (From Jurdy & Stefanick 1988.)

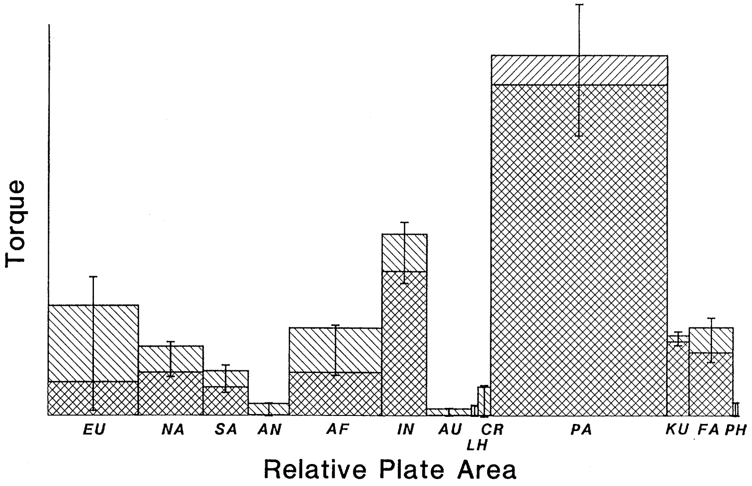

Figure 5. Torque comparison for individual plates between balanced torque and drag torque for the interval 64–56 Ma shown in figure 2. Plate velocities are in the hotspot framework (Gordon & Jurdy 1986, table 3). The torques and misfits are depicted as in figure 4. (From Jurdy & Stefanick 1988.)

for the past 43 Ma, shows an elbow and then a linear increase back in time to 64 Ma (figure 6). Alternatively, the misfit could be described as a hyperbola as shown by the dashed curve in figure 6. The hyperbola corresponds to the mean square error being the sum of two independent parts, one a constant (model misfit?), and the other proportional to $(\text{time})^2$, i.e. a systematic error growing with age (errors in reconstructions for boundaries and plate motions?). A generalization of this one-dimensional force model to two dimensions yields a torque model which is fairly stable over the Cenozoic Era.

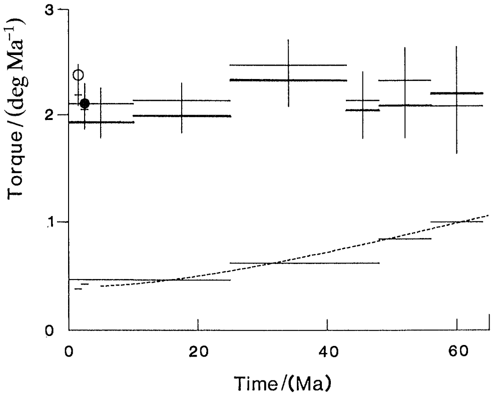

Figure 6. Drag torque and balance torque magnitudes for present and Cenozoic time, with the line segments corresponding to the six time intervals used for reconstructions (Gordon & Jurdy 1986). Drag torque for the present is shown as the open circle for the plate motion model of Minster & Jordan (1978) and the solid circle for the model of Chase (1978*a*); for display these are arbitrarily displaced from the ordinate. The upper sequence shows $|\tau_B|$, $|\tau_D|$, and $|\epsilon|$ with time; $|\epsilon|$ is shown with vertical bars about the mean torque value; the heavier of the lines is the drag torque. The lower sequence shows the evolution of the misfit $|\epsilon|$ as a solid line; the dashed curve is the hyperbola showing a systematic increase in the r.m.s. error with time. (From Jurdy & Stefanick 1988.)

5. Two-dimensional model with stress

The motion a rigid plate averages of the torques acting on the plate various combinations of forces can result in the same net motion. However, stress responds more locally, and sets of forces with the same net torques can produce stress patterns that are quite different. Recent compilations of stress measurements show fields changing in character over an individual plate and a tendency for the maximum horizontal stress direction, $S_{\mathrm{H,max}}$ to be parallel to the absolute plate motion (Zoback *et al.* 1989). These observations of stress orientations and magnitudes allow detailed comparison with the predictions of models for various combinations of forces driving the plates. In our study we presented (Stefanick & Jurdy 1991) a set of models for possible forces driving the South American plate and compared them with observed stress measurements. The South American plate was chosen for study because the slab-pull component should be small and the other components are reasonably isolated geographically. Thus the plate balance is largely between ridge push and plate drag, with the opportunity of resolving the effects of trench suction or collision at the subduction zones. We estimated the ridge-push force to be about 5×10^{13} N m^{-1}, where the ocean floor is oldest, with an estimated age of 144 Ma, and the lithosphere has a thickness of 6×10^4 m. If the ridge-push force is balanced by drag acting over the entire plate, and the proportion of oceanic plate is 50%, then the stress due to the net force is a maximum at the midpoint and is about 500 MPa. Two small slabs supply extra forces, at the Scotia and Caribbean arcs, contributing about 20% of the ridge-push force. Most remarkable is the nearly uniform E–W orientation of the $S_{\mathrm{H,\,max}}$ directions in the regional stress field (figure 7), which at high altitudes are extensional. The two-dimensional horizontal stress patterns are compared for successive models of combinations of driving forces. Models with ridge push, slab pull at the Scotia and Caribbean arcs, and trench suction near the west coast, all balanced by plate drag, produce similar stress patterns to those observed (Zoback *et al.* 1989). A model for the stress orientations for the North American plate

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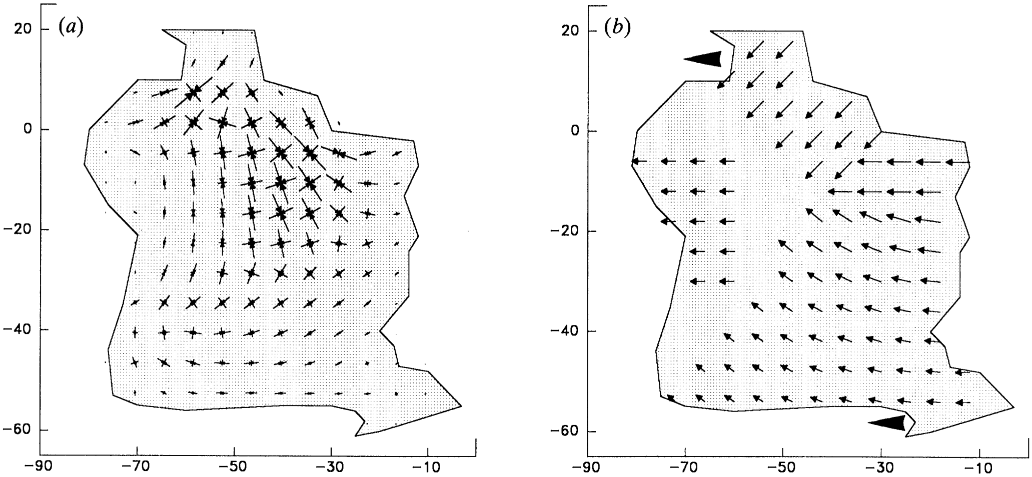

Figure 7. Stress pattern for the South American plate resulting from ridge push and slab pull (heavy arrows at the Scotia and Caribbean arcs), as well as trench suction at the western boundary, balanced by plate drag. Latitude and longitude are used as cartesian coordinates. (*a*) Principal horizontal stresses shown with outward arrows indicating tension and inward arrows for compression. Every other grid point shown. (*b*) Forces acting on plate shown as arrows at grid points.

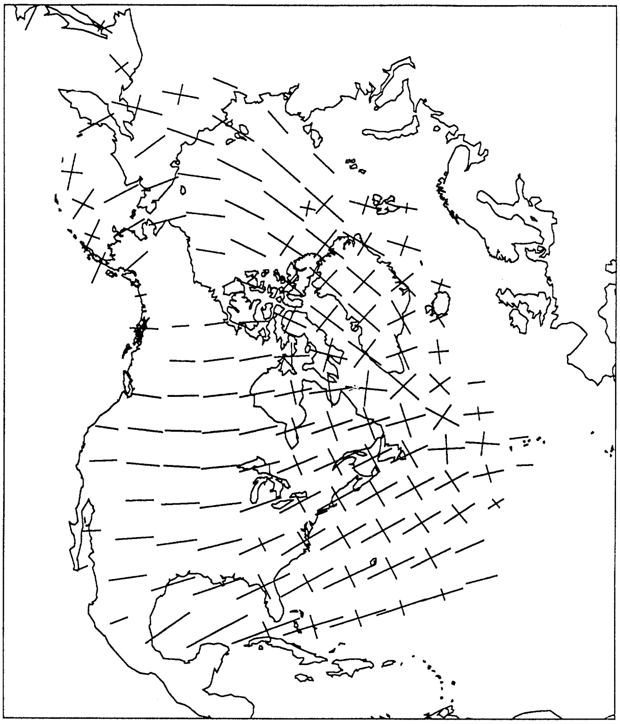

Figure 8. Stress orientation for the North American plate resulting from ridge-push and collision force at Aleutian arc. The line segments indicate directions of compression on a logarithmic scale. Extension not shown.

Figure 9. The pole position ellipses for the relative motion of NA and EU for the following plate motion models: MJ, Minster & Jordan (1978); C, Chase (1978); N, DeMets *et al.* (1990). The trend lines, B, are great circle arcs through Norway showing the range of stress directions from earthquakes (Bungum *et al.* 1991) and the pole positions as V for VLBI measurements of Herring *et al.* (1986).

is shown in figure 8, for the case of ridge push, with a small amount of collision force at the Aleutian arc.

The force field acting on a plate is a combination of the body and boundary force densities. Ridge push is a body force acting over the oceanic part of the plate, whereas plate drag is a passive body force acting over the entire plate. Slab pull is treated as a boundary force, as is collision. We find the force field for the combination of the forces hypothesized to be acting. Using this force field we calculate the stress tensor field and also the directions of the two principal horizontal stresses; these define the stress régime when compared with the vertical stress. Directions and stress régime are compared with observations.

For simplicity a planar model is described. The force (f_x,f_y) and torque M_z due to ridge push (and trench suction or collision) are calculated and the plate velocity (v_x, v_y) and angular velocity ω_z, required so that the net plate drag force and torque will balance, are calculated. The stress field is then calculated from the momentum equations (iteratively using a relaxation method on the displacements)

$$\partial \tau_{xx}/\partial x + \partial \tau_{xy}/\partial y + f_{ax} + f_{px} = 0, \tag{7}$$

$$\partial \tau_{yx}/\partial x + \partial \tau_{yy}/\partial y + f_{ay} + f_{py} = 0, \tag{8}$$

and boundary conditions. Here $\tau_{xx}, \tau_{xy}, \tau_{yx}, \tau_{yy}$ are the stress components, f_{ax}, f_{ay} the components of the active force per unit area and f_{px} the drag force per unit area. The boundary conditions specify the stress values at the appropriate points and these must be consistent with the net force calculations or the iteration misfit will not converge to zero. We treat the collision as a given (active) force rather than a passive (response) force. This is because we are treating the plate by itself. In a global model the collision force would adjust itself and so would be a passive force analogous to drag. Comparison of the derived kinematics and deformation with our dynamical models, including stress, should constrain possible force magnitudes and distributions on the plates. Observations from the World Stress Map will provide additional constraints, in that quite different stress patterns can result from sets of forces that produce the same net motion.

Norway has a low level of seismicity, with only a few earthquakes with magnitude greater than 5. Bungum *et al.* (1991) studied the focal mechanisms of Norway and argue that their solution indicates that the maximum compressive stress direction is due to ridge push. However, the maximum stress direction is only roughly parallel to the pole they use at 52° N, 126° E for the ridge-push force. Previous estimates of the rotation for Eurasia to North America at 62° N, 135° E are based on average motions over the past 3–5 Ma. In fact, the pole improved with VLBI measurements comes closest to fitting the current stress directions, as indicated by earthquake focal mechanisms shown in figure 9 by great-circle arcs through Norway.

6. Discussion

Present-day kinematic models show that oceanic plates move most rapidly and in the direction of the attached subducting slabs. Continental plates move more slowly and away from their ridges, but the errors in their motions are perhaps 30 % of the motion. Absolute plate motion models suggest that oceanic plates are driven by a combination of slab pull and ridge push, balancing plate drag. These force models must be first converted to torque models because plates are spherical shells moving over the Earth's surface. Since these forces are different functions of age and speed, coefficients are determined and these are used to estimate the relative magnitudes of these forces. The same coefficients can then be used to estimate the motion for continental plates and this works well for North and South America but not for Eurasia. Physically, we should expect a collisional force between Eurasia and the Indian and Pacific plates and this force is not modelled yet, but seems to balance the ridge push from the Atlantic. Modelling collision force is a prerequisite for more sophisticated models.

Plate reconstructions provide an important test for kinematic and dynamic models. Velocities at subduction zones are reconstructed and from these the ages and forces acting on the plates are inferred. Using the provisional force estimates, and converting these to torques, we find that global torque is nearly constant throughout the Cenozoic. For the earlier reconstructions the misfit to the model increases, probably due to uncertainties in locations of subduction zones and the velocities there. The global fit over the Cenozoic suggests that the force balance model is generally valid.

Stress observations, even if only directional, can be compared with the output of stress models using different combinations of boundary and body forces. At this stage conclusions can be only provisional, but for South America a combination of ridge push and slab pull (from two small arcs) balancing plate drag and some small collision along the west coast seems to give a more realistic model of the observed stress orientations than other combinations of forces. Stress responds locally to forces on the plate, so in detail, the stress orientations cannot always be in the direction of absolute plate motions. More accurate modelling of the ridge-push field and an allowance for lateral inhomogeneity, particularly for continental regions, would seem to be necessary as the next step. Stress magnitudes would further constrain driving force models, but these observations are at present very limited. However, some inferences can be made from the observed stress régimes about the relative magnitudes of the horizontal and vertical stresses: non-extensional focal mechanisms in the Andes at depths of more than 30 km correspond to a lower bound of 830 MPa for the maximum horizontal stress. Stress orientations, as estimated from earthquakes for the area near Norway, seem to be aligned along the small circles of the relative pole vector of North America and Eurasia which brings us full circle to the kinematics. In summary, stress observations in combination with stress models will improve our estimates of the relative importance of the forces (torques) driving the plates.

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Discussion

M. H. P. Bott (*Durham University, U.K.*). Does Professor Jurdy have any handle on the viscosity underneath the plates, as it varies from one plate to another?

D. M. Jurdy. No, by using a linear drag model we are assuming a constant viscosity model. I do not think we want to add a lot of individual parameters at this stage.

M. J. R. Wortel (*Utrecht University, The Netherlands*). Is the misfit between the observations and the model predictions due to the relation used between the absolute velocity and the age of the lithosphere at the Trench?

D. M. Jurdy. Most of the misfit is due to uncertainties in the reconstruction, both for subduction velocities and plate geometry. These uncertainties are the portion that grow as we go back in time.

L. Fleitout (*École Normale Supérieure, Paris, France*). It can be argued that slab pull is proportional to the square root of lithospheric age and not to $(\text{age})^{\frac{3}{2}}$. Would the uncertainty in the relationship used to calculate the slab-pull force have an important effect on these models and the calculated stress distribution?

D. M. Jurdy. The $vt^{\frac{3}{2}}$ law that is used for slabpull is generally agreed to be the correct one, and it gives good correlations for the present.

J. Cartwright (*Imperial College, London, U.K.*). Is there a correlation between the plates with large areas of continental lithosphere, which seem to move slower than the oceanic plates and the absence of a low velocity zone beneath cratonic cores?

D. M. Jurdy. At least for the Cenozoic Era, large continental plates lack subducting slabs and thus move more slowly than oceanic plates. This may not always have been true.