Some Simple Physical Models for Absolute Plate Motions

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Although the relative angular velocities of the earth's plates are well known, the velocities relative to the underlying mantle and the nature of the driving forces are not. We calculate several solutions to the 'absolute' velocity field from the hypothesis that no net torque is exerted on the lithosphere as a whole and a series of assumptions about the forces driving plate motions. The force models include viscous drag at the base of all plates (plus arbitrary forces at ridges and trenches that exert torques of equal magnitude but opposite sign on adjacent plates), drag concentrated beneath continents, drag concentrated to oppose the horizontal translation of sinking slabs, gravitational pull by sinking slabs, and linear combinations of these. These models generally give absolute plate velocities that are very similar to those calculated on the premise that a set of 'hot spots' provides a fixed reference frame. This removes some of the rationale for attributing to these hot spots any significant contribution to the driving forces. The similarity of plate motions inferred from markedly different driving mechanisms precludes using the velocity fields to discriminate among proposed models. Many of the hot spots may be simply due to intraplate tensional stress associated with the forces acting on present plate boundaries. This suggests that calculation of intraplate stress can ultimately serve to choose among force models.

The theory of plate tectonics, which dictates that the earth's surface is made up of a relatively small number of rigid spherical shells or plates of lithosphere that move with respect to each other, has synthesized a wide range of observations from various fields of geology and geophysics. Although the relative motion of the larger plates, about 10 in number, is reasonably well determined [*Morgan*, 1968; *Le Pichon*, 1968; *Chase*, 1972; *Minster et al.*, 1974], the 'absolute' motion of the plates relative to the underlying mantle and the physical mechanisms governing plate motions are not. In this paper we will examine the implications for absolute plate motions of several possible simplified driving mechanisms and relate the results to the origin of seamount chains and midplate stress.

Previous estimates of the absolute velocities of plates were based on the premise that one plate is stationary [*Knopoff and Leeds*, 1972; *Burke and Wilson*, 1972] or that some set of 'hot spots' provides a reference frame fixed with respect to the lower mantle [*Wilson*, 1965; *Morgan*, 1971, 1972, 1973]. Our philosophy in this paper will be first to postulate the nature of the forces driving plate motions and then to examine whether any particular plate might be more or less fixed or whether the 'hot spot poles' have an underlying physical explanation. We shall find that a number of independent postulates for the driving forces produce absolute velocity fields that are very similar to those that have been calculated with respect to a set of hot spots.

DRIVING FORCES

The absolute velocities of the earth's plates may be calculated from simple physics and three main assumptions: (1) the boundaries and relative velocities of the plates are known, (2) there is no net torque on the lithosphere as a whole, and (3) motions in the underlying mantle may be neglected in comparison with plate motions. The first assumption is quite good. We show below that changes in the catalog of plates or in relative rotation vectors within current uncertainties do not appreciably affect absolute velocities. The second assumption is also quite reasonable. It follows as a condition for mechanical equilibrium from the postulate that plates of lithosphere are rigid and transmit horizontal forces, and it is equivalent to the statement that the lithosphere is not accelerating. Torques arising from sources external to the earth (e.g., tides) have not been included. The third assumption may not be correct. It is included for want of better information to give meaning to the motion of absolute velocity. If mantle velocities were known, the calculations below could be repeated, since all forces considered are either independent of or linearly proportional to the relative velocity between plate and mantle.

Possible mechanisms for exerting torque on plates include viscous drag on the base of plates and buoyancy forces at midocean ridges and subduction zones. We treat ridges and subduction zones as line forces, though strictly, these features have finite width.

It is more convenient to treat the lithosphere as a whole than to consider the balance of torques on individual plates for at least two reasons. (1) The uncertain transfer of forces between plates at transform and thrust faults then does not enter into the problem. As an example of such potential difficulties, normal forces across transform faults are not a general property of this type of plate boundary but depend on the general state of stress in the lithosphere. (2) Bilaterally symmetric features such as ridges do not need to be considered explicitly in the torque balance, since they exert no net torque on the lithosphere. An obvious corollary of this approach is that our models for velocity cannot be used to constrain the forces associated with such symmetric structures.

Drag at the base of plates due to the viscosity of the asthenosphere is an important element in the equations balancing torques for any force model. We assume throughout that drag obeys a simple viscous law, so that the drag force is linearly proportional to the velocity of the lithosphere relative to the presumedly fixed underlying mantle. In the simplest model a uniform drag coefficient beneath all plates is adopted. There are grounds for believing that the drag law is complicated by frictional heating [*Schubert and Turcotte*, 1972] and a power law dependence of viscosity on strain rate

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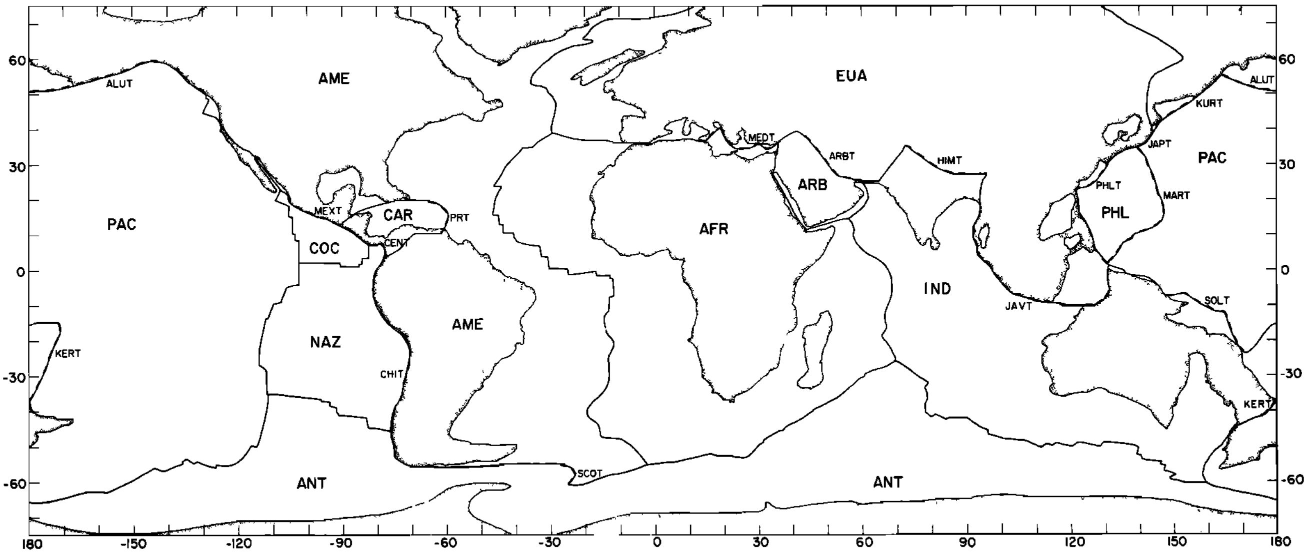

Fig. 1. Outline of the plates, continental regions (shaded borders), and subduction zones (heavy dashed lines) considered in this study. Cylindrical equidistant projection.

[*Weertman*, 1970]. Incorporation of these effects is probably premature at this time.

The drag coefficient may be regionally variable. Continents, which generally have less well-developed low-velocity zones than oceans, may experience greater drag [*Knopoff*, 1972; *Minster et al.*, 1974; *Alexander and Sherburne*, 1972]. It has also been proposed that drag opposing the horizontal motion of downgoing slabs may provide the major resistance to plate motion, although the physical mechanism for this is unclear [*Talwani*, 1969; *Tullis*, 1972].

Pull on the lithosphere due to negative buoyancy of the downgoing slab is an important element of most dynamical models for plate motions [*Elsasser*, 1969; *Jacoby*, 1970; *Isacks and Molnar*, 1971; *Richter*, 1973*a*]. According to *Morgan*'s [1972] model the absolute velocity of each of the abutting plates at most subduction zones has a component toward the trench, though the trenchward component of velocity of the subducted plate is generally larger than that of the overthrust plate. This would imply that whereas the subducted slab appears to exert a torque on both plates, the torque exerted on the downgoing plate may be larger in magnitude. Such a net torque would probably be independent of absolute plate velocity, since no coupling to the lower mantle is explicitly involved. The direction of the force is likely to be normal to the trench by reason of symmetry.

COMPUTATION OF ABSOLUTE VELOCITIES

We compute absolute velocity fields for various possible driving mechanisms by balancing the torques on the plates. As the relative velocities of all plates are reasonably well known, the principal unknown is the absolute velocity of any chosen plate. A three by three system of equations in the vector components of that velocity results when torques are summed (appendix).

The boundaries of the plates that we considered in these calculations are shown in Figure 1. The six major plates (PAC, AME, AFR, EUA, IND, and ANT) compose most of the earth's surface area. We included five additional smaller plates (NAZ, PHL, ARB, CAR, and COC) for which the boundaries and the motions relative to a larger plate are

TABLE 1. Adopted Values for Relative Plate Motions

					Relative Rotation Vector†			
Plate	Area*	Continental Area*	Latitude, deg	Longitude, deg	ω, 10^{-7} deg/yr	ω_x	ω_y	ω_z
PAC, Pacific	2.664	0.046			0.			
EUA, Eurasian	1.675	1.463	63.5	-90.1	8.88	-0.01	-3.96	7.95
AME, American	2.486	1.494	52.0	-73.0	7.86	1.41	-4.63	6.19
IND, Indian	1.503	0.531	58.3	-6.5	12.90	6.73	-0.76	10.97
AFR, African	1.931	0.872	57.6	-63.6	11.06	2.64	-5.31	9.34
ANT, Antarctic	1.477	0.442	69.4	-72.8	9.81	1.02	-3.30	9.18
NAZ, Nazca	0.405	0	59.0	-97.0	14.60	-0.92	-7.46	12.51
COC, Cocos	0.076	0	36.3	-108.5	23.71	-6.06	-18.11	14.05
PHL, Philippine	0.141	0	5.8	-21.2	4.87	4.51	-1.75	0.49
CAR, Caribbean	0.087	0.034	65.3	-75.0	7.76	0.84	-3.14	7.04
ARB, Arabian	0.121	0.104	56.5	-32.4	13.23	6.17	-3.91	11.03

*Earth's radius is set equal to 1.

†The listed rotation vector for a plate is appropriate for a coordinate frame in which PAC is stationary. A right-hand rule is used for the vector $\vec{\omega}$. The Cartesian coordinates x, y, and z are measured along the radius vectors through latitude-longitude pairs (0°, 0°), (0°, 90°), and (90°, 0°). North and east are positive.

reasonably well known. The plate boundaries that we adopted were taken primarily from seismicity maps and are those generally accepted except that the boundary between the American and Eurasian plates from the Nansen ridge to the Japan trench was taken from *Chapman and Solomon* [1973].

The relative plate velocities that we adopted are given in Table 1. The rotation poles and angular velocities are appropriate for a coordinate frame in which the Pacific plate is fixed. Rotation vectors for the major plates and for the Nazca and Cocos plates are from *Chase* [1972]; those for the Philippine and Arabian plates are from *Fitch* [1972] and *McKenzie and Sclater* [1971], respectively. We estimated the rotation vector for the Caribbean plate. The rotation pole for motion between the Caribbean and American plates that best fits the strikes of the El Pilar fault, the Puerto Rico trench, and three segments of the Cayman trough is at 28°S, 69°W. The angular velocity of the American plate with respect to the Caribbean plate is 1.8×10^{-7} deg/yr about this pole if the rate (0.66 cm/yr) of postglacial right lateral movement on the Boconó fault [*Schubert and Sifontes,* 1970] can be used as an index. This figure is in approximate accord with inferred post-Eocene displacement (0.5 cm/yr) along the northern boundary of the Caribbean plate [*Malfait and Dinkelman,* 1972] and with the rate of seismic activity along the Antilles island arc [*Molnar and Sykes,* 1969].

The boundaries of the continental regions that we used for velocity models in which drag is concentrated beneath continents are also shown in Figure 1. These boundaries include continental shelves as well as land areas. The limit of the continental shelf was generally taken to be the 2000-m isobath. The subduction zones included for models in which drag on or pull by the downgoing slab was an essential element are listed in Table 2 and shown in Figure 1. Some regions of very slow convergence (e.g., Azores-Gilbraltar and Macquarie-New Zealand) were not considered.

A couple of points are worth noting in passing. First, the conservation of energy equation in general gives little additional information, since symmetrical forces resisting motion at thrust and transform faults and symmetrical driving forces at ridges and perhaps also trenches are unknown and can be added in equal amounts. An exception to this is noted below: conservation of energy is useful for limiting the ratio of forces due to trench pull and to plate drag. Second, if stresses were computed from the driving mechanism models, ridges and faults would need to be included explicitly. More will be learned once this computation is done.

Absolute velocity fields were calculated for several proposed driving mechanisms that could be modeled quantitatively and that affected absolute velocity. Drag forces beneath the lithosphere, higher drag beneath continents, drag at island arcs, and driving forces due to slabs were considered. The resulting absolute velocities are given in Tables 3–5 and Figures 2–5.

DISCUSSION OF ABSOLUTE VELOCITIES

The simplest force model is one in which the drag coefficient is everywhere uniform and torques exerted on adjacent plates at trenches and ridges are equal in magnitude and opposite in sign. The absolute plate motions for such a model, which we designate model A, are illustrated in Figure 2. This model is one in which there is no net rotation of the lithosphere and for which the rms velocity of the lithosphere as a whole is a minimum (for the assumed plate boundaries and relative velocities).

A most interesting feature of Figure 2 is the striking similarity of the absolute velocity field for this simple model to the velocities calculated from the hypothesis of fixed hot spots [*Morgan,* 1971, 1972, 1973; *Minster et al.,* 1974]. *Minster et al.* [1974] commented, in fact, that a velocity model with no net rotation of the lithosphere would be very similar to their velocity model that best fit the traces of proposed hot spots. Although the fit of model A is close to that of the models of Morgan and Minster et al., it is not perfect: PAC in model A is moving slower than it is in the fixed hot spot models (Table 3), for instance, and AFR is moving faster (Table 4). There is also some disagreement in the poles of the more slowly moving plates, a consequence of the sensitivity of the small angular velocity vectors of these plates to small

TABLE 2. Subduction Zones Included in Calculations

Trench or Subduction Zone	Landward Plate	Length*	Depth,† km	Torque*§ T	T_x	T_y	T_z
ALUT, Aleutian	AME	0.601	1.6	0.487	-0.153	0.462	-0.033
MEXT, Mexican	AME	0.346	1.3	0.325	-0.263	0.094	0.165
CENT, Middle American	CAR	0.300	1.3	0.255	-0.207	-0.001	0.149
CHIT, Peru-Chile	AME	1.049	1.8	0.925	0.049	-0.401	0.833
PRT, Puerto Rico	CAR	0.209	2.0	0.161	0.077	-0.006	-0.142
SCOT, South Sandwich	ANT	0.100	3.1	0.085	-0.049	0.054	-0.044
MEDT, Mediterranean	EUA	0.437	0.8	0.318	0.127	-0.291	0.011
ARBT, Arabian	EUA	0.352	...	0.327	0.118	-0.237	0.191
HIMT, Himalayan	EUA	0.406	...	0.372	0.325	-0.115	0.140
JAVT, Java-Banda Sea	EUA	0.898	1.0	0.706	0.580	0.221	0.335
SOLT, New Britain-Solomon-New Hebrides	PAC	0.435	2.1	0.399	0.014	0.288	0.275
KERT, Tonga-Kermadec-New Zealand	IND	0.473	2.4	0.461	0.184	0.192	-0.377
KURT, Kuril	AME	0.389	2.2	0.370	-0.093	0.299	-0.197
JAPT, Japan	EUA	0.062	1.6	0.061	0.002	0.048	-0.037
PHLT, Ryukyu-Philippine	EUA	0.748	1.7	0.575	-0.039	0.219	-0.530
MART, Izu-Bonin-Mariana	PHL	0.703	2.2	0.548	-0.042	0.217	-0.502

*Earth's radius is set equal to 1.
†Average depth of trench below adjacent basin floor is estimated from U.S. Hydrographic Office charts.
§C_t = 1 (see (16) in appendix).

TABLE 3. Absolute Velocity of the Pacific Plate

Pole				
Latitude, deg	Longitude, deg	ω, 10^{-7} deg/yr	v at Hawaii, cm/yr	Explanation
		Models Discussed in Text		
-64.3	114.3	7.21	7.65	A (uniform drag beneath all plates)
-62.2	110.4	9.19	9.66	B (drag beneath continents only)
-63.9	107.1	6.88	7.16	C (drag opposing horizontal motion of slabs without ARBT and HIMT)
-56.4	104.5	7.92	8.18	D (maximum pull by slabs plus plate drag)
-66.5	121.7	7.09	7.61	A1 (model A with relative velocities from *Minster et al.* [1974]
-64.3	113.6	7.15	7.57	A2 (model A without PHL, ARB, and CAR)
-63.1	111.7	8.06	8.50	B1 (continents have 3 times more drag than oceans)
-64.2	104.6	7.12	7.35	C1 (model C with ARBT and HIMT)
		Fixed Hot Spot Hypothesis		
-67	107	10.5	10.9	*Morgan* [1972,1973]*†
-61.8	117.4	7.96	8.52	*Morgan* [1973]§
-67	135	11	12	*Winterer* [1973]*
-72	97	13	13	*Clague and Jarrard* [1973]*
-67.3	120.6	8.3	8.9	*Minster et al.* [1974]

*Hot spots beneath PAC only were considered.
†Discussed in his text
§Discussed in his table.

changes in the net rotation of the lithosphere.

To test the dependence of model A on the assumed parameters of the plates (Table 1), we considered several minor modifications to the model. We treated a model identical to A except that the relative rotation vectors of *Minster et al.* [1974] instead of those of *Chase* [1972] and *McKenzie and Sclater* [1971] were adopted. (We used the average of the North American-Pacific and South American-Pacific rotation vectors of Minster et al. for our AME-PAC pole and rate, since we did not divide AME into two plates.) The absolute velocities for this model (Al) are in essential agreement with those for model A (Table 3). We also treated a model identical to A except that three of the smaller and less well-defined plates were omitted: PHL was incorporated into PAC, ARB into IND, and CAR into AME. The absolute velocities of the major plates in this model (A2) are almost identical to those in model A (Table 3). Thus the present uncertainties in the boundaries and relative rotations of the plates of the world are sufficiently small not to affect significantly the results of this study.

When all of the drag at the base of the lithosphere is concentrated beneath continental regions, the absolute plate velocities are as shown in Figure 3. This model, designated model B, corresponds to no net rotation of the continents; the lithosphere has a net rotation of 2.0×10^{-7} deg/yr about the pole (−53.8°, 100.2°). The velocities in model B are quite similar both to those for model A and to those in models based on fixed hot spots (Tables 3-5). There are some small distinctions: PAC in model B moves faster than it does in either model A or models in which plates move over a suite of fixed hot spots (Table 3), and AFR moves more slowly in B than in A or than in *Morgan*'s [1971, 1972, 1973] absolute velocity models, though even slower rates for AFR have been proposed (Table 4).

Clearly, a linear combination of models A and B is also permissible. A closer fit of the absolute rotation rate of the Pacific plate to the rate past hot spots is obtained by a combination of the two models than by either end-member. The fit is closest if the drag coefficient beneath continents is 3 to 4 times that beneath oceans (model B1, Table 3). This is a very reasonable ratio, since the predominantly continental plates are moving 3 to 4 times slower than the predominantly oceanic plates in these models [*Minster et al.*, 1974].

If the principal drag resisting plate motions is concentrated to oppose the horizontal motion of sinking slabs, the absolute velocities are as pictured in Figure 4. This model, labeled model C, corresponds to no net rotation of island arcs; there is a small (0.5×10^{-7} deg/yr) net rotation of the lithosphere. ARBT and HIMT are not included in the catalog of subduc-

TABLE 4. Absolute Velocity of the African Plate

Pole			
Latitude, deg	Longitude, deg	ω, 10^{-7} deg/yr	Explanation
		Models Discussed in Text	
45.3	-61.2	3.99	A (uniform drag beneath all plates)
35.2	-48.4	2.10	B (drag beneath continents only)
46.7	-54.1	4.34	C (drag opposing horizontal motion of slabs)
55.7	-34.5	3.32	D (maximum pull by slabs plus plate drag)
		Fixed Hot Spot Hypothesis	
25	-55	2.45	*Morgan* [1973]*†
38.3	-36.9	2.37	*Morgan* [1973]§
		0	*Burke and Wilson* [1972]*
42.2	-65.2	1.9	*Minster et al.* [1974]

*Hot spots beneath AFR only were considered.
†Discussed in his text.
§Discussed in his table.

TABLE 5. Absolute Velocity of the Eurasian Plate

Pole			
Latitude, deg	Longitude, deg	ω, 10^{-7} deg/yr	Explanation
Models Discussed in Text			
40.4	-139.5	2.24	A (uniform drag beneath all plates)
-6.6	177.6	1.52	B (drag beneath continents only)
51.8	-130.3	2.26	C (drag opposing horizontal motion of slabs)
49.8	165.3	1.77	D (maximum pull by slabs plus plate drag)
Fixed Hot Spot Hypothesis			
28.4	133.9	0.82	*Morgan* [1973]*
72	10	4.1	*Duncan et al.* [1972]†
-18	132		*Burke et al.* [1973a]†
38.1	-110.5	1.2	*Minster et al.* [1974]

*Discussed in his table.
†Hot spots beneath EUA only were considered.

tion zones for model C, though a model (C1) in which these regions of continent-continent convergence are included in the subduction zone list gives nearly identical velocities (Table 3). The velocities in model C are similar to those of models A and B, though the agreement with velocities determined with respect to fixed hot spots is not quite as good as it is for the other two models; for instance, much of the Indian plate is moving faster than the Pacific plate. A linear combination of velocities from model C with those from models A and/or B can, of course, also be an acceptable solution. Thus the suggestion of *Talwani* [1969] and *Tullis* [1972] that slabs provide a major source of resistance to plate motion is quite consistent with the absolute velocities of the plates.

A number of velocity models in which torques on subducted plates were an essential component of the driving mechanism were considered. The torques exerted by slabs are balanced by drag beneath the plates (see the final two paragraphs in the appendix). Adding a velocity-independent torque $\mathbf{T}_0$ to the vector equation for the absolute plate velocities amounts to moving all absolute rotation poles toward the 'pole' defined by $\mathbf{T}_0$ and increasing the rms velocity of the earth's plates. Both the magnitude and the pole of the vector $\mathbf{T}_0$ defined by the sum of the torques exerted at the individual subduction zones are obviously dependent on the assumptions about the nature of the slab forces. If the pulling force per unit length of trench is for simplicity taken to be constant and if the 15 oceanic subduction zones in Table 2 are included in the force model, then the pole for $\mathbf{T}_0$ is at latitude and longitude −3.8°, 82.3°. The individual torques (arbitrarily scaled) are listed in Table 2. Note that because the force exerted by a slab is a vector, the torques are not proportional to trench length; the ratio of length to torque is always between 1.0 and 1.4 (in the units of Table 2). If the two continent-continent convergence zones (ABRT and HIMT) are also included, the pole for $\mathbf{T}_0$ is at 11.1°, 58.8°. The force per unit length of trench, of course, is probably not a uniform constant. If this force is proportional, say, to the average difference between the depth of the trench and the depth of adjacent ocean basin floor (Table 2), then a force model including 15 oceanic trenches would have a pole for $\mathbf{T}_0$ at −19.7°, 89.4°. Other possibilities for scaling (e.g., force per unit length of trench proportional to total length of subducted slab) might be envisioned.

One important conclusion may be made about all such force models for subduction zones: most of the torques exerted at individual trenches tend to be canceled out by torques at other subduction zones when torque balance is considered for the lithosphere as a whole. The magnitude of the torque sum $\mathbf{T}_0$ for the models discussed above is only 20–30% of the sum of the individual magnitudes of torques at subduction zones. Thus whatever importance the sinking slab may have for driving individual plates, that importance is lessened for the modeling of absolute plate velocities in the manner of this paper. A corollary to this statement is that uncertainties in the relative force per unit length acting at subduction zones are also less important by factors of 3–5 than might initially be imagined.

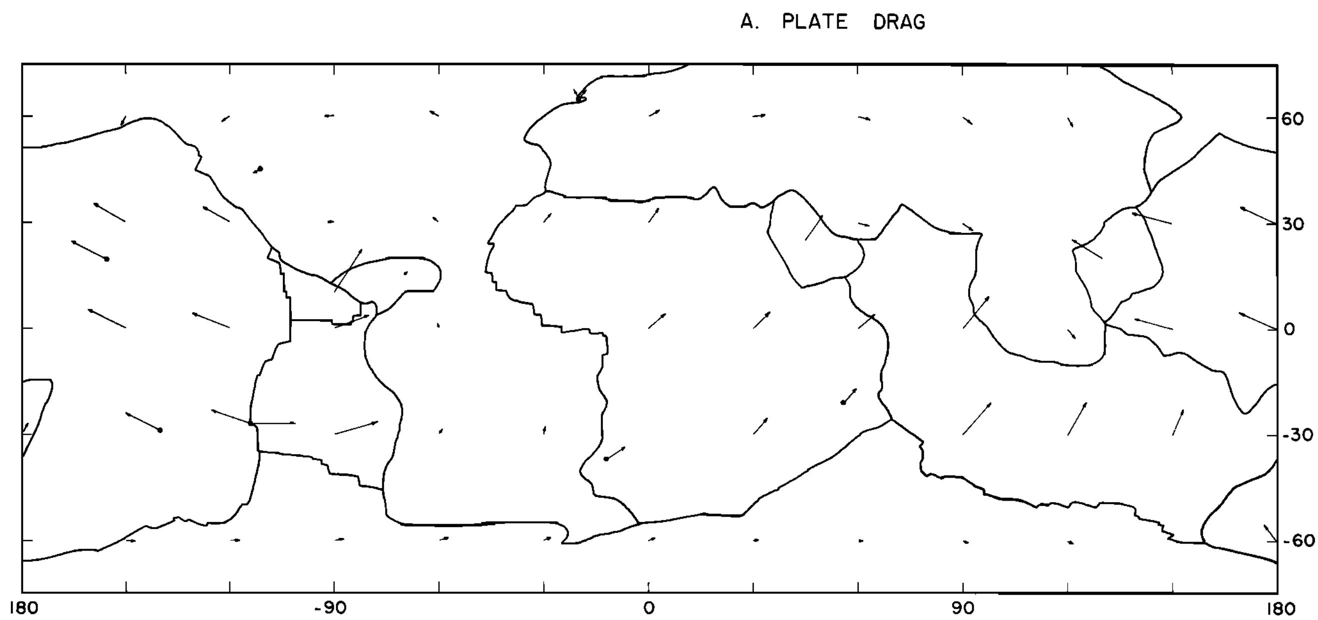

Fig. 2. Absolute velocities of the plates for force model A (uniform drag coefficient beneath all plates). Plate boundaries are from Figure 1. Arrows are proportional to the local plate velocity at the tail of the arrow; a length equal to the distance between tick marks on either the horizontal or vertical axis corresponds to a velocity of 20 cm/yr. Velocities are shown at convenient intervals of latitude and longitude and at several proposed hot spots (dots): Hawaii, Macdonald, Easter, Yellowstone, Iceland, Tristan, Reunion [see *Morgan*, 1973]. Cylindrical equidistant projection.

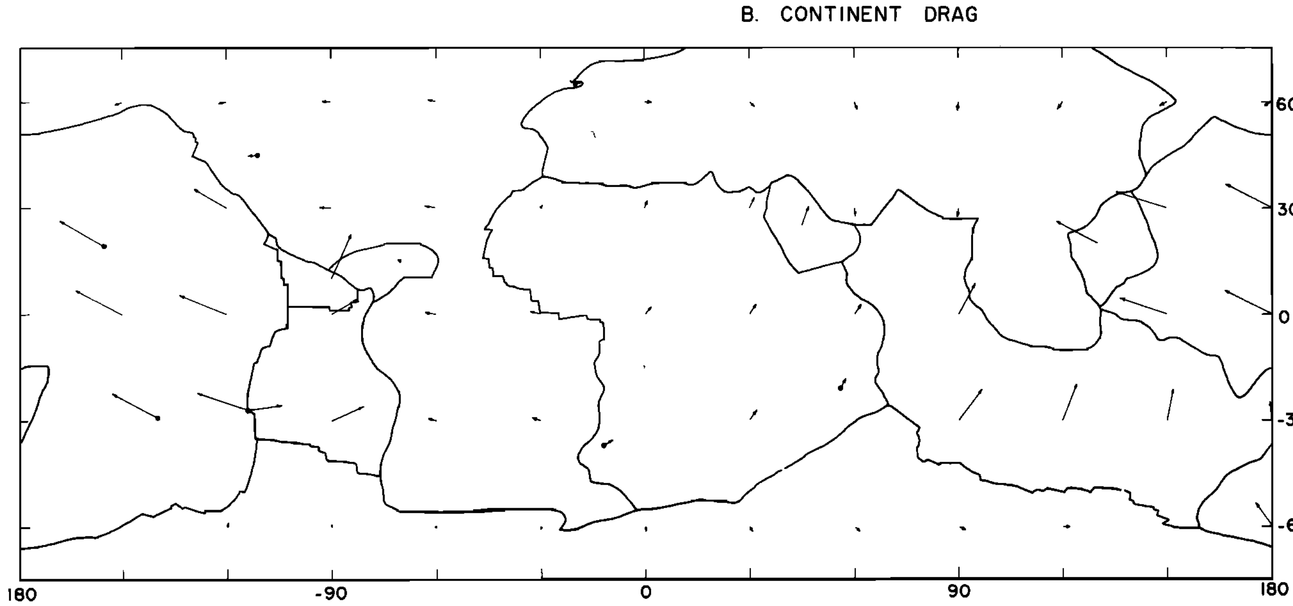

Fig. 3. Absolute velocities of the plates for force model B (drag concentrated beneath continents). All conventions are as shown in Figure 2.

Even when the relative force per unit length at trenches and the relative drag coefficient beneath plates are specified, there is still an arbitrary parameter reflecting the scaling of pull at trenches to drag (see (18) in the appendix). This results in a family of absolute velocity models for a given torque sum $\mathbf{T}_0$ and a given drag model.

A limit may be placed on the effect of driving forces at trenches on plate motions by simple application of conservation of energy. Clearly, if all of the energy dissipated per unit time by plate drag is equated to the power gained by subduction, then we will obtain an upper bound to the magnitude of the forces at trenches. That this estimate is indeed an upper bound follows from the omission in the energy balance of contributions from ridges or from forces on the overthrust plate at island arcs, since both of these terms likely are opposite in sign to the energy dissipated by drag.

A velocity model including the maximum possible effect of pulling by sinking slabs on subducting plates is shown in Figure 5. The model, designated model D, has been constructed by assuming a uniform drag coefficient beneath all plates and a uniform force per unit length at the 15 oceanic trenches listed in Table 2. (The model is developed in the appendix, (18)–(20), $C/D = 8.4$.) The velocities in this model are again quite similar to those in the force models previously discussed and to those in models constructed from a set of fixed hot spots (Tables 3–5). There is a net rotation of the lithosphere of 1.4×10^{-7} deg/yr about the pole (−3.8°, 82.3°) in model D.

There are two important conclusions that may be made from these various velocity models. The first is that the absolute velocities of the plates cannot serve to discriminate among models for the forces driving plates. A wide assort-

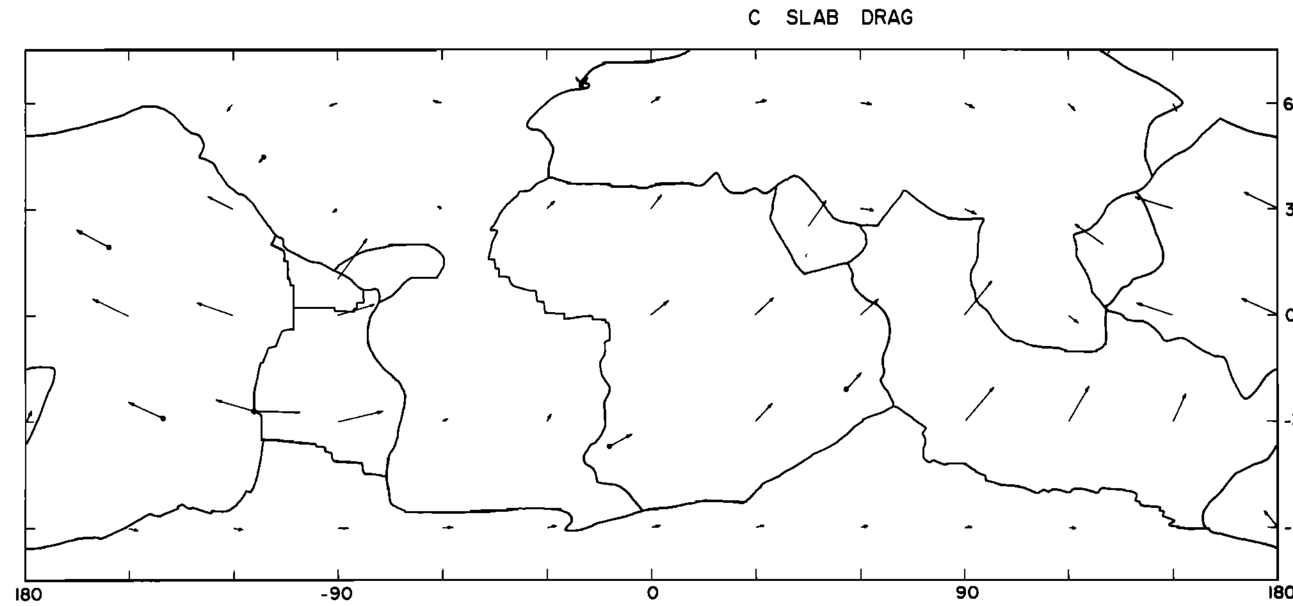

Fig. 4. Absolute velocities of the plates for force model C (drag concentrated to resist horizontal translation of sinking slabs). All conventions are as shown in Figure 2.

ment of assumptions about drag forces and about forces at subduction zones all yielded remarkably consistent patterns of absolute plate velocity. The similarity of velocities in different drag models presumably reflects the fact that either the earth's continental regions or the island arcs or probably the Precambrian shields provide an adequate sampling of the slower-moving plates. The similarity of velocities in different models for subduction zones is principally a consequence of the efficient cancellation of most of the torque exerted by slabs, especially torque about the z axis (through the north pole). It should be noted, however, that there are small differences among the various velocity models that might be used to cast one or more of them into disfavor. Models with net lithosphere rotation greater than perhaps 0.5×10^{-7} deg/yr (e.g., B and D) about an axis significantly different from the earth's spin axis, for instance, can be questioned on paleomagnetic grounds [*McElhinny*, 1973].

To be sure, we assumed a priori the relative plate velocities, which may also contain information about the driving forces. This information may be no easier to unravel, however. Are the predominantly continental plates moving more slowly than the predominantly oceanic plates because there is greater drag beneath continents [*Minster et al.*, 1974] or because the predominantly continental plates are not generally being subducted at island arcs, presumably because of the low density of continental and island arc lithosphere?

The second conclusion is that all of the absolute velocity fields from the various force models are very similar to plate velocities calculated with respect to a global set of fixed hot spots. This result adds a physical basis for the present motions of plates over such hot spots but removes some of the rationale for attributing to hot spots any important contribution to the driving mechanism for plates, in particular, for identifying hot spots with 'plumes' of hot material ascending from the lower mantle [*Morgan*, 1971, 1972, 1973; *Vogt*, 1971].

The internal consistency of the plate motions taken with respect to hot spots precludes an appeal to chance to explain the orientation of seamount chains and other proposed hot spot traces. *Minster et al.* [1974] have shown that the hypothesis that all hot spots have remained fixed with respect to one another for the last 10 m.y. is entirely consistent with relative plate velocities and hot spot traces, though the hot spots appear to show relative motion when longer time periods are considered [*Burke et al.*, 1973*b*; *Molnar and Atwater*, 1973]. The notion of plumes, however, has several serious difficulties. The greatest of these is that such plumes apparently cannot be modeled physically and can be defined only vaguely. No physically relevant condition has been found for a plume, with conduit radius much narrower than other dimensions of convection in the earth, to form or to be stable. The lack of interference on proposed plumes by plate-induced flow and flow to replenish the lower mantle is hard to explain, since shear would convert plumes into rolls. A shearing flow associated with plate motions would offset the top and bottom of a plume and cause the plume to tilt. Vertical buoyant forces would cause extension of the hot region into a sheet. The effect of shear on rolls has been discussed at length by *Richter* [1973*b*]. Plumes were not modeled by Richter presumably because conditions for their stability without shear are unknown.

Instead of attempting to refute further a hypothesis that we cannot model we show in the next section that the simple assumptions about driving forces, which give absolute velocities in good agreement with those derived from the hypothesis of fixed hot spots, may also give rise to stresses that can produce seamount chains as a secondary effect without any need for mantle plumes.

Some Comments on Driving Forces and Intraplate Stresses

A qualitative discussion of forces on plate boundaries and the resulting stress field within plates may be made strictly from plane geometry. Forces perpendicular to the absolute direction of plate motion must originate at the plate boundaries and integrate to zero for each plate, since by definition they cannot be resisted by drag on the base of the plate. Zones of compression or tension perpendicular to absolute motion would occur from opposing forces on opposite sides of the plate. Tension is likely in an inside corner formed by subduc-

D. SLAB PULL

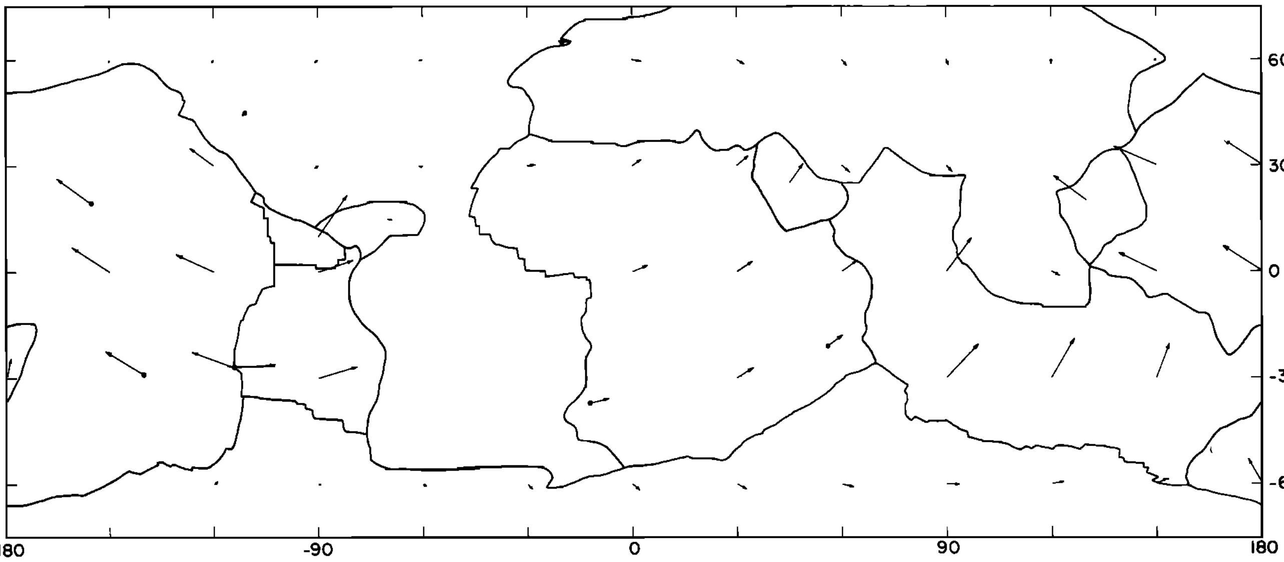

Fig. 5. Absolute velocities of the plates for force model D (maximum pull by slabs on subducting plates plus uniform drag law beneath all plates). All conventions are as shown in Figure 2.

tion zones, which probably pull on the plate. Conversely, plates are probably pushed by forces exerted at spreading centers [*Sykes and Sbar,* 1973], causing compression perpendicular to absolute motion (Figure 6). Gravitational sliding or spreading of the hot buoyant material at midocean ridges is the likely cause of this compressive force [*Lachenbruch,* 1973; *Artyushkov,* 1973].

Stress fields formed in this way are a tempting explanation for seamount volcanism, since tension on the plate can permit volcanic material to upwell passively from the asthenosphere. The heat source for seamounts, which represent only a minor fraction of the magmatic material erupted at midocean ridges, would be according to this hypothesis simply the ambient heat in the interior of the earth. Unlike plume theory the stress field in the interior of plates is amenable to calculation, given a set of forces acting on plate boundaries. Stress models, in addition, are contrained by data, such as midplate earthquake mechanisms [*Sykes and Sbar,* 1973], which are independent of the geometry of seamount chains.

The particular location of a seamount chain in a plate under tension may follow from *Richter*'s [1973*b*] proposal that secondary convention cells in the mantle should line up with absolute spreading directions to minimize destructive interference with the shear at the base of the plates. Although such cells would have no direct effect on the dynamics of a plate because they produce forces that sum to zero, the stress field would be modulated such that the upwelling axes of the cell would be the foci of maximum tension. These cells provide an explanation for the discrete spacing between seamount chains in the Pacific [*Richter,* 1973*b*]. Beneath slow-moving plates, such as Africa, a more random distribution of hot spots would be expected, since the small absolute velocity there would be less effective in aligning cells.

Continual motion of the plate with respect to the force field at its boundaries and secondary convective cells beneath could produce chains of volcanoes as new parts of the plate enter zones of tension. Such a seamount chain would be aligned along the absolute spreading direction, but the rate of seamount propagation could be somewhat different from the absolute spreading rate especially if the tensional crack giving rise to the chain modifies the stress field. When a major change in the plate kinematics occurs, both the absolute motion and the stress field within the plate change. A new direction of seamount tracks would then occur.

A difficulty with this hypothesis is that an explanation for the extinction of volcanoes is required. It may be that the local stresses associated with a mature volcano close the vents and preclude further eruption. The stress field also may be such that most of the strain occurs near the active volcanoes. A better understanding of this point will come once quantitative models for intraplate stresses are constructed.

Turcotte and Oxburgh [1973] have proposed that translation of plates over an ellipsoidal earth and lateral thermoelastic stresses, rather than the mechanism discussed above, cause tensional cracks that produce seamount chains and rift structures. Although these processes may provide an explanation for some tensional features, their failure to explain the spatial and temporal distribution of seamounts indicates that other mechanisms must be operating as well.

The greatest stresses from ellipticity are clearly at midlatitudes and on north-south moving plates. Seamount chains in the Pacific, however, are found both far from and near to the equator, and their trend is nearly east-west.

The thermoelastic mechanism of *Turcotte and Oxburgh* [1973] implies that seamount chains should be aligned subparallel to neighboring fracture zones and other fossil lineations rather than along the present direction of absolute motion. It would be hard to dismiss the self-consistent trends of seamount chains at presently active hot spots as coincidence. This hypothesis also cannot readily explain an intersection of seamount chains of different ages, such as the Hawaiian and Marcus-Necker chains, nor changes in the strike of a chain, such as at the Hawaiian-Emperor intersection.

SUMMARY REMARKS

The velocities of the earth's plates with respect to the underlying mantle have been calculated from a number of simple force models for driving forces. Drag beneath plates was in turn supposed to be characterized by a uniform law at

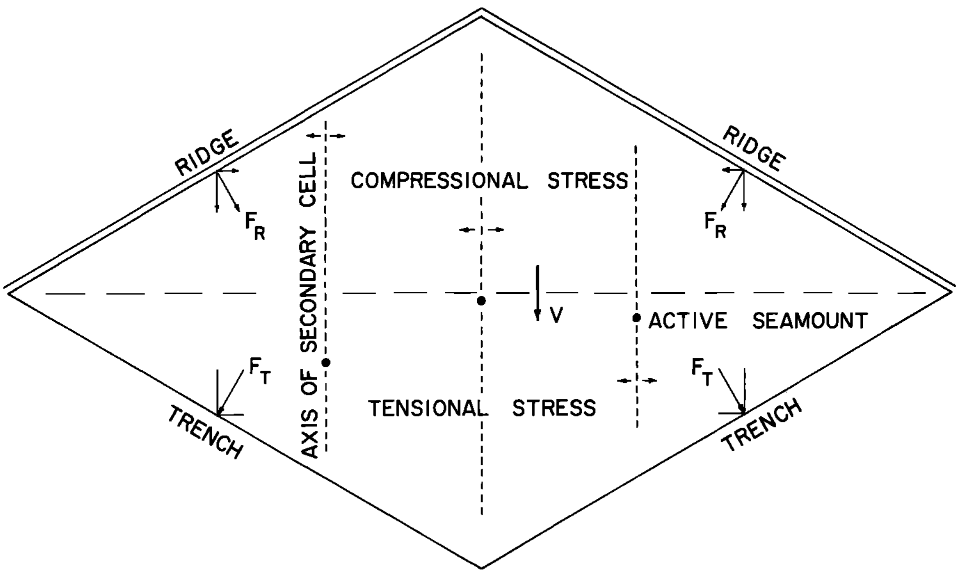

Fig. 6. Notional sketch of forces at plate boundaries (thin arrows), plate motion (heavy arrow), and intraplate stress. The possible relationship among seamount chains, intraplate stress, and secondary convection cells [*Richter,* 1973*b*] are discussed in the text.

the base of all plates, to be concentrated beneath continents, and to be concentrated to resist horizontal translation of subducting slabs. The forces exerted at ridges were always taken to be symmetric about the ridge axis. The forces exerted at trenches were treated both as being symmetric about the trench axis and as being concentrated primarily on the subducting plate.

The global pattern of absolute velocities is nearly the same for every model considered and is similar to that of the plate velocities calculated with respect to a set of presumedly fixed hot spots. This agreement of velocities in the models to motions estimated with respect to hot spots is best when the comparison is made with studies in which a large number of hot spots are simultaneously considered [*Morgan*, 1973; *Minster et al.*, 1974], rather than with studies of individual hot spots (Tables 3–5). These calculations thus lend a physical basis for absolute plate motions previously proposed but provide absolutely no support for the concept that thermal plumes in the lower mantle help to drive the plates. A good case can be made that intraplate hot spots are the result of tensional stresses arising from forces acting on the plate boundaries.

The absolute plate velocities therefore provide precious little handle on the forces moving the plates. Clearly, the next important calculation to perform is the quantitative modeling of intraplate stress. This stress field should be markedly different for some of the force models considered in this paper, even though the absolute velocities derived from such models are similar. Such indicators of intraplate stress as midplate earthquakes and the seamount chains discussed above should serve to eliminate some of the models proposed for plate driving forces.

APPENDIX

The relative motion of two rigid plates p and q on a spherical surface can be defined by an angular velocity vector $\boldsymbol{\omega}_{pq}$. The local separation velocity $\mathbf{v}_{pq}$ of the plates at a point with radius vector $\mathbf{r}$ is then

$$\mathbf{v}_{pq} = \boldsymbol{\omega}_{pq} \times \mathbf{r} \tag{1}$$

The rotation vectors are additive, e.g.,

$$\boldsymbol{\omega}_{pq} + \boldsymbol{\omega}_{qr} = \boldsymbol{\omega}_{pr} \tag{2}$$

Let 'plate' m be the lower mantle relative to which absolute velocities are calculated. If a linear drag law is assumed, the drag force $\mathbf{F}$ per unit area on any part of the base of the lithosphere is

$$\mathbf{F} = -D\boldsymbol{\omega}_{pm} \times \mathbf{r} \tag{3}$$

where D is the drag coefficient and may vary spatially.

The condition for equilibrium is that there be no net torque on the plates. By noting that the torque associated with drag is given locally by

$$\mathbf{T} = \mathbf{r} \times \mathbf{F} = -D\mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{r}) \tag{4}$$

the torque due to drag beneath an entire plate p is

$$\mathbf{T} = \int_{\text{plate } p} dA\ [D\mathbf{r} \times (\boldsymbol{\omega}_{pm} \times \mathbf{r})] \tag{5}$$

where the integration is carried out over the surface of the plate.

If D is constant on individual plates (one plate can be divided into several plates with different values of D but each having the same rotation), then the condition for equilibrium on the global lithosphere is

$$\sum_p D_p \int_{\text{plate } p} dA\ \mathbf{r} \times (\boldsymbol{\omega}_{pm} \times \mathbf{r}) = 0 \tag{6}$$

To evaluate this integral, we use a vector identity

$$\mathbf{L} \equiv \int dA\ (\mathbf{r} \times \boldsymbol{\omega} \times \mathbf{r}) = \int dA\ (\mathbf{r}\cdot\mathbf{r})\boldsymbol{\omega} - \int dA\ (\mathbf{r}\cdot\boldsymbol{\omega})\mathbf{r} \tag{7}$$

Letting $\mathbf{r} \cdot \mathbf{r} = 1$ (the radius is constant if we ignore variations in plate thicknesses), we obtain

$$\mathbf{L}_p = A_p\boldsymbol{\omega}_{pm} - \int dA\ (\mathbf{r}\cdot\boldsymbol{\omega}_{pm})\mathbf{r} \tag{8}$$

where A_p is the area of plate p. We can also write this as

$$\mathbf{L}_p = A_p\boldsymbol{\omega}_{pm} - \mathbf{S}_p\boldsymbol{\omega}_{pm} \tag{9}$$

Here $\mathbf{S}_p$ is a symmetric matrix defined by

$$S_{ij} = \int_{\text{plate } p} d\phi \int d\theta\ x_i x_j \sin\theta \tag{10}$$

where $i, j = 1, 2, 3$ are Cartesian indices and θ and ϕ are the spherical coordinates, colatitude and longitude, respectively. Defining

$$\mathbf{Q}_p = (A_p\mathbf{I} - \mathbf{S}_p) \tag{11}$$

where $\mathbf{I}$ is the three by three identity matrix, we can write (6) as

$$\sum_p D_p\mathbf{Q}_p\boldsymbol{\omega}_{pm} = 0 \tag{12}$$

Note that $\mathbf{Q}_p$ depends entirely on the geometry of plate p.

In general, any velocity-independent torque $\mathbf{T}_0$ on the plates may be added to the right-hand side of (12). Further, since from (2) $\boldsymbol{\omega}_{pm}$ may be written as the sum $\boldsymbol{\omega}_{po} + \boldsymbol{\omega}_{om}$ for some arbitrary plate o, (12) may be regarded as a three by three equation in the absolute velocity $\boldsymbol{\omega}_{om}$ of plate o, i.e.,

$$\boldsymbol{\omega}_{om} \sum_p D_p\mathbf{Q}_p = \mathbf{T}_0 - \sum_p D_p\mathbf{Q}_p\boldsymbol{\omega}_{po} \tag{13}$$

which can be easily solved. A further simplification is possible if D_p is uniform for all plates, since

$$\sum_p \mathbf{Q}_p = \frac{8\pi}{3}\mathbf{I} \tag{14}$$

For line segments having drag, such as island arcs, (13) may still be used except that $\mathbf{Q}_p$ is defined by

$$Q_{ij} = \int_{\text{line}} dl\ D_p(\delta_{ij} - x_i x_j) \tag{15}$$

where δ_{ij} is an element of the identity matrix.

Torques due to gravitational pull by subducted slabs are given by

$$\mathbf{T}_t = C_t \int_{\text{line } t} \mathbf{r} \times (\mathbf{dl} \times \mathbf{r}) \tag{16}$$

where C_t is a constant (assumed to be independent of local subduction rate) and where the line integral is taken counterclockwise about the subducted plate. By analogy to (7), in taking $\mathbf{r} \cdot \mathbf{r} = 1$,

$$\mathbf{T}_t = C_t \int_{\text{line } t} d\mathbf{l} = C_t(\mathbf{r}_2 - \mathbf{r}_1)_t \qquad (17)$$

where $\mathbf{r}_1$ and $\mathbf{r}_2$ are radius vectors to the two ends of the trench. The force exerted by a sinking slab is assumed in writing (16) to act in a direction normal to the strike of the trench.

When both torque exerted on the sinking plates by the subducted slabs and drag beneath all plates are included, then (13) becomes

$$\boldsymbol{\omega}_{om} \sum_p D_p \mathbf{Q}_p = \sum_t C_t(\mathbf{r}_2 - \mathbf{r}_1)_t - \sum_p D_p \mathbf{Q}_p \boldsymbol{\omega}_{po} \qquad (18)$$

Even in the simplified version of (18) in which all D_p are equal (to D, say) and all C_t are equal (to C, say), there is an arbitrary scaling of C to D that will affect $\boldsymbol{\omega}_{om}$. The maximum value of C/D (see below) can be fixed by equating the energy dissipated per time by drag forces to the power gained by subduction. The former quantity is

$$\int_{\text{all earth}} \boldsymbol{\omega} \cdot \mathbf{T} \, dA = D \sum_p \boldsymbol{\omega}_{pm} \cdot (\mathbf{Q}_p \boldsymbol{\omega}_{pm}) \qquad (19)$$

The latter is

$$\sum_t \boldsymbol{\omega}_{tm} \cdot \mathbf{T}_t = C \sum_t \boldsymbol{\omega}_{tm} \cdot (\mathbf{r}_2 - \mathbf{r}_1)_t \qquad (20)$$

where $\boldsymbol{\omega}_{tm}$ is the absolute angular velocity of the subducted plate at trench t. Both (19) and (20) are quadratics in C/D, and both have identical leading terms in $(C/D)^2$ for this simple case of uniform D_p and uniform C_t. Thus by equating the two expressions the desired limit on C/D follows directly. To derive this equality, it was assumed that no work was done at boundaries with symmetric forces such as ridges. If these had been included, an additional term, probably positive, would have appeared on both sides of (20). The value of C/D obtained from equating (19) and (20) would then be reduced. Thus our value of C/D is an upper bound if positive net work is done by symmetric boundaries. In the limit $D \to 0$ a very large absolute velocity about a pole defined by the torque would be necessary to balance (18), and (20) would be set equal to the work done at symmetric resistive boundaries.

It should be noted that the case of a net torque on the plates resulting from trenches accrues from our division of the earth into horizontal plates, sinking slabs, and the asthenosphere. Clearly, radially directed buoyant forces resulting from gravity can produce no net torque on the earth as a whole. There can also be no net torque supplied to the interior of the earth by plates and slabs, since there is no balancing source of torque at the base of the mantle. The slabs and the plates thus must exert equal and opposite torques on the interior. The magnitudes of the torque due to drag at the base of the plates, the torque exerted on the plates by slabs, and the torque exerted on the asthenosphere by slabs must therefore be numerically equal. The case of very large C/D is not likely to occur, since both C and D involve coupling of plates to the asthenosphere.

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