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# MANTLE CIRCULATION AND THE LATERAL MIGRATION OF SUBDUCTED SLABS

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Abstract. The irregular motions of plates and the irregular distribution of plate consumption and generation require that subduction zones and descending lithospheric slabs migrate laterally. Absolute plate motions indicate that slab migration is generally retrograde; that is, it is opposite to the direction of motion of the plates to which the slabs are attached, at rates of 10-25 mm $yr^{-1}$. As a result, the downward motions of slabs are generally steeper than their dips, probably because of their negative buoyancy relative to the surrounding mantle. An important consequence of lateral slab migration is the displacement of material away from one side of the slab and inward flow of an equal volume toward the other side. This generates a mass flux in the mantle that is comparable in magnitude with the flux involved in the overturn of the oceanic lithosphere. The flow induced by slab migration is, therefore, an important part of the large-scale mantle circulation associated with plate motions. Two-dimensional numerical models with retrograde slab migration explicitly prescribed as a boundary condition show that migrating slabs, in contrast with nonmigrating ones, are at an angle to streamlines in the surrounding mantle. Accordingly, the parallelism of Benioff-Wadati zones and streamlines cannot be used to discriminate among mantle flow models. Laterally migrating slabs do not separate streamlines that turn in different directions at depth, and these slabs do not turn backward beneath the plates to which they are attached. Instead, these slabs become parts of the circulations beneath the overriding plates, and even at depth they continue to move away from their oceanic ridge sources. Migrating slabs do not separate mantle convection cells. The numerical simulations also show that slab migration slows the flow under the attached plate by diverting part of it to the circulation beneath the overriding plate. The enhanced flow under the overriding plate pulls it more forcefully toward the subduction zone by increasing both the magnitude of the basal drag and the length of the overriding plate subject to a trench-directed drag. This drag on the overriding plate is the source of the "trench suction" force that appears in models of plate-driving mechanisms. Retrograde slab migration increases trench suction and may, thereby, play an important role in initiating and maintaining back arc spreading. Over long periods of time, migrating slabs sweep out large volumes of the mantle, altering flow patterns and dispersing material to great distances. By preventing the formation of regular closed cells, slab migration helps to mix the mantle and make it more chemically homogeneous. Slab migration is an important factor that causes mantle flow to be geometrically complex and time dependent.



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## Introduction

The earth's lithospheric plates have notably irregular motions and are produced and consumed at uneven rates. As a result, the configurations and positions of plate boundaries are constantly changing. At present, the Atlantic Ocean is widening, and the Pacific Ocean is shrinking, so that the subduction zones on the two sides of the Pacific Ocean are migrating towards each other (Figures 1a and 2). Therefore the subducted slabs are not only descending parallel to their dips, but they are also moving transversely [Elsasser, 1971]. At least some slabs move backward relative to the plates to which they are attached, a phenomenon that Elsasser [1971] termed retrograde motion. Because of this behavior the downward motions of slabs are closer to the vertical than their dips are (Figure 1b). This can be associated with the tendency of slabs to sink because of their negative buoyancy relative to the surrounding mantle [Elsasser, 1969; Turcotte and Schubert, 1971; Schubert et al., 1975]. When descending slabs move transversely through the sublithospheric mantle, some volume must be displaced away from their leading sides (lower sides in the case of retrograde motion, see Figures 1b and 1c), while an equal volume must move toward their other sides. The important point is that the magnitude of this mass flux is comparable to the mass flux involved in the recycling of all the oceanic plates [Garfunkel, 1975]. The flow related to slab migration is expected, therefore, to be a significant component of the mantle circulation that accompanies plate motions.

The purposes of the present work are to examine the geometry of transverse migration of subducted lithospheric slabs and to study the

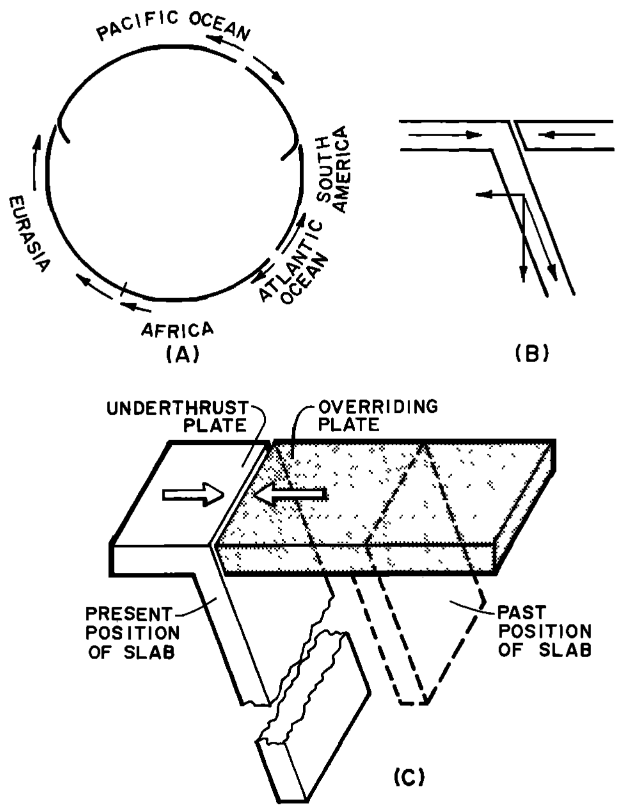


Fig. 1. The retrograde motion of subducted slabs. (a) Cross section through the earth plates. Owing to the opening of the Atlantic Ocean, the Pacific Ocean is shrinking, and the slabs on opposite sides of the Pacific Ocean are approaching each other. (b) The retrograde motion of a slanting slab causes the descent of subducted material to be steeper than the slab dip. (c) The manner in which retrograde migration takes place.

way in which this influences the flow in the mantle. First, we examine the geometry of slab migration and show that it generally appears to be retrograde. Next, some kinematic consequences for mantle circulation are presented. The properties of the flow driven by retrograde slab migration are then explored in simple two-dimensional models. The results are used as a guide to infer the contribution of retrograde slab motion to the more complex mantle flow and to examine some consequences of this additional component of mantle flow. It will be shown that slab migration is an important factor that causes mantle flow to be geometrically complex and time dependent.

## Retrograde Motion of Subducted Slabs

Lateral migration of plate boundaries, in particular subduction zones, is related to the lack of local balance between seafloor spreading and plate consumption that causes the areas and shapes of plates to change (Figure 3) [Garfunkel, 1975]. While the Atlantic Ocean opened, the sides of the American and Eurasian plates that face the Pacific Ocean have approached each other by several thousand kilometers (Figure 2). The slabs that descend along the bordering subduction zones must have moved through the same distances. Otherwise, all slabs on at least one side of the Pacific Ocean would have been overrun by the neighboring continents and would have become practically horizontal, which generally did not happen (but see below). Thus the occurrence of lateral migration of descending slabs can be inferred from the relative plate motions. Since oceans closed several times in the more distant geologic past, this being an essential aspect of the Wilson cycle, it is expected that the approaching continents overran old subduction zones and that ancient descending slabs also migrated through the mantle, as in the present situation. Thus slab migration probably took place as long as the plate tectonic regime operated in its present form.

Since migration of slabs through the mantle is demonstrable through relative plate motions, its occurrence does not depend on the reference frame in which these motions are described. However, it is important to use a frame in which the motions of many plates can be included. Slab migration is not apparent when the relative motion of just two plates is examined because this is usually done in a coordinate system attached to the overriding plate. The motions of the entire plate system and of descending slabs are most meaningfully described only within an "absolute" reference frame which is not attached to the plates. The two viewpoints are actually the Lagrangian and Eulerian representations of motion; a distinction between them should also be made when dealing with plate kinematics. Wilson [1963] and Morgan [1972] suggested that such an absolute frame is provided by hotspots that do not participate in plate motions but whose relative positions appear to change very slowly. Another possible absolute frame of reference is that in which the entire lithosphere has no net rotation. At present, these two reference frames are quite similar [Lliboutry, 1974; Solomon and Sleep, 1974] and may well be identical.

Present-day plate motions relative to hotspots are best determined from the trends and age progressions of volcanic island and seamount chains in the Pacific Ocean. These define the motion of the Pacific plate relative to the hotspot frame of reference, from which the absolute motions of all other plates can be found by adding their relative motions. All estimates of the Pacific hotspot motion [Morgan, 1972; Clague and Jarrard, 1973; Chase, 1978a; Minster and Jordan, 1978; McDougall and Duncan, 1980] give similar locations of the Euler pole but different velocities, ranging from 90 to 110 mm $yr^{-1}$ along the Hawaiian chain. These velocities are distinctly higher than the long-term rate of migration of volcanism along this chain, about 80 mm $yr^{-1}$ [Dalrymple et al., 1980]. The high velocities are based on the ages of young exposed volcanics, whereas the really important dates, the beginnings of volcanism at each site, may be a few million years older. A bias of this magnitude leads to a significant overestimate of the rate of migration of volcanism along the young part of the chain but is not important along its older parts. The long-term rate,

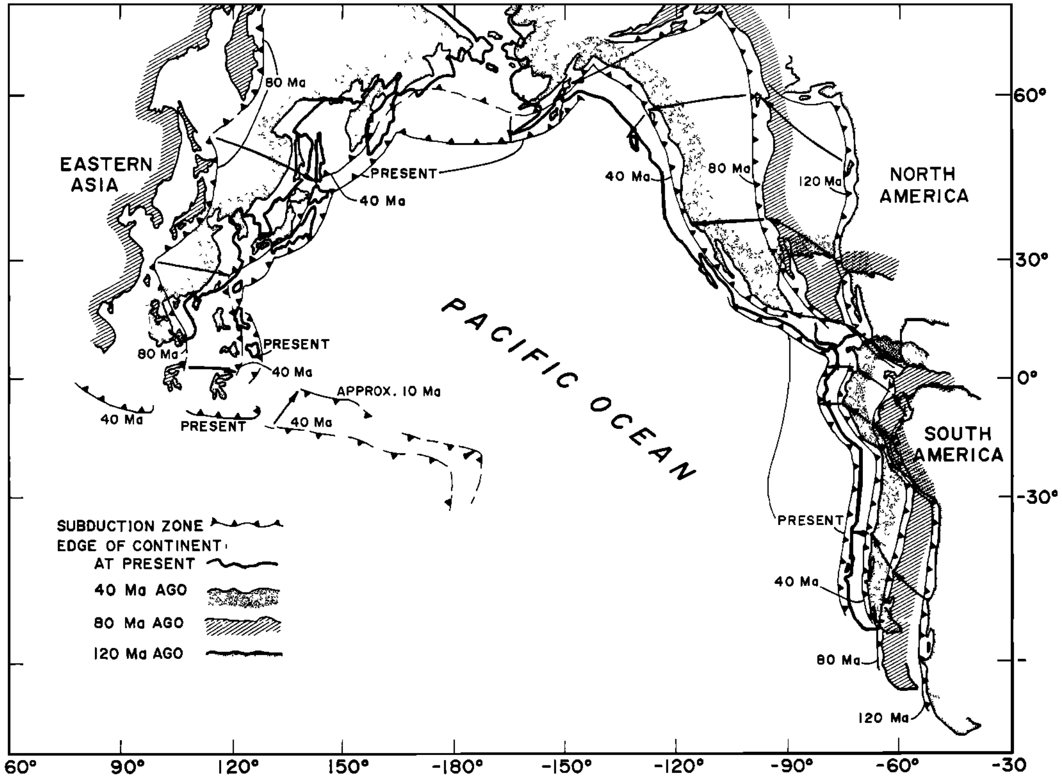


Fig. 2a.

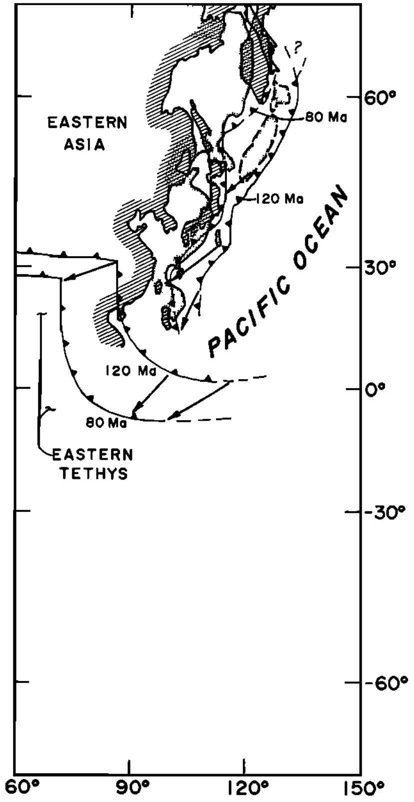


Fig. 2b.

Fig. 2. Absolute motions of subduction zones around the Pacific Ocean since 120 Ma according to the fixed hotspot model of Morgan [1982]. Motions of all trenches are shown in Figure 2a except those along eastern Asia between 120 and 80 Ma which are shown in Figure 2b. See text for further discussion.

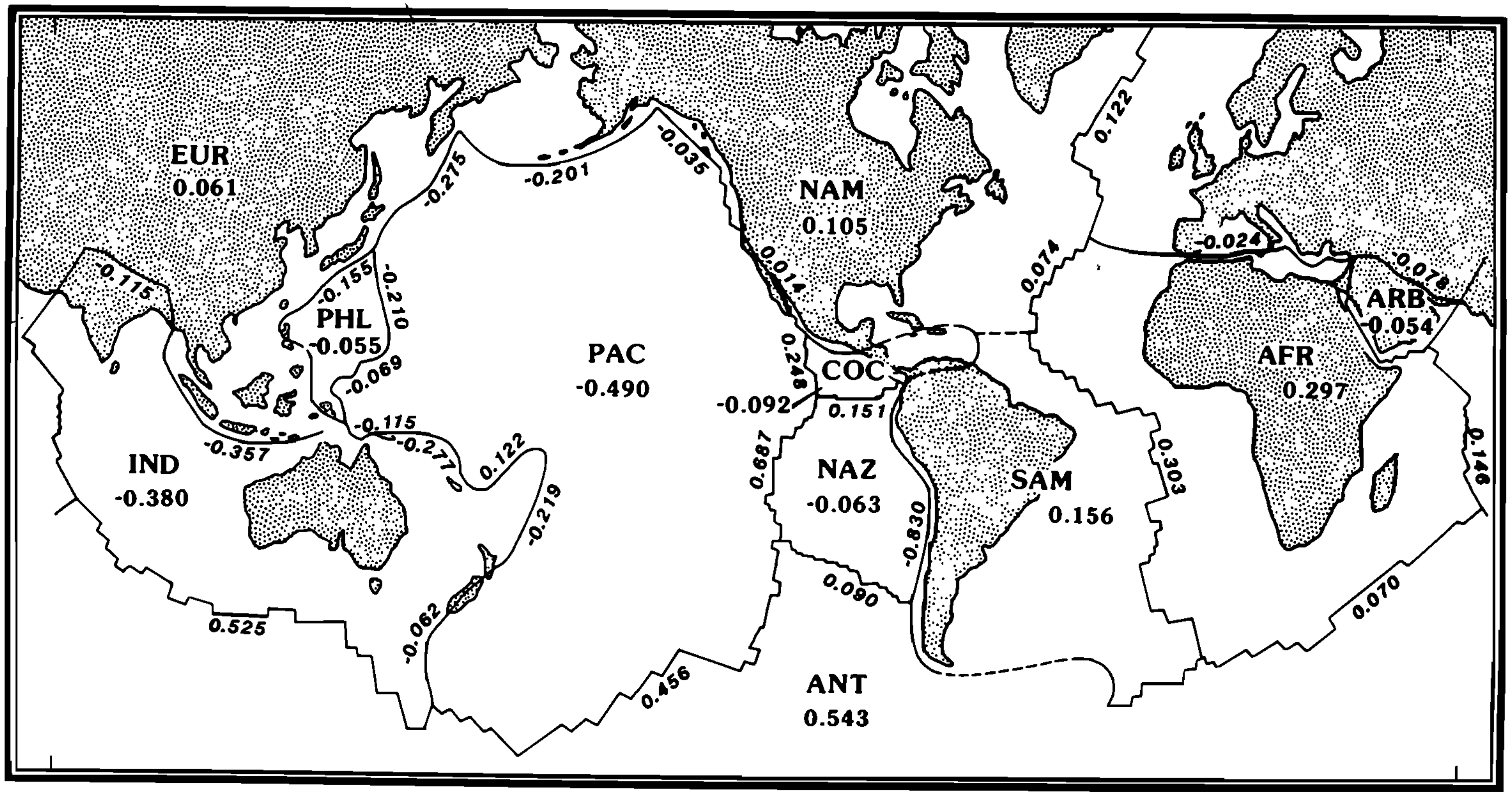


Fig. 3. Time rates of change of the areas of plates (bold numbers) and the rates of change of area along plate boundaries (in square kilometers per year). Positive means a gain in area, negative a loss of area. The numbers are derived from the relative plate motions of Minster and Jordan [1978]. Similar results were obtained by Garfunkel [1975] and Parsons [1981]. The changes of plate areas are significant over periods of a few tens of million years and require significant changes of locations of plate boundaries.

therefore, is probably a better estimate of the present velocity of the Pacific hotspot motion [cf. Cox and Engebretson, 1985]. Unfortunately, age progressions along other island chains [Jarrard and Clague, 1977] do not provide better resolution. Minster and Jordan [1978], using their model of relative plate motions, found that for the lithosphere to have no net rotation the absolute motion of the Pacific plate should be about an Euler pole that is indistinct from the pole of the Pacific hotspot motion with a velocity of 78 mm $yr^{-1}$ along the Hawaiian chain. This is close to the long-term rate of migration of volcanism along this chain, supporting the suggestion made above that this is the correct rate of absolute motion. Still another model was proposed by Morgan [1982] on the basis of the long-term motion of plates relative to the hotspots in the Atlantic and Indian oceans and on the adjacent continents. The present-day plate motions should be close to their average motions since 10 Ma; this model resembles the no net lithospheric rotation model.

The absolute motions of points along the edges of major plates that override subduction zones are listed in Table 1 for the no net torque model of Minster and Jordan [1978]. The areas swept out by the migrating subduction zones in this model are given in Table 2. The average migration velocities are obtained by dividing these rates by the lengths of the subduction zones. The absolute transverse motion of any slab through the mantle is given by the motion of the overriding plate perpendicular to the strike of the slab (Figures 1b and 1c). Strictly speaking, this defines the migration of the hinge where the subducted plate bends downward, but in general, the slab will follow to avoid drastic changes of its dip (see also Furlong and Chapman [1982]). Where active back arc basins are absent, the overriding plate is rigid near the subduction zone, so that its motion gives the absolute slab migration. However, where such a basin is present, it is its edge, not the rigid part of the major neighboring plate, that is in direct contact with the subduction zone. Therefore the spreading in back arc basins must be added as a component of retrograde slab motion.

This is important mainly in the southwestern Pacific [Karig, 1971; Hilde et al., 1977; Packham, 1982]. For example, the Lau basin opened behind the Tonga trench during the last 5 m.y. at an average rate of up to 40 mm $yr^{-1}$ [Weissel, 1977]. Therefore the Tonga slab has a retrograde motion, though the nearby edge of the Indian plate may move away from this subduction zone. If we adopt for the Philippine plate the motion suggested by Fitch [1972] and take into account back arc spreading reaching 50 or 80 mm $yr^{-1}$ in the Mariana trough [Karig et al., 1978; Hussong and Uyeda, 1982], then we find that the entire Izu-Mariana slab has a retrograde motion; only its northern part may be nearly stationary. The probable southward motion of Indonesia relative to Asia [Tapponier et al., 1982] and the back arc spreading in the Andaman Sea [Curray et al., 1979] lead to the retrograde motion of the entire Java-Sunda slab. The motion of southeast Asia eastward relative to the Eurasian mainland [Molnar and Tapponier, 1975] increases the retrograde motion of the Ryukyu and Philippine slabs. The small Scotia slab in the southern Atlantic also has a fast retrograde motion to allow the fast spreading in the adjacent back arc basin [Barker, 1972]. Thus, at present, retrograde slab motion is the rule, as was also found by Chase [1978b] and Uyeda and Kanamori [1979] for different models.

Tables 1 and 2 provide good estimates of subduction zone migration velocities, but it must be emphasized that the uncertainties in the absolute plate motions are significant because these motions are obtained as differences between the Pacific hotspot motion and relative plate motions, all of which are much faster than absolute plate motions [cf. Minster and Jordan, 1978]. As noted above, the main uncertainty concerns the velocity of the Pacific hotspot motion. For our purpose it suffices to note that while the uncertainties of slab migration velocities may reach several millimeters per year, this will not alter our conclusions.

To check whether retrograde subduction also was the rule in the geologic past, the older absolute plate motions should be examined. The main features of these motions since 200 Ma are given by the model of Morgan [1982] (Figure 2). In that model the western sides of the Americas generally overrode the adjacent subduction zones, though occasionally some segments moved essentially parallel to themselves. The record of subduction-related magmatism indicates that the subducted slabs generally moved along with the edges of the overriding continents, so that their retrograde motions amount to several thousand kilometers. The eastern edge of Eurasia overran the bordering subduction zones about 80 Ma when Eurasia split away from North America (at first along the Baffin Bay, later along the North Atlantic), implying considerable retrograde displacement of the slabs that descended on the western side of the Pacific Ocean. Prior to 80 Ma, Eurasia was attached to North America. Its eastern side could not have moved toward the Pacific Ocean if it remained rigid and was attached to mainland Eurasia. However, paleomagnetic data [Jarrard and Sasajima, 1980] and the record of Mesozoic orogenic activity in northeastern Asia [Nalivkin, 1973] show that this area was considerably distorted, so that its motion is uncertain. Southeastern Asia moved southward, probably overriding the adjacent subduction zones fringing the eastern Tethys Ocean, although the Mesozoic geometry of this area is incompletely known. In early Tertiary times a large subduction zone, where the Pacific plate was consumed, existed in the Melanesian area [Hilde et al., 1977; Packham, 1982] (Figure 2). This was overrun by the Indian-Australian plate, implying large retrograde displacement of the descending slab.

The foregoing analysis demonstrates that since 150 Ma, continents generally overrode subduction zones, indicating that subducted slabs usually migrated in a retrograde sense, similar to the present situation. This also follows from the interpretation of the geoid [Chase and Sprowl, 1983]. Migration velocities were generally 10-25 mm $yr^{-1}$; sometimes they were slower, but rarely were they faster. These velocities are much

TABLE 1. Motions of Points Along the Edges of Overriding Plates

| | Point Along Trench Latidude °N | Point Along Trench Longitude °E | Strike of trench, deg | Plate Convergence Rate, mm $yr^{-1}$ | Azimuth of Relative Motion, deg | Azimuth of Motion, deg | Angle with Normal to Trench, deg | $\bar{V}_{\perp}$, mm $yr^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| | | | Eurasion Plate Overriding (68.4°, -115.9°, 28 mm $yr^{-1}$)* | | | | | |
| Kuril Trench | 52 | 160 | 40 | 92 | 120 | 124 | 6 | 18.2 |
| Kuril Trench | 44 | 150 | 55 | 100 | 113 | 118 | 27 | 19.4 |
| Japan Trench | 35 | 143 | 10 | 106 | 110 | 114 | 14 | 24.0 |
| Ryukyu Trench | 27 | 130 | 40 | 27 | 125 | 110 | 20 | 25.2 |
| Philippine Trench | 10 | 126 | -10 | 52 | 113 | 109 | 29 | 24.5 |
| Indonesia Trench | -5 | 100 | -45 | 71 | 24 | 103 | -58 | -13.8 |
| Indonesia Trench | -12 | 115 | -75 | 77 | 22 | 108 | 87 | 1.3 |
| Indonesia Trench | -10 | 125 | 70 | 78 | 20 | 110 | 50 | 17.0 |
| | | | Philippine Plate Overriding (26.1°, 132.4°, -94.5 mm $yr^{-1}$)* | | | | | |
| Mariana Trench | 30 | 143 | -10 | 91 | 114 | 160 | -80 | -2.9 |
| Mariana Trench | 15 | 146 | 0 | 72 | 127 | -137 | -37 | -21.9 |
| 50 mm $yr^{-1}$ backarc spreading, E-W | | | | | | 123 | 33 | 31.2 |
| | | | North American Plate Overriding (8.4°, -81.2°, 17 mm $yr^{-1}$)* | | | | | |
| Aleutian Trench | 52 | 170 | 120 | 86 | 130 | -160 | 10 | 16.6 |
| Aleutian Trench | 53 | -160 | 80 | 74 | 148 | -176 | 14 | 16.0 |
| Mexico Trench | 16 | -100 | 115 | 67 | 39 | -160 | 5 | 5.8 |
| | | | South American Plate Overriding (-33.9°, -153.3°, 10 mm $yr^{-1}$)* | | | | | |
| Chile Trench | 0 | -82 | 0 | 80 | 82 | -35 | 55 | 5.6 |
| Chile Trench | 20 | -71 | 5 | 92 | 78 | -31 | 54 | 5.6 |
| Chile Trench | -30 | -72 | 5 | 93 | 79 | -27 | 58 | 4.9 |
| | | | Indian Plate Overriding (39.1°, -145.5°, -82 mm $yr^{-1}$)* | | | | | |
| Tonga Trench | -20 | -172 | 20 | 93 | 100 | 46 | 64 | 17.8 |
| 30 mm $yr^{-1}$ back arc spreading to 110° | | | | | | 73 | 37 | 48.1 |
| Tonga Trench | -38 | -178 | 20 | 55 | 100 | 13 | -87 | -1.8 |
| | | | Pacific Plate Overriding (64.7°, -73.2°, -82 mm $yr^{-1}$)* | | | | | |
| New Hebrides Trench | -15 | 167 | -20 | 100 | 85 | -66 | 44 | 53.0 |
| Solomon Trench | -10 | 160 | -50 | 109 | 81 | -68 | 72 | 23.1 |

For each point along a trench we give (1) its geographic coordinates; latitude positive northward, longitude positive eastward, (2) the strike of the trench at the point (positive when clockwise to the north), (3) rate of plate convergence according to the Minster and Jordan [1978] model, (4) direction of relative plate convergence, positive when clockwise from north. For the absolute plate motion model RM1-2 of Minster and Jordon [1978] we list (1) direction of motion (clockwise from north) of the overriding plate, (2) the angle between this motion and the normal to the trench (positive when the overriding plate moves toward the trench and negative when it moves away from the trench), (3) velocity of motion perpendicular to the trench $V_{\perp}$ (with the same sign convention).

*Motion of overriding plate: latitude of pole (positive when north), longitude of pole (positive when east), rate of maximal motion (positive when clockwise about the pole).

TABLE 2. Area Swept Out by Migrating Trenches and Volume Displaced by Slabs Around the Pacific Ocean

| Trench | Length of trench, km | Depth of slab, km | ds/dt $km^2 yr^{-1}$ | $\bar{V}_\perp$ mm $yr^{-1}$ | dV/dt $km^3 yr^{-1}$ |
|---|---|---|---|---|---|
| Kuril | 2000 | 600 | 0.0390 | 19.5 | 23.40 |
| Japan | 850 | 650 | 0.0194 | 23.7 | 12.61 |
| Ryukyu | 2200 | 250 | 0.0452 | 20.5 | 11.30 |
| Philippine | 2900 | 500 | 0.0685 | 24.0 | 32.25 |
| Mariana North of 11°* | 2700 | 500 | 0.0492 | 20.8 | 24.55 |
| Aleutian | 3000 | 300 | 0.0507 | 16.7 | 15.21 |
| Mexico | 4000 | 300 | 0.0144 | 3.6 | 4.32 |
| Chile North of -40° | 5000 | 600 | 0.0224 | 4.5 | 13.64 |
| Chile South of -40° | 2250 | 200 | -0.0021 | -0.9 | -0.42 |
| Tonga† | 2400 | 600 | 0.0782 | 32.6 | 46.92 |
| New Hebrides | 1900 | 300 | 0.0691 | 36.4 | 20.73 |
| Solomon | 1300 | 300 | 0.0162 | 12.5 | 4.86 |
| Totals | | | | | 209.8 |

The area swept out by migrating trenches is calculated from the absolute plate motions given in Table 1. It is positive when trench migration is retrograde. Subduction north of New Guinea was not included because of the complexity of the area. $\bar{V}_\perp$ Average velocity of retrograde trench migration (averaged over trench length).

*Back arc spreading producing 0.06 $km^2 yr^{-1}$ included north of 11° N. (Average spreading rate of 22 mm $yr^{-1}$ in back arc.)

†Back arc spreading producing 0.03 $km^2 yr^{-1}$ included. (Average spreading of 12.5 mm $yr^{-1}$ in back arc).

smaller than rates of plate consumption, typically, 60-100 mm $yr^{-1}$. In addition, the edges of some overriding plates moved parallel to themselves at rates often comparable to, or even larger than, the perpendicular motion (cf. Table 1). It is clear that descending slabs are not stationary anchors in the mantle, as has sometimes been suggested [e.g., Tullis, 1972], though they move slowly. In fact, the models of absolute plate motions approximately minimize the migration of plate boundaries [Kaula, 1975].

The most probable cause of retrograde migration of descending slabs is, as noted above, their negative buoyancy relative to the surrounding mantle. This causes them to sink and pull at the plates to which they are attached. As a result, the hinges on which these plates bend downward migrate backward and so do the slabs themselves (cf. Figure 1). All descending slabs are expected, therefore, to move in a retrograde way. The foregoing discussion shows that the available data confirm the generality of retrograde slab motion, even though some ambiguous cases exist. Only very young and still hot slabs may not be negatively buoyant. The older and colder a slab is, the harder it should pull down on the hinge and the faster it should migrate backward. To test this, the rates of retrograde slab motion as a function of slab age are plotted in Figure 4. There is indeed a positive correlation between the two variables. However, other factors besides age, such as slab dip and flow in the nearby mantle probably also influence the rates of slab migration.

Uyeda and Kanamori [1979] and Uyeda [1982] have shown that along some subduction zones, like the Chilean, coupling between the converging plates is strong and back arc basins are absent, whereas along other subduction zones, like the Mariana, back arc spreading occurs and coupling between the converging plates is weak. Table 1 shows that the overriding plates move with generally similar absolute velocities toward subduction zones of both types. Thus absolute plate motions in themselves do not discriminate clearly between the two different types of subduction zones. The controlling factor appears to be the difference between the migration of the trench and the motion of the edge of the main part of the overriding plate, and not the latter alone, as was suggested, for example, by Wilson and Burke [1972] and Chase [1978b]. Assuming that

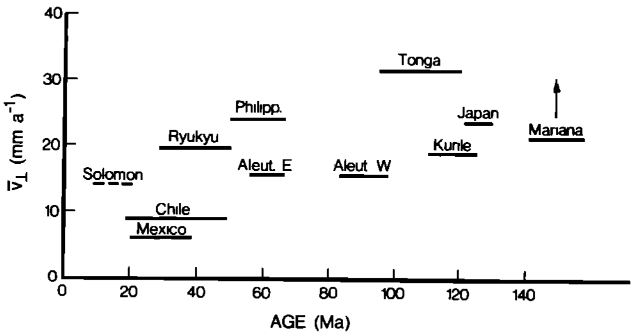


Fig. 4. Relation between rate of retrograde slab motion $\bar{V}_\perp$ and slab age based on the absolute plate motion model of Tables 1 and 2. The age of the Solomon slab is uncertain. The velocity of the Mariana trench may be higher, depending on interpretation of back arc spreading behind this trench.

descending slabs always move in a retrograde way, then Mariana type zones and back arc basins will form not only when the overriding major plates move away from the subduction zones but also when these plates cannot keep pace with the retreat of the slabs. This is expected to occur preferentially where old slabs are subducted. In fact, Molnar and Atwater [1978] and Ruff and Kanamori [1980] found a correlation between the type of subduction zone and the age of the consumed slab. This finding supports the expectation that slab age should correlate positively with the rate of its retrograde migration (Figure 4). Younger slabs are expected to generally retreat at lower speeds, so that subduction zones of the Chilean type will generally form along them. If such a young slab retreats more slowly than the advance of the overriding plate, it may become flattened along the base of the overriding lithosphere. At present, 30 to 50 m.y.-old slabs descend beneath Central and South America [Sclater et al., 1980], but only their upper parts have very shallow dips [Barazangi and Isacks, 1976]. Slabs of these ages apparently sink fast enough into the mantle to preclude their complete flattening by overriding continents. During the early Tertiary, however, the western United States overran a practically horizontal slab of very young and light oceanic lithosphere that was subducted shortly before a mid-oceanic ridge was consumed [Dickinson, 1981], but such situations are probably uncommon.

## Kinematic Consequences

The retrograde migration of slabs has important consequences for both the motion of subducted lithosphere and the flow in the surrounding mantle. The dip-parallel velocity of a slab that has a retrograde motion is larger than the absolute velocity of the plate to which it is attached. This can be seen by considering an underthrusting plate whose absolute velocity is zero (Figure 5a). As the hinge along which it bends retreats, the slab hanging down into the mantle becomes longer, so that it acquires a velocity equal to the velocity of the overriding plate (and of the retreating hinge). In general, the dip-parallel velocity of any slab is equal to the rate of plate consumption or the rate of relative plate convergence (Figure 5b).

Because the retrograde motion of slabs is considerably slower than the rate of plate consumption, the angle $\gamma$ between slab dip and the direction of its overall motion is not large (Figures 5b and 5c). It depends on slab dip $\delta$ and on the ratio between the velocities of plate consumption $v_c + v_o$ and retreat of the hinge v (Figure 5c). From the geometry of Figure 5c and the law of sines we can write

$$\frac{(v_c + v_o)\ \Delta t}{\sin(\gamma + \delta)} = \frac{v_o\ \Delta t}{\sin \gamma} \tag{1}$$

where $\Delta t$ is an arbitrary time interval. It follows that

$$\gamma = \text{arc cot}\left\{ (\csc \delta) \left[\frac{v_c + v_o}{v_o}\right] - \cot \delta \right\} \tag{2}$$

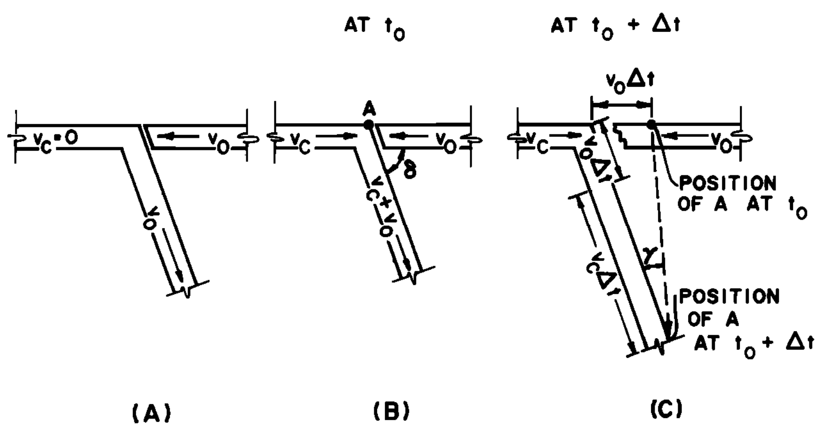


Fig. 5. The geometry of retrograde slab descent. (a) Slab descent into the mantle can occur even if the plate attached to the slab is fixed. In this case the dip-parallel velocity of the descending slab equals the velocity of the overriding plate. (b) and (c) Subduction geometry at two closely spaced instants of time; $\delta$ is slab dip; $\gamma$ is the angle between slab dip and the descent trajectory of a material point in the slab.

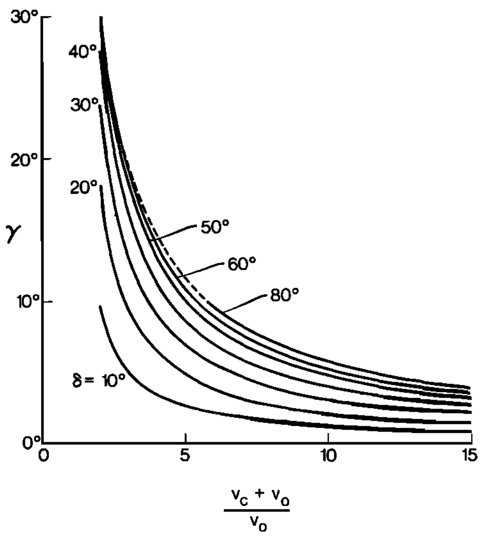


Fig. 6. Dependence of $\gamma$, the angle between slab dip and the direction of particle motion (Figure 5), on slab dip ($\delta$) and the ratio of the velocities ($(v_c + v_o)/v_o$) of the converging plates (see Figure 5).

Figure 6 shows $\gamma$ as a function of $(v_c+v_o)/v_o$ with $\delta$ as a parameter. For the velocities listed in Tables 1 and 2, $\gamma$ does not exceed 20° if slab dip remains constant. When slabs are not exactly planar, this discussion applies to their average dips.

The migrating slabs interact with the mantle flow in several ways. Since slabs move at an angle to their dips, viscous coupling causes the surrounding mantle to move in the same way. The streamlines in the vicinity of slabs are, therefore, oblique to the slabs, as if crossing them, though at only small or moderate angles (Figures 5 and 6). More importantly, slab migration drives a mass flux from the undersides toward the upper sides of the slabs. Assuming that slabs are continuous at least to the base of the Benioff-Wadati zones, the motions listed in Table 2 require a flux of at least 160-200 $km^3$ $yr^{-1}$ away from the lower sides of the slabs around the Pacific Ocean, while an equal volume must fill the space on their other sides. For comparison, a global flux of about 300 $km^2$ $yr^{-1}$ is needed along the entire mid-ocean ridge system to produce a 100-km-thick lithosphere at the present rate of about 3 km $yr^{-1}$. This is less than twice the mass flux due to slab migration, confirming a previous rough estimate that these two fluxes are comparable [Garfunkel, 1975]. If, however, the slabs extend much deeper than the Benioff-Wadati seismic zones [Creager and Jordan, 1984], then the flux associated with slab migration is even more comparable to the ridge spreading circulation.

The above calculation is valid only if slabs are laterally continuous. In reality, slabs may be segmented [Barazangi and Isacks, 1976; Isacks and Barazangi, 1977], but the generally orderly arrangement of earthquake foci in Benioff-Wadati zones suggests that slabs consist of large coherent units. Only a limited mass flux can pass through gaps between these slab segments [Alvarez, 1982]. Slabs can also become detached, but the present situation suggests that this does not happen often and that most of the time quite long slabs exist. Moreover, since subduction is a continuous process, detachment of slabs need not always produce large gaps. On the other hand, any detached slanting slab, because of its negative buoyancy, will continue to descend in a retrograde manner and will still displace mantle material. We conclude, therefore, that retrograde slab motion has always been associated with an important mass flux.

The mass flux due to retrograde slab migration is only one component of the mantle flow resulting from coupling with plate motions. Another component is produced by viscous drag at the base of the plates, while yet an additional component of mantle flow arises from the overturn of oceanic lithosphere. Relative to the sublithospheric mantle the ridges act as mass sinks, while the slabs act as diffuse mass sources of equal strength from which there is a return flow towards the ridges. The latter two components of mantle flow have been extensively discussed [Richter, 1973; Richter and McKenzie, 1978; Hager and O'Connell, 1978, 1979; Chase, 1979; Parmentier and Oliver, 1979; Alvarez, 1982]. The flow associated with slab migration has been treated only briefly [Chase, 1979; Hager and O'Connell, 1981; Alvarez, 1982; Hager et al., 1983].

Realistic modeling of three-dimensional mantle circulation incorporating the known slab migration is probably not feasible at present. On the other hand, experience has shown that two-dimensional models successfully simulate many features of plate tectonics [e.g., Turcotte and Oxburgh, 1967; McKenzie et al., 1974; Schubert, 1979]. Therefore, in order to identify the main characteristics of the component of mantle flow associated with retrograde slab motion and to understand its contribution to the overall circulation, we have simulated it with two-dimensional finite element models that explicitly prescribe retrograde slab motion as a boundary condition.

## Two-Dimensional Models

The models studied consist of rectangular boxes filled with a uniform Newtonian viscous fluid having constant properties. The upper surface of each box is divided into two segments or plates which move toward each other at constant, but unequal, velocities. Along the junction between the plates a "slab" is attached to the faster moving plate, and it extends downward into the box. Its down dip velocity is the sum of the surface velocities of the plates. In addition, the slab can also have a retrograde velocity equal to the velocity of the "overriding" plate. The flow within the box is driven by the viscous coupling to the surface plates and to the slabs. The bottom of the box and the vertical walls are impenetrable, stress-free boundaries. In order to identify the specific contribution of retrograde slab

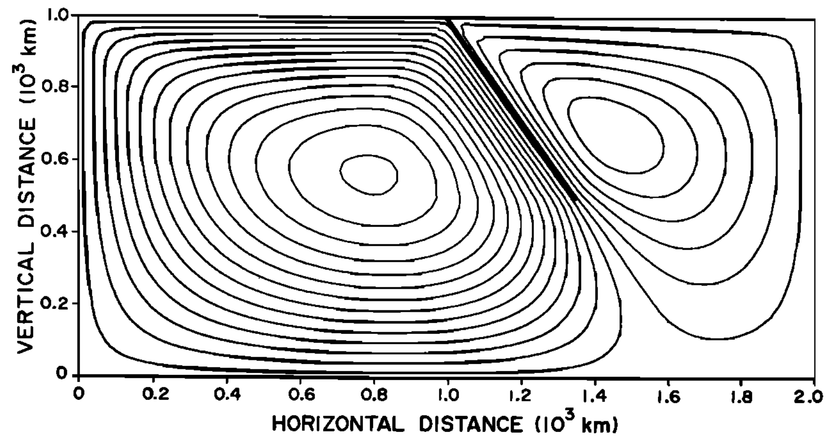


Fig. 7a.

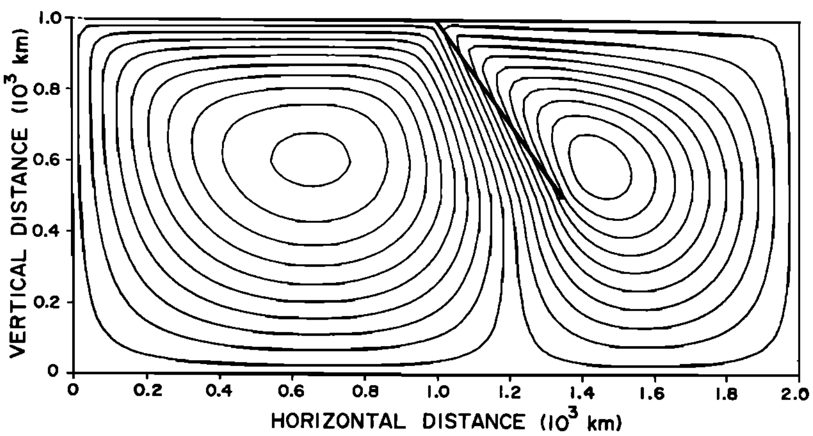


Fig. 7b.

Fig. 7. Instantaneous circulation patterns in a box of aspect ratio 2 (a) without and (b) with retrograde slab migration. The left half of the top boundary moves with speed 80 mm $yr^{-1}$ to the right; the right half of this boundary moves with speed 20 mm $yr^{-1}$ to the left. The dip-parallel velocity of the slab is 100 mm $yr^{-1}$. In Figure 7b the trench and slab also move with speed 20 mm $yr^{-1}$ to the left. The streamline contour interval for Figures 7a and 7b are $1.14 \times 10^{12}$ and $1.29 \times 10^{12}$ $mm^2$ $yr^{-1}$. In Figure 7a the slab divides the two counterrotating cells. In Figure 7b the slab is part of the cell under the overriding plate, and instantaneous streamlines intersect the slab.

migration to the overall circulation, calculations are carried out for models that differ only by the inclusion or absence of retrograde slab migration.

Inertial forces are neglected in the momentum equation, as is appropriate to the mantle [e.g., Schubert, 1979] so this equation does not depend explicitly on time. A unique instantaneous flow that does not depend on time is thus determined by the specified boundary velocities and a balance of viscous and pressure forces. Though the instantaneous flow is time independent, the circulation in reality can change continuously with time since the junction between the surface plates moves together with any retrograde slab migration and the position of the slab in the box also changes. Thus the time dependence of the flow enters the problem through the boundary conditions. Because the flow is time dependent, the paths of material particles differ from the instantaneous streamlines, and the position of any particle depends on the previous history of the system (through the changing boundary conditions). The time independence of the instantaneous flow signifies that the flow of the system adjusts instantaneously to changes of the boundary conditions, not remembering the previous motions. In the mantle, however, particles have a "memory" of their previous history because properties such as temperature vary slowly. This is particularly true of descending slabs that consist of relatively cold material. The formulation of our models does not allow us to consider this aspect of the flow history because we ignore buoyancy forces and temperature variations and simulate the observed behavior of slabs through prescribed boundary velocities. Therefore the models give the instantaneous flow associated with any given position and motion of a descending slab regardless of how this state was attained.

The use of kinematic boundary conditions reproduces the observed behavior of the plates and slabs without the necessity of modeling the poorly known body forces acting on them and on the rest of the system. If these forces could be completely specified, the plate motions would be simulated correctly to the extent that realistic material properties are used. Conversely, the forces acting on the system could be deduced if its kinematics were completely known. In our models the motion of only a part of the system is prescribed, but this part simulates some of the most important forces that drive mantle flow, i.e., viscous coupling with the plates and negative buoyancy of descending slabs [Forsyth and Uyeda, 1975; Chapple and Tullis, 1977; Turcotte and Schubert, 1982]. In particular, the models simulate the essential aspect of the problem studied here since they include slab migration.

The calculations have been carried out with a finite element numerical code previously used to model high Rayleigh number thermal convection [Schubert and Anderson, 1985]. A brief description of the method and a discussion of the meshes used to model the slabs are given in the appendix[1]. More "realistic" simulations of actual subduction zones are considered in the next section. Figure 7 shows the flow in a box with aspect ratio 2. The top boundary is divided into two plates of equal size. The plate on the left moves at a speed of 80 mm $yr^{-1}$ to the right; the plate on the right moves at a speed of 20 mm $yr^{-1}$ to the left. The dip-parallel velocity of the slab is 100 mm $yr^{-1}$; in Figure 7a there is no slab or trench migration, while in Figure 7b the trench and slab move to the left at 20 mm $yr^{-1}$. The dip of the slab was specified according to the natural inclination of the streamlines in a flow field induced only by the moving surface plates.

Comparison of Figures 7a and 7b reveals that retrograde slab migration has several important consequences. As expected, the instantaneous streamlines in Figure 7b are at an angle to the slab, as if crossing it, whereas in the model without slab migration (Figure 7a), streamlines are parallel to the slab. Consequently, retrograde migration of the slab makes it part of the cell beneath the overriding plate. In contrast, a slab that does not migrate laterally is aligned along the boundary between the cells, as was found in all previous studies of mantle circulation. The cell beneath the overriding plate expands at the expense of the cell beneath the plate to which the slab is attached. This happens because lateral slab migration through the surrounding fluid diverts some mass from beneath the consumed plate and causes it to flow beneath the slab and toward the overriding plate. This modifies not only the geometry of the flow but also the velocity field. The cell under the fast moving consumed plate is considerably slowed down, whereas the cell beneath the overriding plate is substantially speeded up. The flow in the cell beneath the overriding plate can be as fast as the flow under the consumed plate, as shown in Figure 7b. This provides the flux necessary to fill the space on the receding side of the slab. On the other hand, when slab migration does not occur, flow in the cell under the overriding plate is much slower than the flow under the consumed plate, which was also found in previous models of flow induced by nonmigrating slabs [Richter, 1973; Richter and McKenzie, 1978]. It is also important to note that the streamlines will appear to be at an angle to the slabs in any coordinate system in which the entire model of Figure 7a moves laterally. However, the other features of the flow in the model of Figure 7b are not reproduced in that way, being intrinsic consequences of the motion of the slabs relative to the model boundaries.

It can be seen in Figure 8 that the horizontal velocity in the cell beneath the overriding plate has a local maximum within the cell, at least for distances sufficiently close to the trench. The top of the cell is y = 1000 km and the bottom is y = 0 km. The slab intersects the upper boundary at x = 1000 km. Thus the first location, x = 1100 km, is at a distance of 100 km from the trench on the side of the overriding plate. Subsequent profiles are located at 50-km intervals. Positive horizontal velocities are directed away from the trench. Profiles marked by squares give the instantaneous horizontal velocities for a migrating slab; the curves denoted by crosses are for a nonmigrating slab. The sharp changes in slope occur where the profile crosses the slab; while velocity is continuous across the slab, velocity gradients or shear stresses are not. The local velocity maxima of concern here are the ones that occur beneath the overriding plate and above the slab; these are local maxima in the trenchward directed velocities. They are primarily a consequence of proximity to the trench. Such maxima are also present in the analytic corner flow models of Tovish et al. [1978]. The velocity maxima are clearly enhanced by lateral slab migration. Associated with the velocity maxima are trenchward directed shear stresses on the base of the overriding plate. Lateral slab migration increases the magnitude of these shear stresses and increases the distance from the trench over which shear stresses of this sign act on the overriding plate. These shear stresses are the source of the trench suction force in models of plate driving forces, a point we elaborate on later.

Results similar to the above were also found in two-dimensional models by Hager and O'Connell [1981], who simulated the behavior of descending slabs by assigning them a negative buoyancy. Though not requiring the slabs to be attached to the consumed plates or to move in a retrograde manner, the slabs in their models are at an angle to the streamlines, they sink at an angle to their dips, and they are not boundaries between cells. In addition, the circulation in the cells containing the slabs is relatively fast. In another model, Hager et al. [1983, Figure 12] obtained a velocity maximum in the middle of the cell containing the slab. (Kinematic return flow models with primarily upper mantle flow also show a maximum [Harper, 1978; Chase, 1979; Parmentier and Oliver, 1979].) The similarities between our results and those of Hager and O'Connell [1981] and Hager et al. [1983] strongly support the interpretation that retrograde slab migration is a consequence of the negative buoyancy that

[1]Appendix is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N. W., Washington, D. C. 20009. Document B86-003; $2.50. Payment must accompany order.

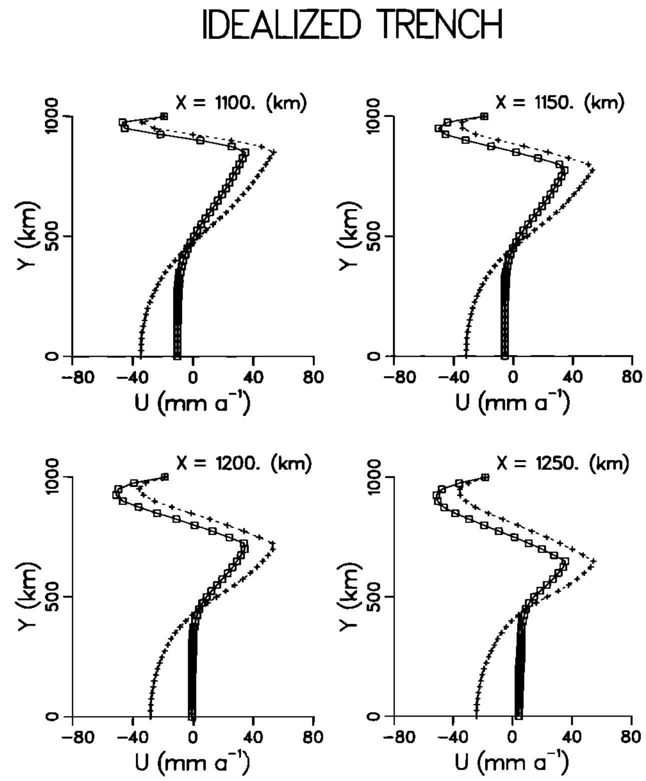


Fig. 8. Horizontal velocity U verses depth (y = 1000 km is at the top) for the idealized trench configuration and plate velocities of Figure 7. The horizontal coordinate is x, and x-1000 km is the horizontal distance to the trench corner. Negative values of U are directed trenchward. Squares, with lateral slab migration; crosses, without slab migration.

causes slabs to sink. This motion, in turn, pushes the mantle to make room for the settling slab. The real situation is more complicated because the slab is attached to a plate, but this will not be considered here.

## Implications for Mantle Flow

The models of this paper are two-dimensional and describe instantaneous flows controlled by specified velocity boundary conditions. These models differ from the flow in the mantle which is fully three-dimensional and time dependent, characteristics that are necessary consequences of the irregular, nonperiodic arrangement of divergent and convergent plate boundaries and the lack of local balance between rates of seafloor spreading and subduction [Garfunkel, 1975]. As a result, the return flow can be balanced only on a global scale, and it must have a complex pattern that is not everywhere antiparallel to the plate motions. The return flow cannot consist of cells in which material particles follow simple closed trajectories. Kinematic models of mantle flow that are linked to the observed shapes and motions of the plates [Hager and O'Connell, 1978, 1979, 1981; Chase, 1979; Parmentier and Oliver, 1979] indeed possess these characteristics, even though they do not include retrograde slab motions. Another consequence of the complex plate geometry is that the sizes and shapes of the plates, as well as the locations of their divergent and convergent boundaries, change continuously. Therefore the associated mantle flow must also be time dependent, undergoing major changes over time periods of a few hundred million years. Retrograde slab motion is, in fact, one of the main manifestations of the time dependence of mantle flow.

Our models, not being intended to simulate the full scope of mantle convection, do not have these complex characteristics. However, they allow slab migration and flow between neighboring cells, which are essential features of the mantle flow. Therefore despite their simplicity and the closed boundary conditions of the sides of the boxes, the models can be used as good indicators of how retrograde slab motion influences mantle flow. This component of mantle flow combines with the other flow components excited by the overturn of lithosphere and by the drag at the base of the plates to give the total circulation. Because of the time dependence of mantle flow it is also necessary to distinguish between the short- and long-term consequences of slab migration.

Regarding the instantaneous flow, the models confirm that when retrograde slab motion occurs, the instantaneous streamlines are at an angle to the slabs. This has the important consequence that the slabs do not separate streamlines that at depth turn in different directions; that is, slabs are not the boundaries of cells in the mantle. This should remain true even in the presence of other components of mantle flow. Migration of this flow pattern with the slabs results in the long-term addition of new material to the streamlines that extend from the lower (retreating) sides of the slabs. This material will follow the descending slabs and move differently from the rest of the material beneath the consumed plate. Therefore, at depth, the slabs need not turn backward beneath the plates to which they are attached, but they can extend beneath the overriding plates. In such cases, the material comprising the slabs will be reabsorbed in the mantle far from the ridges which generate the plates to which the slabs are attached. Hence there need not be any local balance between rates of plate generation and consumption. Rather, overturn of oceanic lithosphere can transport material from one part of the earth to another [Garfunkel, 1975].

To investigate these points further, models resembling the Peru and Kuril subduction zones are examined (Figures 9 and 10). These models demonstrate the influence of variations in plate and slab migration velocities and of different aspect ratios; they also simulate more "realistically" the situation in the shrinking Pacific Ocean. In the models of the Peru trench the slab is bent, simulating the shape of the Benioff-Wadati zone in this area (Figure 10) [Barazangi and Isacks, 1976]. The widths of the cells in the Peru trench model equal the distances from the trench to the Mid-Atlantic Ridge and to the East Pacific Rise (Figure 9). In the models of the Kuril trench the slab again simulates the observed Benioff-Wadati zone (Figure 10) [Isacks and Molnar, 1971]; the cell

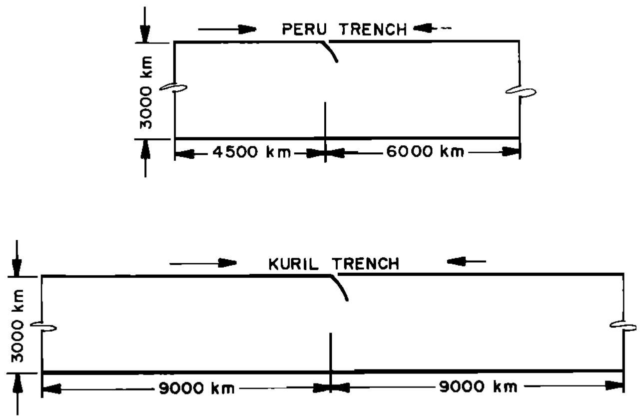


Fig. 9. Cell geometries for models of the flow induced by the Kuril and Peru slabs. The 3000 km depth simulates whole mantle flow. The horizontal dimensions of 4500 and 6000 km represent distances from the Peru trench to the East Pacific Rise and the Mid-Atlantic Ridge, respectively. The 9000 km dimension represents the distance from the Kuril trench to the East Pacific Rise.

under the "Pacific" plate has a width comparable to the distance from the trench to the East Pacific Rise (Figure 9). The other cell has the same width, but this does not correspond to any particular feature. The velocities of the plates and of slab migration are those of Table 1. In each case the instantaneous two-dimensional flow is calculated as explained in the appendix. The actual flow, not being two-dimensional, is probably not exactly in the planes of the examined cross sections. However, departures from two dimensionality should be most important where subduction zones have trends that are very different from neighboring ridges. Such is the case, for example, in the southwestern Pacific Ocean where the deep flux toward the fast spreading south Pacific ridge must be at an angle to the neighboring subduction zones that have very different trends. Since such complications are not important in the areas crossed by the studied sections, mantle flow is probably nearly parallel to them and can be approximated by two-dimensional models. The closed end wall boundary conditions, though not realistic for the mantle, have little consequence for the migration-associated flow in the vicinity of the slab since the walls are far from the slab (Figure 9).

In the first set of models (Figures 11 and 12) the cells are 3000 km deep, simulating whole mantle convection. In these models the results of lateral slab migration are similar to those seen in Figure 7. When slab migration occurs, the cell under the overriding plate expands at the expense of the other cell, and streamlines are at an angle to the slabs. These effects become more pronounced as the ratio between the velocity of slab migration and the velocity of the consumed slab increases. The velocity structure changes appreciably over distances of thousands of kilometers away from the slab. This is only a small fraction of the large aspect ratio cells in Figures 11 and 12, whereas when the aspect ratio is small, as in the model of Figure 7, the flow under the entire overriding plate may be influenced by slab migration. The models also show (Figures 11 and 12) that the migrating slabs are surrounded by streamlines that at depth bend away from the Pacific Ocean. As slab migration continues, such streamlines will include more and more of the mantle beneath the Pacific Ocean, and therefore the descending slabs are not expected to bend back under this ocean. Thus the motion of the migrating slabs evacuates material from underneath the Pacific Ocean because the material ascending at the East Pacific Rise is eventually brought to parts of the mantle that are not under the Pacific Ocean. Additional mass is evacuated by the flow induced by slab migration which causes material to move beneath the slabs and toward the overriding Eurasian and South American plates. Therefore a less significant deep return flow toward most of the East Pacific Rise is expected (though there should be an undiminished return flow toward the southern Pacific ridge).

The flows associated with convergence at the Kuril and Peru trenches (Figures 11 and 12) exhibit local maxima in the horizontal trenchward velocities beneath the overriding plates and above the slabs (Figures 13 and 14) similar to

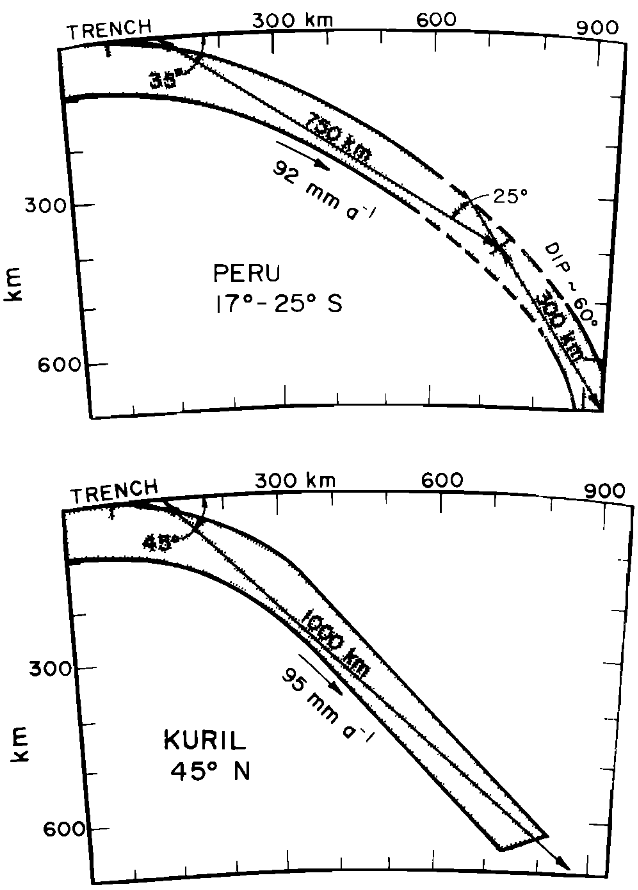


Fig. 10. The Benioff-Wadati zones (shaded regions) and the approximations to these shapes (thin straight lines) employed in the finite element calculations of flow induced by the Peru and Kuril slabs.

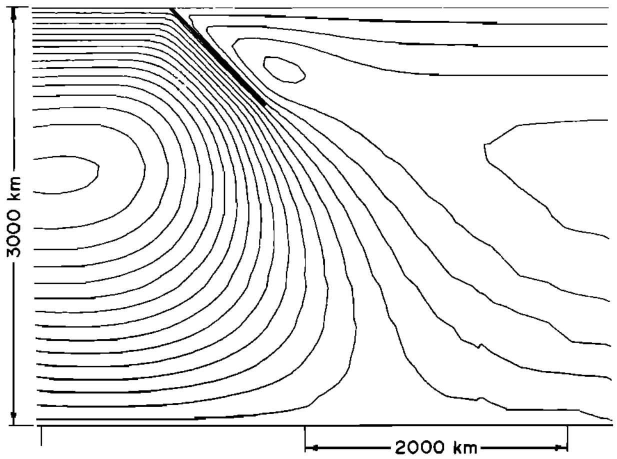


Fig. 11a

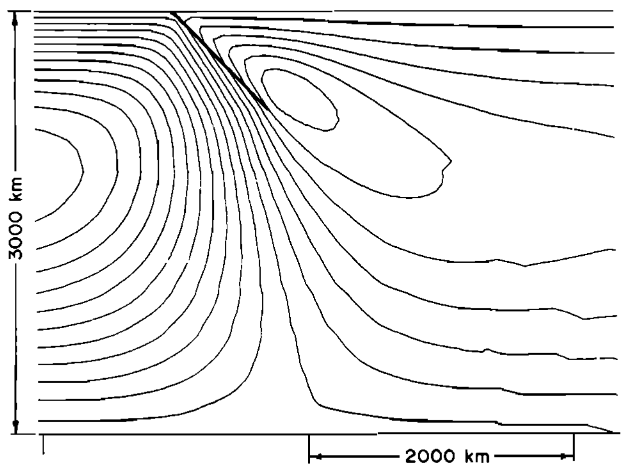


Fig. 11b

Fig. 11. Instantaneous whole mantle circulation patterns for the flow induced by the Kuril slab (a) without and (b) with lateral slab migration. The left half of the top boundary moves to the right with speed 75 mm $yr^{-1}$; the overriding plate moves to the left with speed 20 mm $yr^{-1}$. The dip-parallel velocity of the slab is 95 mm $yr^{-1}$. In Figure 11b the trench and slab also move with speed 20 mm $yr^{-1}$ to the left. The streamline contour intervals for Figures 11a and 11b are $2.65 \times 10^9$ and $3.06 \times 10^9$ $mm^2$ $yr^{-1}$. See also Figures 9 and 10.

those already encountered in the idealized trench configuration (Figure 8). Lateral slab migration enhances the velocity maxima; that is, it increases the flux of mantle material that flows toward the trench directly beneath the overriding plate. Velocity maxima occur at greater horizontal distances (about 750 km farther) from the trench corner as a consequence of slab migration. The shear resulting from the downward increasing trenchward velocity drags the overriding plate toward the subduction zone; that is, the mantle flow enhances the plate's motion. In contrast, when the velocity decreases downward, the resulting shear opposes plate motion and the motion of the plate actually helps to drive the flow in the mantle. Hitherto, models of plate driving mechanisms [Solomon and Sleep, 1974; Solomon et al., 1975; Forsyth and Uyeda, 1975; Chapple and Tullis, 1977] generally assumed that the viscous shear stresses at the bases of plates always oppose their motions, in accordance with flow models having velocity maxima only at the boundaries of cells and not in their interiors. However, Lux et al. [1979] showed that this need not always be the case and that when plate velocities are not too high, mantle flow can drive the plates. The finite element models (Figures 8, 13 and 14) show that the motions of the slow overriding plates are enhanced by the drag of the mantle flow on the undersides of the plates that are close to the subduction zones. This trenchward pull on the bases of the overriding plates can explain the "trench suction force" found in models of plate-driving mechanisms. The trenchward drag at the bases of the overriding plates will be most efficent when the plates comprise continents with old and cold parts under which the low-velocity and low-viscosity layers are poorly developed.

By increasing the trenchward flow beneath the overriding plate and the trenchward directed shear stress on the base of the plate, lateral slab migration becomes a major factor in controlling the mechanical and thermal processes in subduction zones. This control is evident in the geologic record of subduction regression and oceanward migration of volcanism on North Island, New Zealand [Brothers, 1984]. Potassium-argon ages of calc-alkaline volcanics and $K_2O$-$SiO_2$ indices for magma source depths indicate an oceanward migration pattern for volcanism from NW to SE toward the Hikurangi Trench. The movement of the volcanic front is clearly associated with subduction zone regression. In areas of accelerated subduction retreat, tensional tectonism caused widespread foundering of Mesozoic graywacke basement [Brothers, 1984].

Continuing retrograde slab migration modifies the motion of the material beneath the consumed

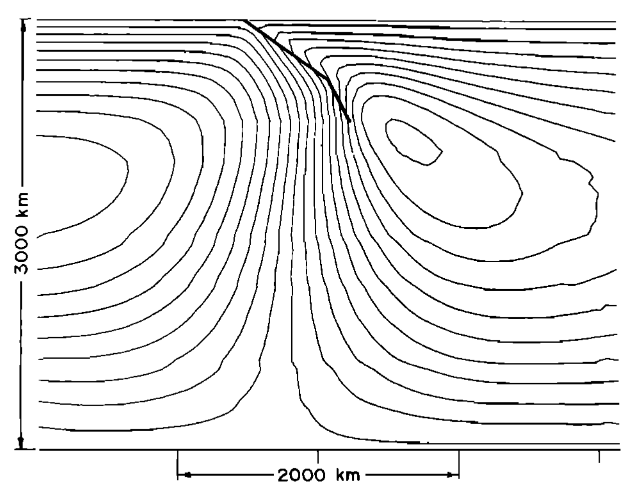


Fig. 12. Similar to Figure 11b but for the Peru trench. The left half of the top boundary moves with speed 60 mm $yr^{-1}$ to the right; the overriding plate moves to the left with speed 32 mm $yr^{-1}$. The dip-parallel velocity of the slab is 92 mm $yr^{-1}$. The trench and slab also move with speed 32 mm $yr^{-1}$ to the left. The streamline contour interval is $2.90 \times 10^9$ $mm^2$ $yr^{-1}$ See also Figures 9 and 10.

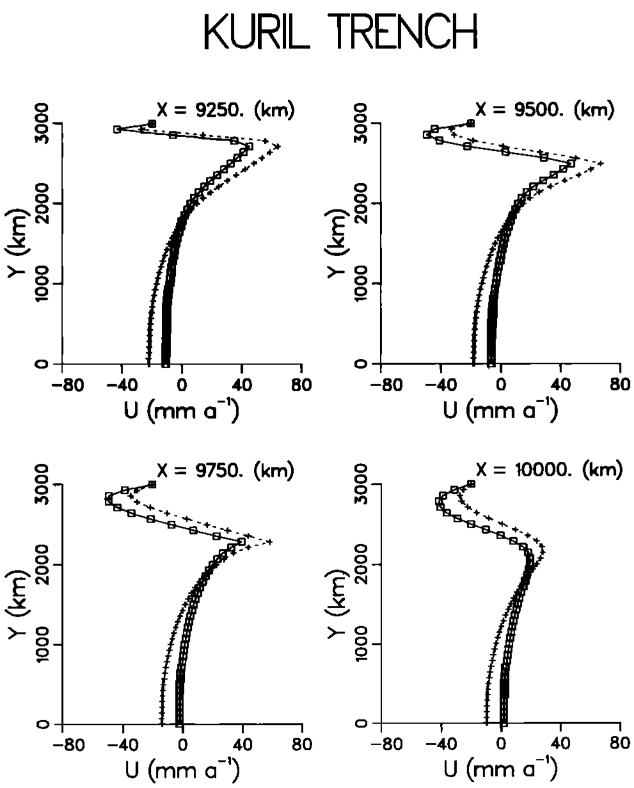


Fig. 13. Horizontal velocity U verses depth (y = 3000 km is at the top) for the Kuril trench configuration (Figures 9 and 10) and plate velocities of Figure 11. The horizontal distance to the trench corner is x-9000 km. Negative values of U are directed trenchward. Squares, with lateral slab migration; crosses, without slab migration.

plates. As noted already, this material is continuously being engulfed in the flow that is associated with the migrating slab and is diverted beneath the overrriding plate. Under much of the consumed plates away from subduction zones the flow in large volumes (the equivalent of the cell centers in Figures 11 and 12) can be quite slow and nearly stagnant. The material in these regions can be nearly isolated chemically from the rest of the mantle; this material is not mixed efficiently with other parts of the mantle and especially not with material of descending slabs. Such a situation can persist for several hundred million years, as is the case under the Pacific plate, for example. When material from such an isolated region is engulfed in the flow associated with a migrating slab, it becomes incorporated into a more vigorously flowing part of the mantle, is swept toward the boundary layer at the base of the convecting region, and can be efficiently mixed with other material. In the long term this has the important consequence of preventing the development of convection cells in which material particles move along simple closed paths. With typical velocities of 10-25 mm $yr^{-1}$, migrating slabs sweep through 1000-2500 km every 100 m.y. Several slab systems, similar to the present ones, can modify the flow in a significant part of the mantle in less than 0.5 b.y.

Migrating slabs thus have the important function of stirring the mantle and distributing material to large distances. The isolation of parts of the mantle is made more difficult as a result of slab migration. Global scale geochemical anomalies that survive for a billion years [Hart, 1984] are hard to reconcile with the efficient mechanical mixing of the mantle by migrating slabs. Richter et al. [1982] have recognized that single closed cells cannot disperse material on length scales large compared to cell size and that long range dispersal requires time dependent flow on a time scale comparable to convective overturn times. They carried out numerical experiments to demonstrate the large-scale mixing induced by imposed motions of cell boundaries. Migrating slabs, though not cell boundaries, stir the mantle the way moving cell boundaries stir the boxes in the numerical calculations.

Entrainment and dispersal of mantle material by migrating slabs also helps the mantle give off the heat which is generated in it by radioactive decay. The mechanisms of heat flow [Sclater et al., 1980] allow mantle material to give off its heat only when it approaches the earth's surface closer than about 150 km. By constantly modifying the flow pattern, slab migration removes different parts of the mantle from slowly flowing regions and thus eventually helps them approach the surface where they have an opportunity to cool.

There are many arguments for whole mantle convection [Davies, 1977; O'Connell, 1977;

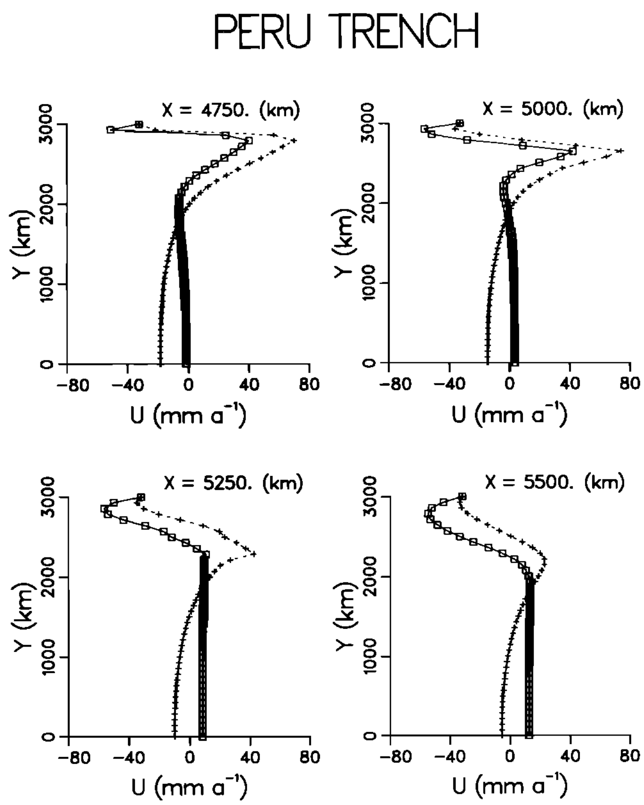


Fig. 14. Same as Figure 13 for the Peru trench configuration (Figures 9 and 10) and plate velocities of Figure 12. The horizontal distance to the trench is x - 4500 km.

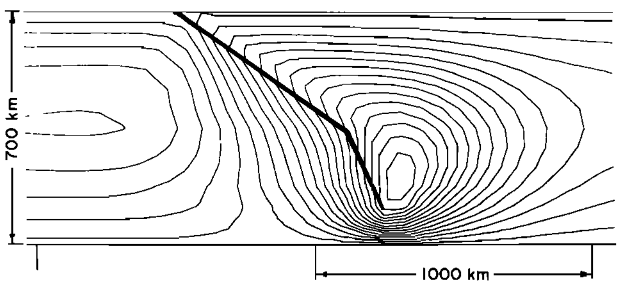


Fig. 15. Same as Figure 12 but for upper mantle circulation around the Peru trench confined to 700 km depth. The streamline contour interval is 1.55 x $10^9$ $mm^2$ $yr^{-1}$.

Schubert, 1979; Peltier, 1980], but there are also arguments suggesting that convection in the upper mantle does not extend below about 700 km and that at greater depth an independent flow system may exist [McKenzie and Weiss, 1975; Richter and McKenzie, 1978; Jeanloz and Richter, 1979; McKenzie, 1983]. Since this is still a controversial problem, we also examined models of the Peru and Kuril trenches in which the flow extends only to a depth of 700 km but which otherwise are similar to the previous models. In the upper mantle model of the Peru trench (Figure 15) the effects of lateral slab migration generally resemble those found in the whole mantle model (Figure 12). However, a notable difference is that in the shallow circulation model the flow generated by lateral slab migration is forced to pass through the narrow region between the lower tip of the slab and the base of the circulating system, and therefore it is much stronger than in the previous models. Similarly strong flows were also found by Hager et al. [1983] and Vassiliou et al. [1984] in models in which the slabs extended close to the bottom of the system.

The strong flow beneath the slab of Figure 15 is to some extent an artifact of the two dimensionality of the shallow flow model and of neglecting the mass transported by the slabs themselves. In fact, this is the only way to have slab migration in such a model. However, when three-dimensional motion is possible, slab migration can also generate a flow parallel to the slab, especially when it extends very close to the bottom of the system, thereby precluding a strong flow beneath the tip of the slab [Harper, 1978]. In the earth this may be the case beneath the very deep Japan, Mariana, Tonga, and Indonesia slabs if a barrier to convection exists at a depth of 650-700 km. Even the Peru and Kuril slabs are deep enough for such an effect to be important. Thus, if upper mantle circulation does not penetrate below 700 km, the two-dimensional models are probably not very good simulations of the slab tip regions. A similar difficulty does not arise when circulation is mantle wide because then slab material becomes hot and weak long before it reaches the base of the mantle.

Hager and O'Connell [1978] and Hager et al. [1983] attempted to discriminate between upper mantle and whole mantle circulation by comparing their flow models with observed dips of Benioff-Wadati zones. They assumed that in successful models the predicted streamlines should parallel the Benioff-Wadati zone dips. On this basis they preferred whole mantle circulation. The foregoing considerations do not support this reasoning. Rather, they show that successful models should pass two tests. First, the streamlines should be at an angle to the slabs, and second, the dip-parallel velocities of the slabs should equal their consumption rates. Reexamination of the models of Hager et al. [1983] from this point of view shows that their whole mantle convection model fits better the slab velocities, though these are too low, but it does not have the adequate slab migration, since streamlines tend to be parallel to the slabs. On the other hand, their shallow flow model (with no slip at the base of the system) fits better the first criterion since it predicts retrograde slab migration, though the predicted angles between the streamlines and the slabs seem to be unacceptably large in view of Figure 6 and the data of Table 1. This probably arises because in the shallow flow models the predicted slab velocities are very low and are comparable with the rates of lateral slab migration. Because of these inadequacies, these models cannot resolve whether mantle flow is shallow or not. Moreover, our considerations show that the locations of slabs cannot be inferred from the shapes of streamlines because the slabs cut across streamlines and they are not passive features carried by the ambient flow. Rather, since slabs have an important influence on the flow, a successful model must incorporate either their negative buoyancy or their motion explicitly. The adequacy of models cannot be judged on the basis of their predictions about the angles between streamlines and slabs because these are not known a priori in the three-dimensional mantle flow.

Our models also do not allow us to decide whether the flow is shallow or not. However, if the flow is shallow, then the backward migrating slabs are expected to bend and flatten out as they reach the base of the circulation system at about 700 km depth. Our models show that this will be enhanced by the strong flow beneath the slabs as they approach this barrier. The available data on the shapes of the deepest Benioff-Wadati zones generally do not reveal such effects, though the Tonga and Mariana slabs are bent near their eastern and northern edges, respectively [Isacks and Molnar, 1971; Isacks and Barazangi, 1977; Cardwell and Isacks, 1978]. The generally rather simple geometry of these zones [cf. Giardini and Woodhouse, 1984] is more in line with the slabs penetrating into the lower mantle, as was also suggested by Vassiliou et al. [1984]. A seismic extension of slabs below 700 km depth is also supported by Creager and Jordan's [1984] analysis of P and PKIKP travel times from intermediate and deep focus earthquakes in the Kuril-Kamchatka slab. If slabs indeed penetrate the lower mantle, then the shapes of the deep Benioff-Wadati zones show that slabs can migrate easily without bending across the phase change at about 700 km. Therefore there cannot be a large increase in viscosity across this boundary.

## Summary

The main points arising from the present work are that the descending lithospheric slabs migrate laterally through the mantle and thereby generate a circulation with a magnitude comparable to the circulation that is involved in the creation of new lithosphere along the entire world ridge system. Thus the occurrence of lateral slab migration must have an important influence on the large-scale mantle flow. These conclusions follow from the relative plate motions. In the framework provided by the absolute plate motions, slab migration is generally retrograde at typical rates of 10-25 mm $yr^{-1}$. Retrograde slab migration is probably caused by the tendency of negatively buoyant slabs to sink in the surrounding mantle. Because slabs migrate, they must be at an angle to streamlines in the nearby mantle, and they cannot be boundaries between convection cells. The flow generated by migrating slabs engulfs new parts of the mantle and changes the flow in these regions. In the long term, slab migration causes the mantle flow to be three-dimensional and time dependent and also helps to mix the mantle on a large scale. Slab migration enhances trench suction and promotes back arc spreading.

These conclusions do not depend on the assumptions regarding the depth of mantle flow. However, if the flow is shallow, then a strong flow might develop underneath the slabs and tend to flatten the lower parts of the slabs, which has not been observed. Alternatively, the flow near migrating slabs might be fully three-dimensional, especially if the slabs reach close to the base of the convecting system, thereby precluding a strong flow beneath them. Such a limitation does not arise if convection is mantle wide.

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