Recent Movements of the Juan de Fuca Plate System

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Analysis of the magnetic anomalies of the Juan de Fuca plate system allows instantaneous poles of rotation relative to the Pacific plate to be calculated from 7 Ma to the present. By combining these with global solutions for Pacific/America and "absolute" (relative to hot spot) motions, a plate motion sequence can be constructed. This sequence shows that both absolute motions and motions relative to America are characterized by slower velocities where younger and more buoyant material enters the convergence zone: "pivoting subduction." The resistance provided by the youngest portion of the Juan de Fuca plate apparently resulted in its detachment at 4 Ma as the independent Explorer plate. In relation to the hot spot framework, this plate almost immediately began to rotate clockwise around a pole close to itself such that its translational movement into the mantle virtually ceased. After 4 Ma the remainder of the Juan de Fuca plate adjusted its motion in response to the fact that the youngest material entering the subduction zone was now to the south. Differences in seismicity and recent uplift between northern and southern Vancouver Island may reflect a distinction in tectonic style between the "normal" subduction of the Juan de Fuca plate to the south and a complex "underplating" occurring as the Explorer plate is overridden by the continent. The history of the Explorer plate may exemplify the conditions under which the self-driving forces of small subducting plates are overcome by the influence of larger, adjacent plates. The recent rapid migration of the absolute pole of rotation of the Juan de Fuca plate toward the plate suggests that it, too, may be nearing this condition.

INTRODUCTION

The Juan de Fuca plate is one of the last continuing remnants of the Farallon plate, which converged with the western margin of North America over the last 150 million years. The collision of the Pacific-Farallon ridge with the American plate between 25 and 30 Ma led to the independence of the Juan de Fuca plate at about 20 Ma. (Ma is used here to denote age in million years before present.) Since that time its area has progressively diminished as the bounding, southern triple junction has migrated northward (for a recent review, see *Riddihough* [1982*b*]). A series of detailed magnetic anomaly maps [*Raff and Mason*, 1961; *Potter et al.*, 1974; *Currie et al.*, 1982] provide a uniquely comprehensive data base with which to study the seafloor spreading and plate motions of the Juan de Fuca plate region since 10 Ma. In general, the ridge and spreading changes are characterized by reduction in spreading rate and clockwise ridge and plate rotation [*Riddihough*, 1977, 1980; *Carlson*, 1981*a*]. The principal period of change appears to have occurred between 6 and 3 Ma.

The pattern of ridge segmentation and rotation observed in the magnetic anomalies was first suggested by *Menard and Atwater* [1968] as being a response to interaction between the oceanic plates and the continental (America) plate. Certainly, the proximity of the Juan de Fuca plate convergence zone to the ridge (Figure 1) makes some form of interaction extremely likely. Examinations of the forces driving plate motions [e.g., *Forsyth and Uyeda*, 1975; *Solomon et al.*, 1975] conclude that the buoyancy of the subducted slab and the resistance to subduction at the convergence zone are important components of the forces controlling plate movement. The probable effect on small plates close to triple junctions was detailed by *Menard* [1978] in the idea of "pivoting subduction." The local complexity of movements near the two triple junctions at the north and south ends of the Juan de Fuca plate system (Figure 1) [e.g., *Davis and Riddihough*, 1982; *Silver*, 1971; *Carlson and Stoddard*, 1981] is certainly indicative that in the extreme case, plate motions respond in a complex interactive manner.

However, as emphasized by *Hyndman* [1972] and recently discussed in more detail by *Dewey* [1980], *Uyeda and Kanamori* [1979], and *Molnar and Atwater* [1978], many aspects of plate motion can only be examined through their motions relative to the underlying asthenosphere. In a subduction zone, plates move down into the mantle so that at least part of the driving or resisting buoyancy force is a function of the speed of the plate relative to the asthenosphere. A full examination of local plate interactions must therefore involve documentation of "absolute" as well as "relative" motions.

POLES OF RELATIVE MOTION OF THE JUAN DE FUCA SYSTEM

Assessments of the geometry of present and recent convergence between the Juan de Fuca plate and the America plate [e.g., *McKenzie and Parker*, 1967; *Atwater*, 1970; *Silver*, 1971; *Riddihough*, 1977] have usually been based on completing a plane vector triangle between Juan de Fuca/Pacific spreading assumed as parallel to the Blanco fracture zone and Pacific/America motion derived from global solutions or the San Andreas–Gulf of California system. To the extent that the NE Pacific region is small, this approach gives solutions which are essentially correct but which mask any geographical variations in interaction rates.

Attempts to establish poles of relative rotation between the Farallon (later Juan de Fuca) and Pacific plates using spreading rate variations and fracture zone orientations for periods before 25 Ma [*Franchetau et al.*, 1970; *Handschumacher*, 1976] showed that such poles lay in the Bering Sea–Canada Basin region. One of the first attempts to determine a contemporary pole of motion for the Juan de Fuca plate was that of *Morgan* [1972], which was interpreted by *Carlson* [1976] as indicating a pole of relative Juan de Fuca/Pacific motion to the southwest of the plate near 30°N, 140°W. By contrast, *Carlson*

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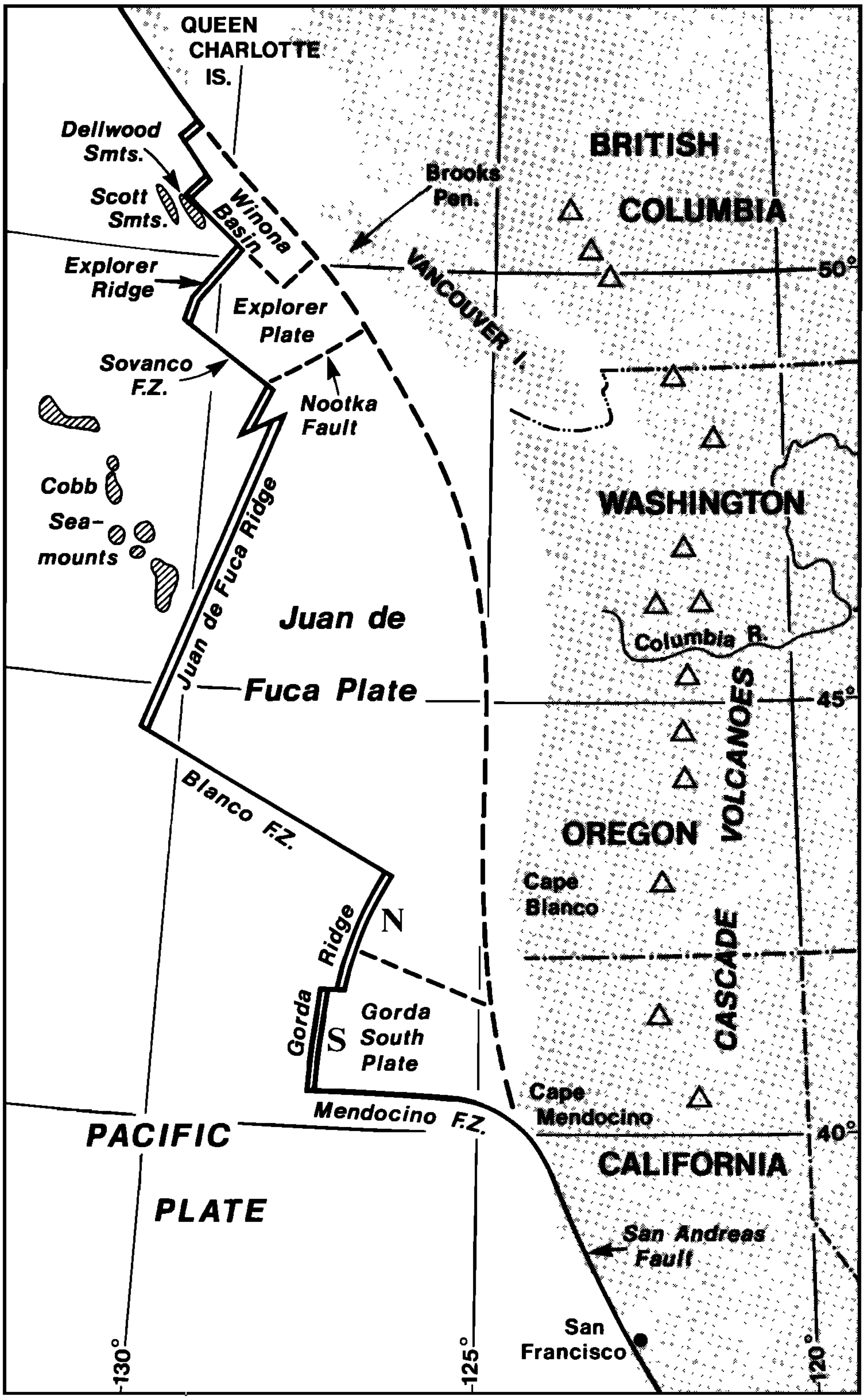

Fig. 1. Location map of the Juan de Fuca plate system.

[1976] used four earthquake fault plane solutions (two on the Blanco fracture zone and two on the Medocino fracture zone) to determine a pole to the northeast of the plate at 57°N, 119°W.

Independent determinations using spreading rate variations and Blanco fracture zone orientation [*Riddihough*, 1980] and numerical inversion via magnetic anomaly superposition [*Nishimura and Hey*, 1980; *Nishimura et al.*, 1981] have located the present Juan de Fuca/Pacific pole near 15°S, 150°W, to the southwest of the plate. *Hey and Wilson* [1982] have more recently calculated a sequence of pole positions to form the basis for their study of propagating rifts (see also *Nishimura et al.*, [1984]). This is further discussed below.

Method: Magnetic Anomaly Analysis

If plate tectonics were always to occur in a geometrically simple manner (with orthogonal and symmetric spreading), then spreading rates along a ridge system would decrease systematically toward the pole of rotation, fracture zones would always occur along small circles centered on the pole of rotation, and ridge segments and linear magnetic anomalies would always follow great circles passing through the pole. Further, the sense and differences in azimuth of equivalent anomalies on either side of a ridge system (fanning) would indicate the direction and amount of cumulative angular rotation between the two plates involved (Figure 2, left). In practice, divergences from such ideal behavior are widespread. Nevertheless, the geometrical concepts have formed the foundation of many plate tectonic analyses and often offer the only route to the determination of individual plate motions. Over the Juan de Fuca system, accurate contoured maps of magnetic anomalies with predominantly north-south orientation in a high magnetic latitude provide an opportunity to attempt to use such concepts in detail.

Although transform fracture zones commonly represent one of the most important constraints in determining plate motions, the Sovanco and Blanco fracture zones (F.Z.) (Figure 1) present a number of problems. The Sovanco F.Z. is not clearly defined by bathymetry, magnetic anomalies, or seismicity [e.g., *Milne et al.*, 1978]. The Blanco F.Z. may have had an extremely complex history [*Hey and Wilson*, 1982] and apparently contains a number of different segments of varying orientation including "pull-apart" basins (R. W. Embley, personal communication, 1984). For the purposes of examining the recent history of the Juan de Fuca system, neither fracture zone provides a clear record of past spreading directions.

For this study, all data were determined from magnetic anomaly orientation and spacing. Anomaly ages were assigned using the work by *Ness et al.* [1980], and individual anomalies or sequences disturbed by transforms or known "pseudofaults" were discounted. Anomalies were grouped into epochs of 1 million years duration, and measurements were made as in Figure 2 (right).

For Juan de Fuca relative to Pacific (JDF/PAC) plate spreading, it was assumed that the great circle containing the epoch pole of Juan de Fuca/Pacific plate motion could be determined from the azimuths of anomalies on the Pacific plate. (Those on the Juan de Fuca plate will have been cumulatively rotated.) This method assumes orthogonal spreading; however, any random deviations from this condition should be compensated by sampling. In practice, the 95% confidence limit on mean azimuth within all epochs except 4.5 Ma ($\pm 3.1°$) was $\pm 2°$ or less. Nevertheless, an arbitrary confidence limit of $\pm 5°$ was assigned to this determination. Clearly, this method does not allow for systematic oblique spreading along the whole ridge for periods of 1 million years or greater.

Spreading rates were measured perpendicular to anomalies as in Figure 2 (right) and projected onto the Pacific plate anomalies representing the epoch great circle (ridge) in swaths of approximately 1° of colatitude. An example of the results for epoch 3.5 Ma is shown in Figure 3. Plate tectonic geometry requires that ideally these spreading rates will conform to a sine function of colatitude. A simple test shows that for all points on such a curve the linear slope over a distance of less than 7° will differ from the slope of the sine function at the mean center point by less than 0.5%. For the present analysis, therefore, the slope was determined by linear regression, 95% confidence limits being assigned by the standard methods for small samples. With the slope and spreading rate at the mean point (with confidence limits) known, the colatitude and rotation rate of the pole can be uniquely determined. From this and from the great circle the pole can be calculated.

Instantaneous epoch poles determined in this manner, relative to the Pacific plate, are shown in Figure 4. The resulting "sector-shaped" 95% confidence limits are a consequence of the independent determination of colatitude and azimuth.

Juan de Fuca/Pacific Poles

Figure 5 compares the instantaneous poles derived in this paper with those of *Hey and Wilson* [1982] calculated from the finite rotations necessary to rotate isochrons on the Juan de Fuca plate onto the corresponding isochrons on the Pacific plate. Considering the uncertainties in the techniques, the results compare quite closely. One significant departure is in timing. *Hey and Wilson* [1982] consider that there was a "drastic shift" in Juan de Fuca/Pacific motion between the times of anomalies 3a and 3 (around 5 Ma). In fact, detailed studies of anomaly azimuths [*Riddihough*, 1977, Figure 3; *Carlson*, 1981*a*, Figure 5] show that while there may be a slight increase in the rate of clockwise anomaly rotation at 5

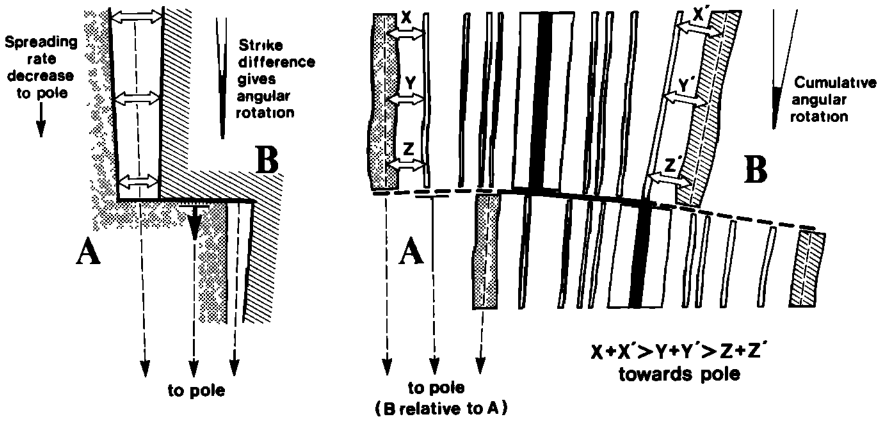

Fig. 2. Pole determination parameters from magnetic anomalies used in this study. (Left) Theoretical geometry of spreading. (Right) Application to observed magnetic anomalies.

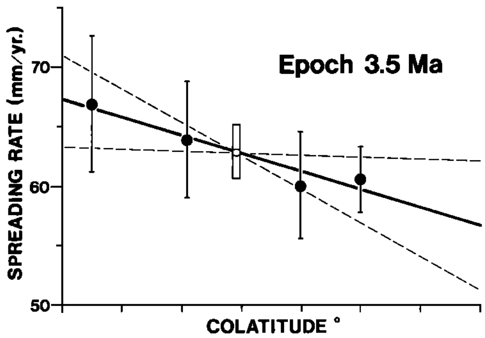

Fig. 3. Spreading rates along the Juan de Fuca ridge at 3.5 Ma. Colatitude is measured in degrees (111 km) along strike of magnetic anomalies on the Pacific plate; error bars are 95% confidence intervals on rates and the mean (open circle and bar); dashed lines are 95% confidence limits on the slope.

Ma, the major change is between 3 and 4 Ma (Figure 6). At this time, most "fanning" ceases. *Nishimura et al.* [1984] considered that the major change occurred between 2.4 and 5.4 Ma with the instantaneous pole remaining in its present position since 2.4 Ma.

The key to the timing discrepancy may lie in the argument that when plate motions change, it may take a finite amount of time for the central rift creating the magnetic anomalies to adjust to the new direction of spreading. *Hey and Wilson*'s [1982] reconstructions assume that spreading remains oblique after a pole change (anomalies are thus created parallel to the old ridge) until a propagator passes through and reorients the ridge system. A difficulty with this is that, as noted earlier, anomaly azimuths of the same age along the Juan de Fuca ridge are remarkably consistent. Further, the most striking contemporary ridge propagation in the region (the Cobb propagator) separates ridge sections which differ in orientation by no more than 1° or 2°.

Studies of detailed ridge structure [e.g., *Macdonald*, 1982] indicate that the "crustal accretion" and "neovolcanic" zone where spreading actually occurs may be less than 2 km wide, although off-axis volcanism does exist and the active faulting zone may exist to ±10 km of the axis. The speed with which a ridge can change orientation without propagation and the extent to which preexisting structure constrains changes are unclear. The fact that propagators break into old crust in an apparently continuous manner [*Hey and Wilson*, 1982] suggests that the constraints may not be strong. For the present studies, therefore, it is assumed that anomaly orientations averaged over 1-million-year time periods are perpendicular to plate motions during the same period and not those of a significantly earlier time.

Significant features of the pole positons in Figure 4 are the eastward drift up to 4.5 Ma and then the rapid increase in distance away from the plate. This movement results in the

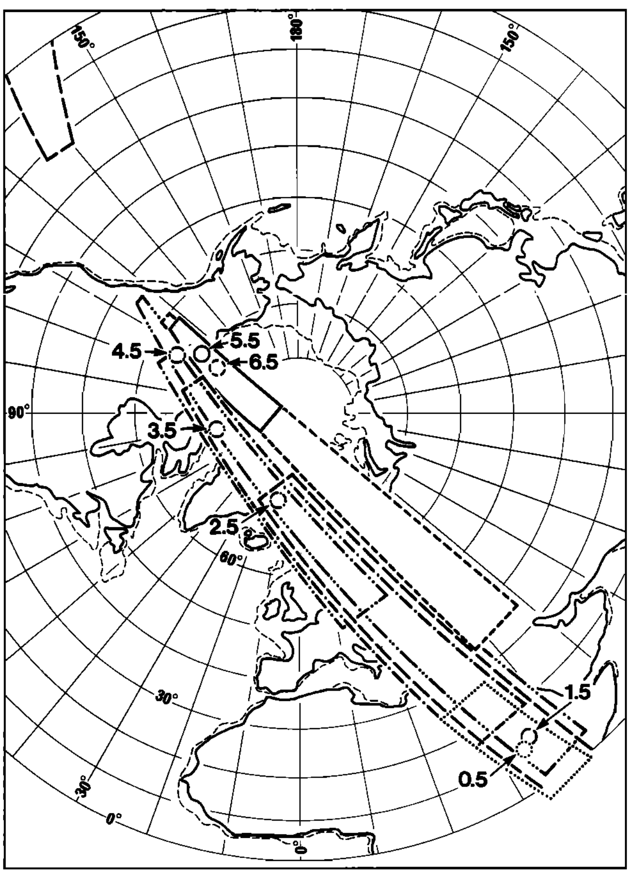

Fig. 4. Juan de Fuca/Pacific poles determined from this study. Numbers are epoch dates in million years before present (Ma). The 95% confidence limits are keyed to each pole position by symbols. For derivation, see text.

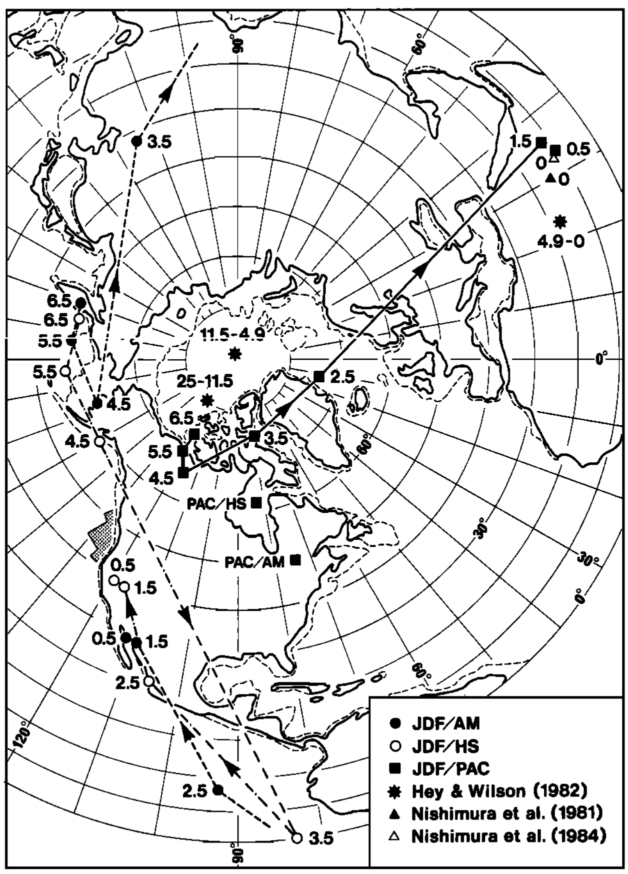

Fig. 5. Mean instantaneous Juan de Fuca/Pacific (JDF/PAC), Juan de Fuca/America (JDF/AM), and Juan de Fuca/hot spot (JDF/HS) poles derived in this paper. Numbers are epoch dates in Ma. Poles derived by other authors are shown for reference, together with contemporary Pacific poles from *Minster and Jordan* [1978]. Coastline is as at present.

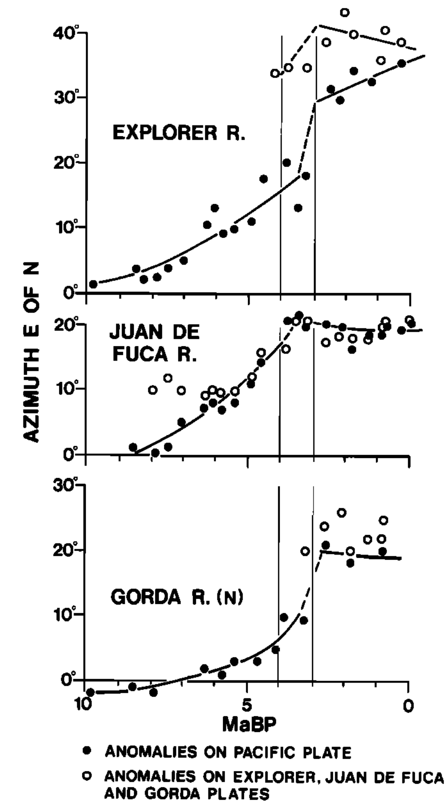

Fig. 6. Magnetic anomaly azimuths plotted against age for three sections of the Juan de Fuca ridge system. Open circles are azimuths on the plates to the east of the ridge; solid circles are from the Pacific plate.

nearest emergent pole of the rotation axis being to the south rather than the north of the plate since approximately 2 Ma. Confidence limits for the epoch-3.5-Ma pole put the closest pole as definitely to the north; limits for the 0.5-Ma pole constrain it to the south of the plate by that time.

Explorer/Pacific Poles

The change in Pacific plate anomaly (ridge) rotation at around 3 Ma can be seen in Figure 6 to occur for all three major sections of the ridge system (Gorda, Juan de Fuca, and Explorer). However, for the Explorer ridge it involves an almost 10° jump in azimuth followed by continuing rotation, not a cessation. It appears that at this time the Explorer plate became independent and no longer pivoted around the same pole relative to the Pacific plate as the rest of the Juan de Fuca system. This is supported by the following facts:

1. All anomalies on the eastern side of the Explorer ridge are "fanned" clockwise in relation to those on the west, indicating a nearby pole to the southwest with a rapid angular rotation.

2. The Explorer ridge spreading rate for epoch 3.5 Ma is much larger than that of the northern Juan de Fuca ridge. This is inconsistent with a single pole to the north.

3. The Pacific plate anomaly azimuth changes of Figure 6 could only be accommodated within a single plate system by a sudden westward Explorer ridge jump followed by continuing westward migration with a rotation pole to the north. This is inconsistent with point 2.

Hyndman et al. [1979] named the transform between the Explorer and Juan de Fuca plates the Nootka Fault and estimated that it came into existence around 7 Ma (see also *Riddihough* [1977]). However, determination of the pole of rotation sequence presented here shows that this may not be geometrically necessary and that the 3–4 Ma initiation is to be preferred.

A sequence of mean Explorer/Pacific (EX/PAC) poles from 3.5 Ma to the present is shown in Figure 7 and listed in Table 1. These were calculated using spreading rates and anomaly azimuths for the Explorer ridge [*Riddihough*, 1977] combined with the average Explorer/Pacific rotation rate determined from the fanning shown in Figure 6. As there is insufficient Explorer ridge length to observe the decrease of spreading rate toward the pole, the latter provides the necessary third parameter to determine the pole.

This process introduces a number of errors, not the least being the assumption of a constant rotation rate. Figure 8 shows the EX/PAC pole error space for epoch 0.5 Ma estimated using $\pm 5°$ great circle error and 95% confidence limits on the rotation rate from the fanning regression.

Gorda/Pacific Poles

Riddihough [1980] confirmed that the South Gorda ridge began to spread at a significantly different rate from the North Gorda ridge betweeen 2 and 3 Ma. Spreading on the North Gorda ridge can be fitted to the same pole of rotation as the remainder of the Juan de Fuca plate up to the present. The South Gorda ridge must therefore have had a separate pole of rotation relative to the Pacific plate since at least 3 Ma. *Riddihough* [1980] showed that significant anomaly fanning between Gorda South and the Pacific plate stopped at about 1 Ma. Thus the pole must have become much more distant for epoch 0.5 Ma.

The question of whether or not the anomaly distortion of the Gorda plate is produced by fanning or some form of internal deformation is being actively debated [e.g., *Silver*, 1971; *Riddihough*, 1980; *Carlson and Stoddard*, 1981]. At this stage, the poles of Figure 7 and Table 1 (calculated as for the Explorer ridge) are presented as the geometrical consequence of the fanning interpretation rather than the final answer to this problem.

"Absolute" Poles of Motion

Calculation of instantaneous absolute or "hot spot" poles for the Juan de Fuca system involves reconstructing the position of the instantaneous JDF/PAC pole at the epoch concerned relative to the hot spot framework and solving the vector addition with the Pacific/hot spot (PAC/HS) poles. A number of PAC/HS poles have been calculated using hot spot traces within the Pacific plate [e.g., *Minster and Jordan*, 1978; *Minster et al.*, 1974; *Chase*, 1978; *Turner et al.*, 1980; *Duncan*, 1981; *McDougall and Duncan*, 1980]. In comparing the orientation of seamount chains and features within the immediate region (in particular the Cobb, Scott, and Dellwood seamount systems; Figure 1), model AM1-2 of *Minster and Jordan* [1978] seems to produce the closest fit. This is the pole used in all absolute motion calculations in this paper. The resulting mean absolute poles calculated in this manner for the Juan de Fuca, Explorer, and Gorda South systems are listed in Table 1 and are shown in Figures 5 and 7.

The main features of the Juan de Fuca/hot spot (JDF/HS) poles are that they occur close to the Juan de Fuca plate to the northwest until 4.5 Ma, then shift to the southeast, and progressively migrate northwestward toward the plate. The Explorer/hot spot (EX/HS) and Gorda/hot spot (GO/HS)

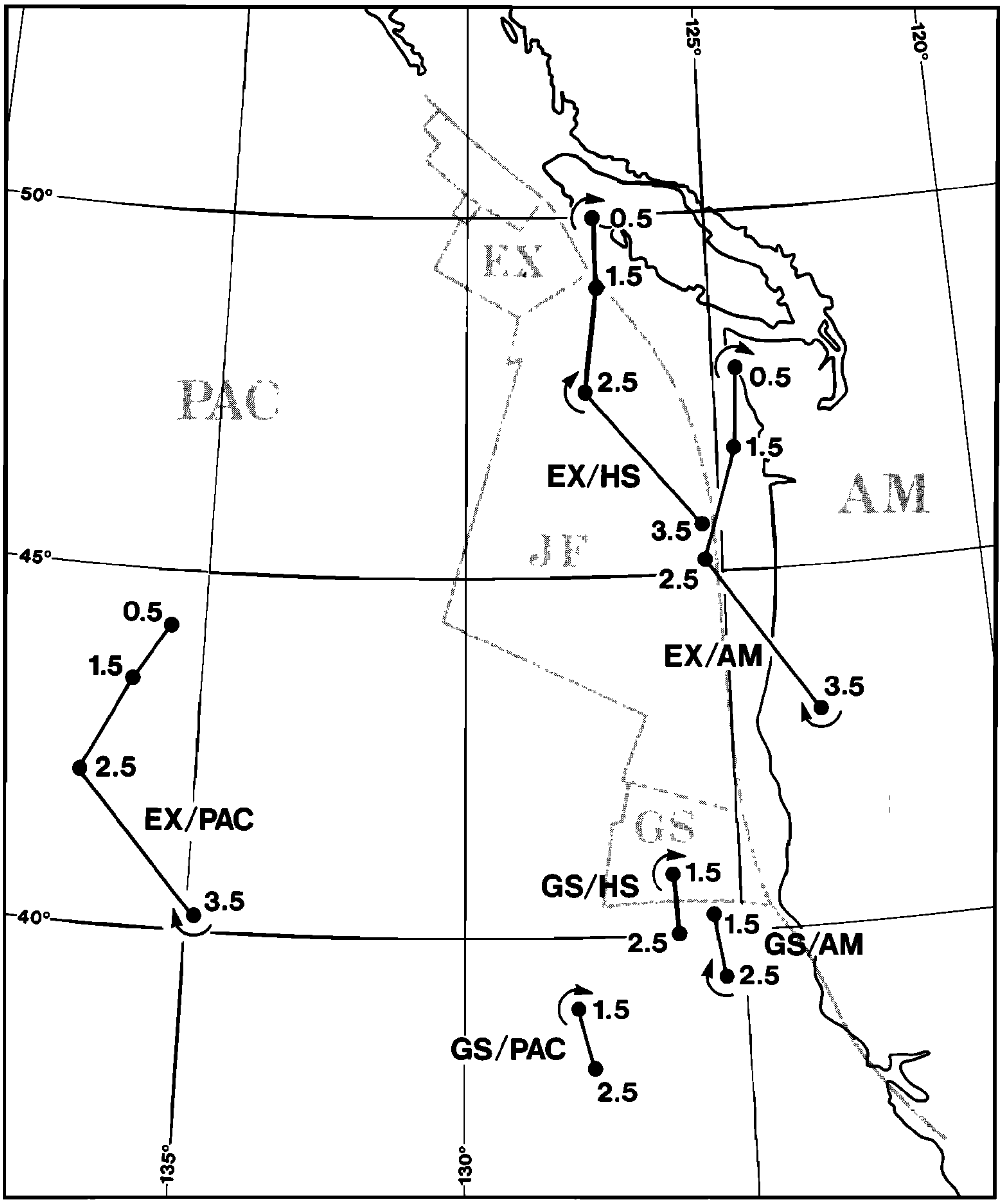

Fig. 7. Mean instantaneous poles for the Explorer and Gorda South plates, PAC, Pacific; HS, hot spot framework; AM, America plate framework; EX, Explorer; GS, Gorda South; JF, Juan de Fuca. Numbers are epoch dates in Ma; directions of plate rotation are shown by arrows. Coastline is as at present.

poles may occur extremely close to or within the Explorer and Gorda plates and consistently involve clockwise rotation.

Poles of Motion Relative to the America Plate

Calculation of mean poles relative to the American plate can be carried out through reconstruction and vector addition using a Pacific/America pole. A number of authors have calculated such a pole for the present, but there remains some uncertainty as to its applicability for periods older than 5 Ma [e.g., *Molnar and Atwater*, 1978; *Engebretson*, 1982]. This uncertainty is of undoubted importance in assessing motions of the Juan de Fuca plate relative to the America plate. However, for consistency the poles listed in Table 1 (shown in Figures 5 and 7) have been calculated assuming model RM2 of *Minster and Jordan* [1978] back to 6.5 Ma. (Using RM2, *Nishimura et al.* [1984] recently calculated a present Juan de Fuca/America (JDF/AM) pole at 29.11°N, 112.72°W at 1.05°/Ma; this compares closely with the 0.5-Ma pole shown in Table 1.)

Confidence Limits for Pole Determinations and Relative Motions

The asymmetric, "sector-shaped" confidence limits for instantaneous JDF/PAC and EX/PAC poles shown in Figures 4 and 8 result from the calculation methods. To estimate confidence limits for JDF/AM, JDF/HS, Explorer/America (EX/AM), and EX/HS poles, the bounding and mean pole positions (and rotation rates) were convolved with the quoted mean poles and 2σ limits on latitude, longitude, and rotation rate for RM1 and AM1-2. Ninety-five percent confidence limits on the resulting matrices of poles are shown in Figures 8 and 9 for epoch 0.5 Ma. (It should be noted from Figure 4 that these 0.5-Ma confidence limits are probably the smallest

TABLE 1. Mean Instantaneous Rotation Poles of the Juan de Fuca Plate System

Epoch, Ma	Relative to Pacific Plate* °N	°W	°/m.y.	Relative to Hot Spot Framework† °N	°W	°/m.y.	Relative to America† °N	°W	°/m.y.
				Juan de Fuca					
6.5	73.5	121.8	+1.42	57.3	195.0	+0.59	57.0	200.3	+0.83
5.5	69.5	124.0	+1.54	56.1	176.4	+0.69	56.9	185.9	+0.93
4.5	65.7	118.3	+1.87	58.8	150.2	+0.98	60.6	162.5	+1.19
3.5	74.9	80.0	+0.96	−19.8	82.6	−0.22	42.1	244.9	+0.43
2.5	73.6	12.3	+0.71	21.0	106.1	−0.47	−4.7	92.9	−0.50
1.5	−11.7	145.3	−0.61	38.5	117.7	−1.16	28.4	110.2	−1.07
0.5	−9.9	146.1	−0.62	39.2	119.4	−1.18	29.4	111.7	−1.09
				Explorer					
3.5	40.2	134.9	−3.1	45.7	125.4	−3.9	43.0	123.4	−3.8
2.5	42.1	137.1	−3.1	47.6	127.6	−3.9	45.2	125.3	−3.8
1.5	43.5	136.3	−3.1	49.0	127.3	−3.9	46.7	124.7	−3.8
0.5	44.2	135.7	−3.1	50.0	127.4	−3.9	47.8	124.5	−3.8
				Gorda South‡					
2.5	38.1	127.8	−13.5	40.0	126.1	−14.5	39.3	125.4	+14.2
1.5	39.0	128.0	−13.2	40.9	126.2	−14.0	40.2	125.5	−14.0
0.5	30.0	129.2	−1.1	46.9	114.5	−1.9	41.2	108.0	−1.7

Poles are given in relation to Pacific, hot spot framework, and America considered fixed in their present positions. Pole named is the emergent pole closest to the Juan de Fuca plate. Rotations are −, clockwise, and +, anticlockwise viewed from the pole.

*For confidence limits, see Figure 4.

†Calculated using Pacific plate motion as determined by RM1 and AM1-2 of *Minster and Jordan* [1978].

‡Poles assuming no internal deformation of Gorda South plate (see text).

of the set being considered.) These simplified confidence limits tend to be slightly smaller than the conventional elliptical limits [e.g., *Minster and Jordan*, 1978] and are also nonsymmetric about the third pole determined by the vector addition of the two mean poles (e.g., JDF/PAC and Pacific/America (PAC/AM)). In terms of the significance to be given to the resulting motions of the Juan de Fuca plate system, they nevertheless provide at least a minimum assessment of the probable errors. For Juan de Fuca plate motions at 0.5 Ma, they suggest errors of ± 7 mm a^{-1} and $\pm 7°$ relative to America and ± 10 mm a^{-1} and $\pm 20°$ relative to the hot spot framework for a point in the center of the plate. Explorer plate motions are less certain, having probable errors for 0.5 Ma of ± 15 mm a^{-1} and $\pm 12°$ relative to America and ± 15 mm a^{-1} and $\pm 100°$ (for a point near Brooks Peninsula that is within the confidence limits of the absolute pole position (Figures 1 and 8)). By comparison, similar calculations for the errors of JDF/AM motion at 3.5 Ma give ± 13 mm a^{-1} and $\pm 17°$.

ABSOLUTE MOTIONS OF THE JUAN DE FUCA SYSTEM

Figure 10 presents a sequential picture of the absolute (relative to hot spots) plate motions of the Juan de Fuca plate system since 7 Ma. The motions are shown on a geometry of the plate system relative to the present coastline and use the mean calculated poles of Table 1 subject to the uncertainties discussed above. This reconstruction does not include the accreting history of the Blanco F.Z. by accumulating propagating offsets as proposed by *Hey and Wilson* [1982]. For the understanding of the motions of the rigid plate system over the mantle and relative to the margin, this may not be critical. America absolute plate motion is as given by AM1-2.

For the period from 7 to 4 Ma, motion of the plate is to the northeast with the slowest motion off Vancouver Island. The occurrence of the slowest rate at the northern end is in agreement with the concept of *Menard* [1978] that the youngest material (where the ridge is closest to the subduction zone) provides the greatest resistance to subduction. In effect, the plate tends to pivot about such a point.

Between 4 and 3 Ma there is a dramatic change. The youngest northern portion of the plate that was providing the maximum resistance breaks off and begins to move independently as the Explorer plate. (The approach of the eastern end of the Sovanco F.Z. to the margin may have contributed to this.) It immediately begins to move about a very local pole so that its motion into the convergence zone is severely reduced. Even with the probable error limits of pole positions, by 2.5 Ma it may be rotating about a point within itself such that in a translational sense it is no longer moving systematically toward the former subduction zone. This type of "spinning" motion continues to 0.5 Ma. The pole uncertainty limits include the possibility that in the hot spot framework it could be moving away from its subduction zone with the America plate.

At the time that the Explorer plate becomes independent, the Juan de Fuca plate becomes notably smaller, and the point of maximum resistance to movement provided by the youngest material entering the subduction zone shifts to somewhere in the Cape Blanco area. By epoch 2.5 Ma, the mean absolute velocity of the plate has dropped to 40% of its previous value, and the slowest motion has shifted to the southeast in conformity with *Menard*'s [1978] concept. The velocity of the plate continues to reduce until epoch 0.5 Ma. The absolute velocity determined from the mean pole now varies from 20 mm a^{-1} near Vancouver Island to 10 mm a^{-1} near Cape Blanco, the pole of absolute rotation being in northern California. However, considering the uncertainties discussed above, it is now possible that the velocity of the southern part of the plate relative to the mantle is close to zero.

A separate pole of motion for the southern Gorda plate is

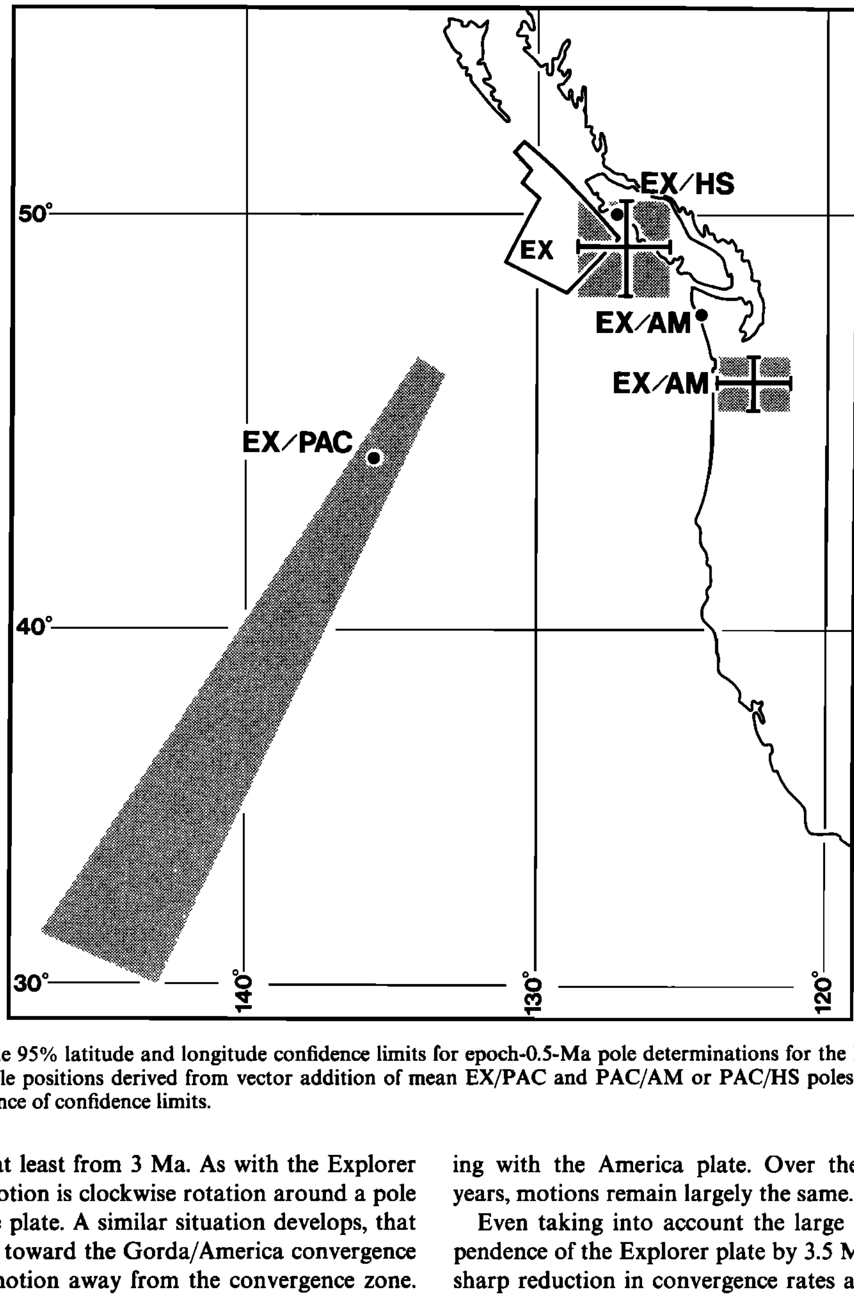

Fig. 8. The 95% latitude and longitude confidence limits for epoch-0.5-Ma pole determinations for the Explorer plate. Circles are pole positions derived from vector addition of mean EX/PAC and PAC/AM or PAC/HS poles, not the mean of the covariance of confidence limits.

probably significant at least from 3 Ma. As with the Explorer plate, the resultant motion is clockwise rotation around a pole close to or within the plate. A similar situation develops, that of little or no motion toward the Gorda/America convergence zone, perhaps even motion away from the convergence zone. The change in the Gorda South pole for epoch 0.5 Ma retains the clockwise motion but could result in movement that is significantly away from the subduction zone and the Mendocino escarpment.

MOTIONS OF THE JUAN DE FUCA SYSTEM RELATIVE TO AMERICA

Figure 11 presents a sequential picture of the motions of the Juan de Fuca plate system relative to the America plate on the same plate layout as Figure 10. Again, these are the motions given by the mean poles of Table 1 and subject to considerable uncertainties. At 6.5 Ma, relative motion is to the northeast at mean speeds varying from 60 mm a^{-1} along the Vancouver Island margin to 70 mm a^{-1} south of Cape Mendocino. As with the absolute motions, the slowest movement is off Vancouver Island where the youngest material is converging with the America plate. Over the succeeding 2 million years, motions remain largely the same.

Even taking into account the large uncertainties, the independence of the Explorer plate by 3.5 Ma probably results in a sharp reduction in convergence rates along Vancouver Island (Figure 12). In relation to the America plate, the Explorer plate again rotates clockwise around a local pole probably to the southeast (see Figure 7), which appears to be migrating northward and becoming closer to the Explorer plate itself.

After the breakaway of the Explorer plate at 3.5 Ma, the remainder of the Juan de Fuca plate behaves in relation to the America plate much as it did when considering absolute motions. The convergence rate probably declines from its 4.5-Ma value at all points along the convergence zone (Figure 12). By epoch 2.5 Ma, the JDF/AM pole has shifted to the southeast of the system, so that the slowest convergence is in the Cape Blanco area where the youngest material is entering the subduction zone. Convergence probably continues to decline to the present, and the pole moves toward the plate.

If, as before, the southern part of the Gorda plate is treated as rigid, this plate apparently rotates clockwise around a local pole close to or within the plate through epochs 2.5 and 1.5 Ma. For epoch 0.5 Ma, convergence may cease, and the plate may move to the northwest at approximately 40 mm a^{-1}.

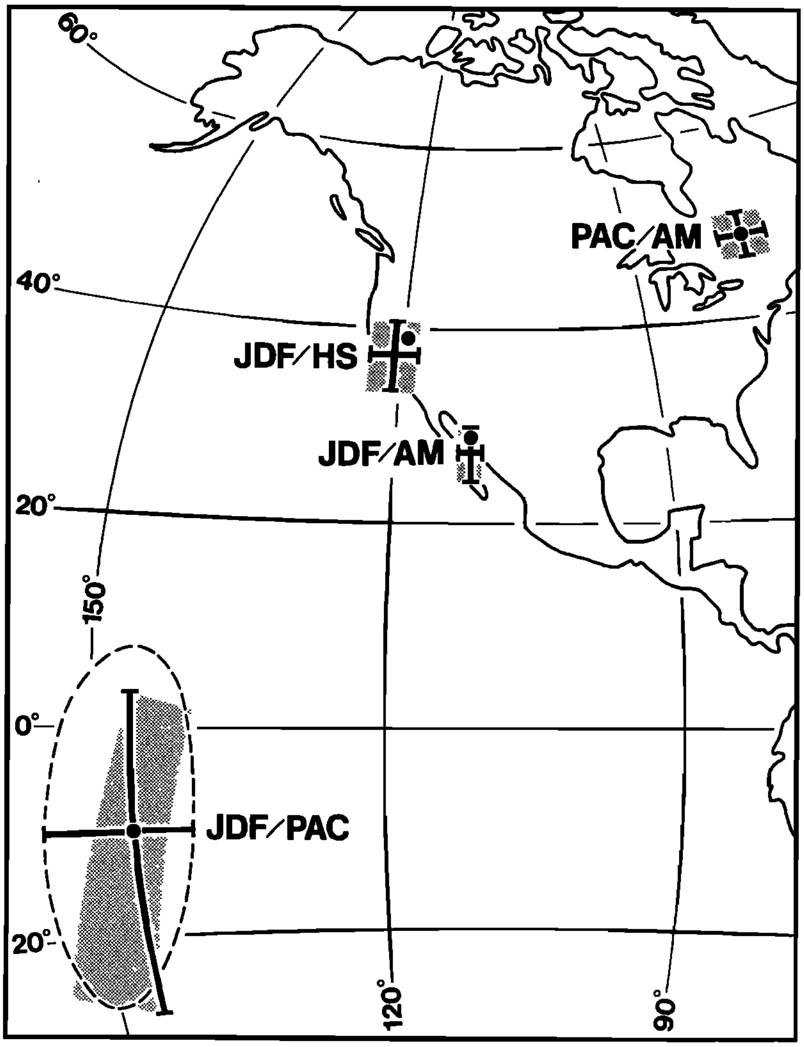

Fig. 9. The 95% latitude and longitude confidence limits for epoch-0.5-Ma pole determinations for the Juan de Fuca plate. Dashed oval is 95% confidence interval for JDF/PAC pole from *Nishimura et al.* [1984].

DISCUSSION OF PLATE MOTIONS

In summary, the plate motions of the Juan de Fuca system as shown by the mean rotation poles both in an absolute (relative to hot spots) and in a relative (to America) sense show similar characteristics:

1. The rate of motion declines beginning at 4 Ma.
2. The motion pattern is such that the youngest converging material moves slowest; this pattern is reestablished for the Juan de Fuca plate after 4 Ma when the Explorer plate becomes independent.
3. After 4 Ma, all closest rotation poles lie to the south and progressively move toward the plates concerned.

The errors of pole positions and rotation rates are probably such as to reduce the significance of characteristic 1 above, but both characteristics 2 and 3 remain true at the 95% confidence limit.

Driving Forces

The enigma of plate driving forces has been examined, both theoretically and by the empirical approach of comparing plate speeds with parameters such as area, ridge length, trench length, etc. *Forsyth and Uyeda* [1975] concluded that there was no obvious relation between plate velocity and area but that there was a striking correlation between velocity and the length of trench with subducted slab. *Chapple and Tullis* [1977] also concluded that the major driving forces are associated with subduction, a pull due to the downgoing slab acting on both upper and lower plates, and a resistance to convergence. Recently, *Carlson* [1981*b*] and *Carlson et al.* [1983] assessed the balance of forces using multiple linear regression and concluded again that slab pull is the dominant force in determining plate velocities.

The data assembled in Figure 10 can be used to calculate the mean integrated velocities of the Juan de Fuca plate relative to the hot spot framework since 7 Ma. These velocities decrease from around 45 mm a^{-1} at 6.5 Ma to 17 mm a^{-1} at 0.5 Ma. Allowing for uncertainties of ± 20 mm a^{-1} for the older epochs and ± 10 mm a^{-1} for the present, this suggests that the velocity has either remained similar or decreased by up to 50% during this period. Using the geometry of the plate system shown in Figures 10 and 11, the total area of the plate has decreased by approximately 50% during the same period. The effective ridge length (normalized by total perimeter) has decreased by approximately 25%, and the effective trench length has remained almost identical. In qualitative terms, therefore, the results may be compatible with other global studies.

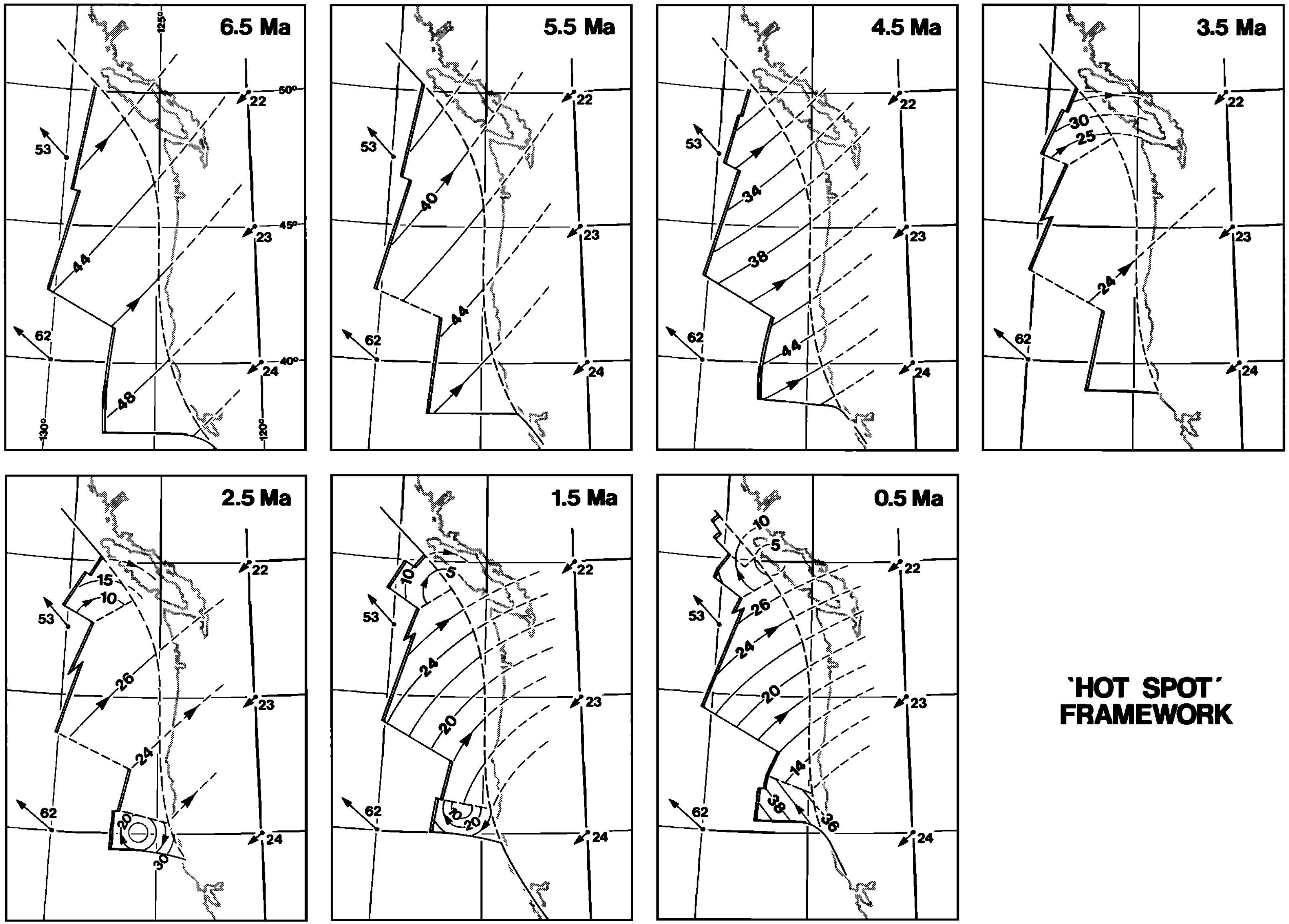

Fig. 10. Motion vectors of the Juan de Fuca plate system since 7 Ma relative to the absolute (hot spot) framework. Numbers are millimeters per year. Dates are center points of 1-million-year epochs. Position of America plate is fixed in the figure. Errors are discussed in the text but are at least $\pm 20°$ and ± 10 mm a^{-1} for Juan de Fuca plate vectors.

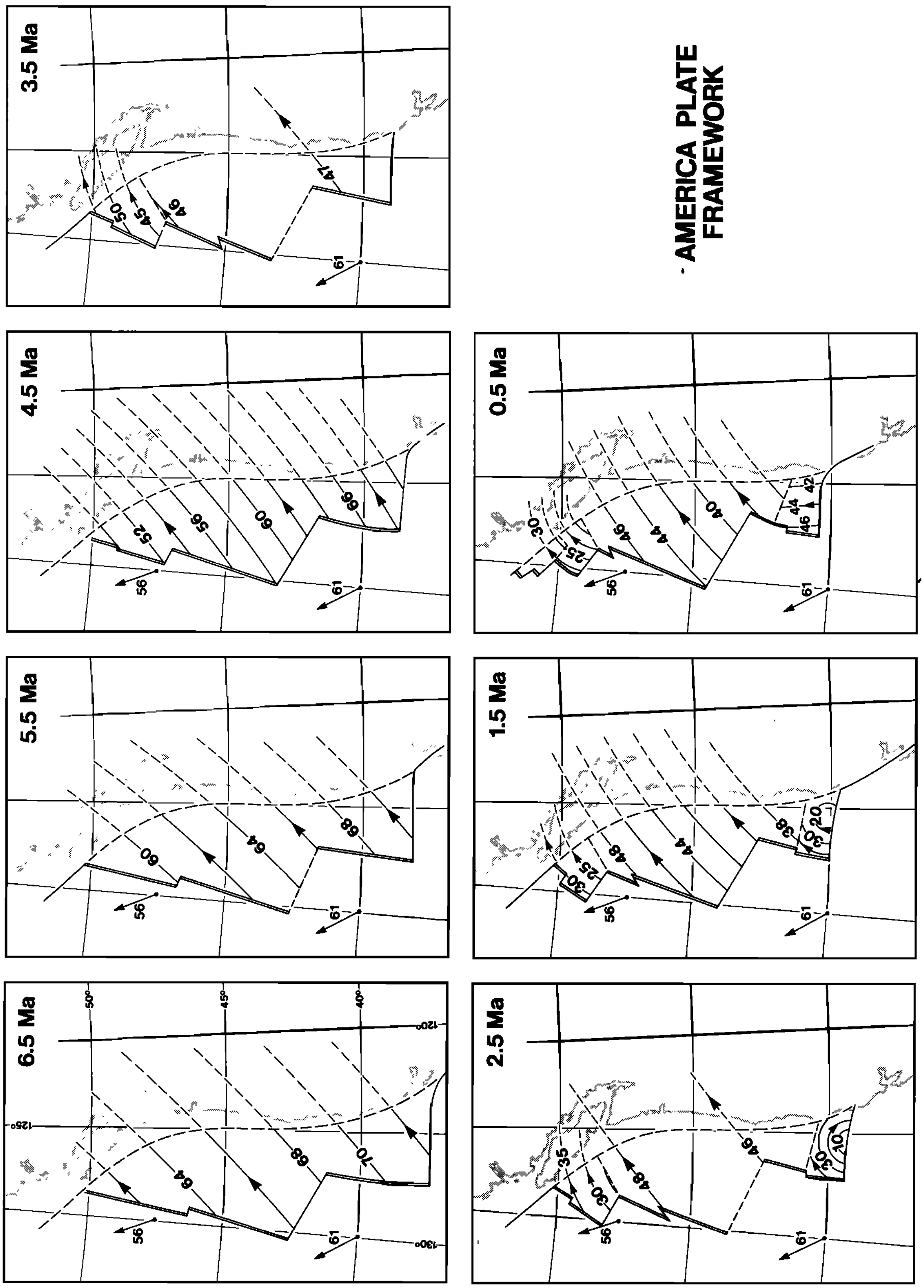

Fig. 11. Motion vectors of the Juan de Fuca plate system since 7 Ma relative to the America plate. Numbers are millimeters per year. Dates are center points of 1-million-year epochs. Errors are discussed in the text but are at least ±7° and ±7 mm a^{-1} for Juan de Fuca plate vectors.

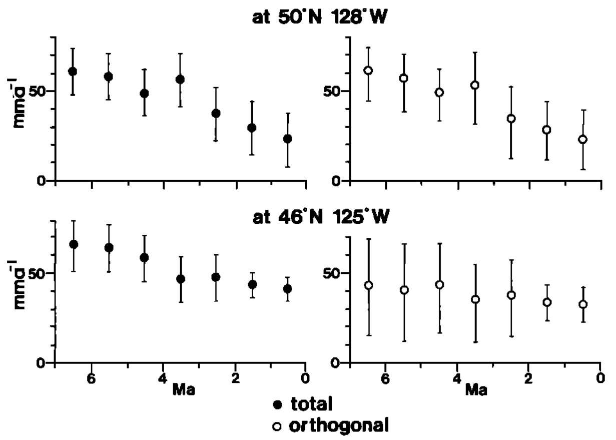

Fig. 12. Interaction rates (in millimeters per year) at two points near the continental margin versus time. Solid circles, movement relative to America; open circles, convergence perpendicular to the margin. Error bars are estimated and may be minimum for older epochs; see text for explanation.

Nevertheless, it is clear that many of the quantitative relations determined from global studies do not fit the Juan de Fuca plate. In particular, the model IV regression of *Carlson* [1981*b*] predicts that the mean velocity of the Juan de Fuca plate would be 98 mm a^{-1} at 6.5 Ma and 94 mm a^{-1} at 0.5 Ma. Figure 8 of *Forsyth and Uyeda* [1975] also suggests that to fit in with the global plate observations, the Juan de Fuca plate, with a present effective trench length of 40%, should have a velocity of 100 mm a^{-1} or greater. Using a plate age at the margin of 10 Ma, the relation derived by *Carlson et al.* [1983] predicts an absolute velocity for the Juan de Fuca plate of 25–35 mm a^{-1}. This is close to the absolute velocities calculated from Figure 10. However, plate reconstructions as in Figure 10 (see also *Engebretson*, [1982]) suggest that the ridge has stayed approximately the same distance offshore since 10 Ma. The age of the plate entering the trench has thus remained similar. If the mean speed has decreased markedly in this period, age seems unlikely to be a significant factor.

Quantitatively, it would seem that the balance of forces controlling Juan de Fuca plate motions may not be the same balance as for other, larger plates. As plates become as small as the Juan de Fuca, the simple linear relations between forces such as those proposed by *Carlson et al.* [1983] may change or cease to apply.

Pivoting Subduction

The process summarized in Figures 10 and 11 seems to support *Menard*'s [1978] concept of pivoting subduction and provides a striking example of the rate and style of response of a small plate system. Some form of resistance at the convergence or subduction zone is apparently an important factor in determining plate motion in this region. Ironically, because both absolute and relative to America motions show the same pattern, it is not immediately obvious whether the predominant factor is the motion of the Juan de Fuca plate into the mantle or its interaction with the overlying continental plate. The latter may provide frictional resistance to convergence; the former may provide buoyancy resistance as the material of the oceanic plate moves downward. However, if the detachment of the Explorer plate reflected a balance point between its resistance to motion and the strength of its attachment to the remainder of the Juan de Fuca plate, then the fact that its absolute rather than relative translational movement rapidly declined to near zero suggests that it is its motion into the mantle which provided the predominant resistance.

The absence of any fault plane solutions showing underthrusting [*Milne et al.*, 1978; *Rogers*, 1979] in the convergence zone of the Juan de Fuca plate system, the low-energy release of Juan de Fuca/America convergence [*Hyndman and Weichert*, 1983], and the steady "back tilting" of coastal areas [*Ando and Balazs*, 1979; *Riddihough*, 1982*a*; *Reilinger and Adams*, 1982] have all been suggested as indicating that Juan de Fuca/America interaction in this region is continuously aseismic. Although these observations cannot necessarily be extended to long-term processes, they do indicate that at least on a short time scale, conditions of low resistance to Juan de Fuca/America convergence can exist.

The fact that once the Explorer plate is detached, the remainder of the Juan de Fuca plate adjusts its motion so that its southern (youngest) part moves slowest is an apparently strong confirmation of the pivoting subduction concept. However, a major dilemma is posed by the data of Figure 10: If the Explorer plate was providing the maximum resistance to Juan de Fuca motion, why does the mean velocity of the remainder of the Juan de Fuca plate decrease and not increase when the Explorer plate becomes detached? One solution to this problem may be that the resulting decrease in plate size is the dominant factor in determining plate speed. Another solution may involve other components of plate motion.

Subduction, Overriding, and "Rollback" Velocities

Dewey [1980] and *Uyeda and Kanamori* [1979] rationalized the movements of plates in a convergence zone into three components. Following Dewey's notation, these components are

V_o absolute velocity of the overriding plate;
V_u absolute velocity of the underlying plate (its rate of insertion into the asthenosphere);
V_r rate of rollback at which a trench moves oceanward due to the rate of "fall" of the subducting plate, V_g, into the asthenosphere. (This is distinct from what might be termed the "forced" rollback due to the advance of an overlying plate.)

Both *Dewey* [1980] and *Uyeda and Kanamori* [1979] argue that the tectonics of a convergence zone are highly dependent upon the relative values of V_r and V_o and are much less dependent upon V_u.

Explorer plate. The rapid decline of Explorer plate velocity and the movement of its pole of rotation has produced a situation where its present rate of insertion along its own length into the mantle, V_u, may be near zero. Although there is, presumably, a section of subducted Explorer plate beneath Vancouver Island, it is not coherently moving down into the mantle. It seems reasonable to argue that, in fact, the only reason that this portion of the plate was previously moving down into the asthenosphere may have been because it was attached to the older and larger Juan de Fuca plate. Once it became detached, the sum of forces driving the Explorer plate changed radically, and it could no longer continue any downward movement. *Dewey* [1980] stresses that rollback velocity V_r is independent of V_u. However, if one of the dominant forces driving plate motion is the negative buoyancy of subducted slabs, then it seems likely that, although independent, both V_r and V_u will approach zero if this buoyancy ceases to be negative. In the case of the Explorer plate, V_u is near zero, and it would seem probable that V_r, the "free" rollback velocity, may thus also be near zero.

In tectonic and structural terms, the result of this situation could be as in Figure 13. The Explorer plate, having ceased to descend into the mantle under its own body forces, is still converging with the America plate and has been overridden by up to 70 km in a southwesterly direction. It may thus be effectively underplating the northern part of Vancouver Island. Such a process would, presumably, involve an increased stress coupling with the overlying America plate and a contrast in recent vertical movement history. These conditions plus the complexity of the interaction with the America plate produced by the local pole of relative movement would seem to ensure that there should be a strong contrast between the tectonic processes affecting northern Vancouver Island and those affecting southern Vancouver Island and the Washington and Oregon margins. This seems to be true of present seismicity [*Milne et al.*, 1978; *Rogers*, 1979], in particular in the zone where the subducted Nootka Fault [*Hyndman et al.*, 1979] marks the boundary between the two regimes. *Rogers* [1983] has also pointed out that the vertical movement pattern [*Riddihough*, 1982*a*] and topography of the northern part of Vancouver Island are distinct from the areas to the south.

Juan de Fuca plate. The dilemma of the apparently continuing reduction in motion of the Juan de Fuca plate after the detachment of the resistive Explorer plate may be resolvable if the independence of V_u and V_r suggested by *Dewey* [1980] does hold true for the nonzero condition. As shown (Figure 10), V_u for the Juan de Fuca plate apparently continues to decline after 4 Ma. However, if the Explorer plate was providing buoyancy resistance to descent into the mantle, then its removal may have resulted in an increase in V_g and thus V_r, the trench rollback velocity. Such an increase would not show in Figure 10 but might be detectable in a vertical cross section through the Juan de Fuca convergence zone.

A series of cross sections derived from seismicity, seismic refraction, and gravity modeling were constructed by *Riddihough* [1979] (see also *Ellis et al.* [1983] and *Michaelson* [1983]). All showed an increase in dip or "bend" in the downgoing slab beneath the Georgia Strait and the Puget Sound. One of these is shown in Figure 14 (top). Figure 14 (bottom three panels) suggests how such a bend could be produced by an increase in V_r and V_g relative to V_o. Previous to 4 Ma, the relation between V_o (America absolute velocity, ~23 mm a^{-1}) and V_r may have been such that the margin was "compressional" [*Dewey*, 1980]. At 4 Ma an increase in V_g and V_r produced by the detachment of the Explorer plate could cause the bend in the plate at the trench to begin to "fall." This increase in V_r might change the characterization of the margin at this time to something closer to that defined by *Dewey* [1980] as "neutral."

The aseismic nature of the Juan de Fuca plate convergence zone and the accretionary nature of the Washington-Oregon margin [e.g., *Silver*, 1972] seem to be in accord with a neutral concept [*Dewey*, 1980]. The initiation of high Cascade volcanism [e.g., *McBirney*, 1978] in the late Pliocene could also be a response to a change in asthenospheric flow between the downgoing and overlying slabs in a similar way to that suggested by *Barazangi and Isacks* [1976] for the Nazca plate. Certainly, the existence of the bend in the downgoing slab in the appropriate lateral position (100–120 km from the margin) to have been produced near 4 Ma seems to be an indication that a change in rollback velocity at about that time is a possible occurrence.

However, this explanation does not account for the fact that globally, most subducting slabs have a "knee bend" at a depth of between 30 and 50 km [*Pennington*, 1983]. The association of the bend in the Juan de Fuca plate with seismicity due to phase changes [*Rogers*, 1983] seems to support the concept of *Pennington* [1983] that the bend is a response to the increase

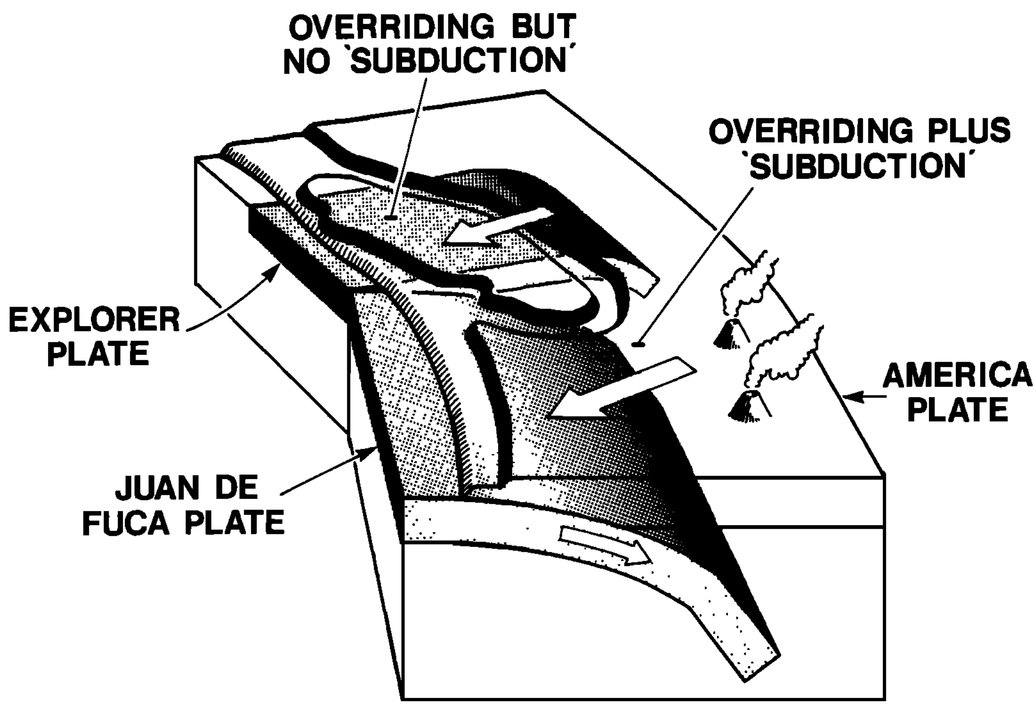

Fig. 13. Block diagram showing proposed plate configuration and contrast beneath Vancouver Island. "Subduction" is used here as movement of the underlying plate downward into the asthenosphere.

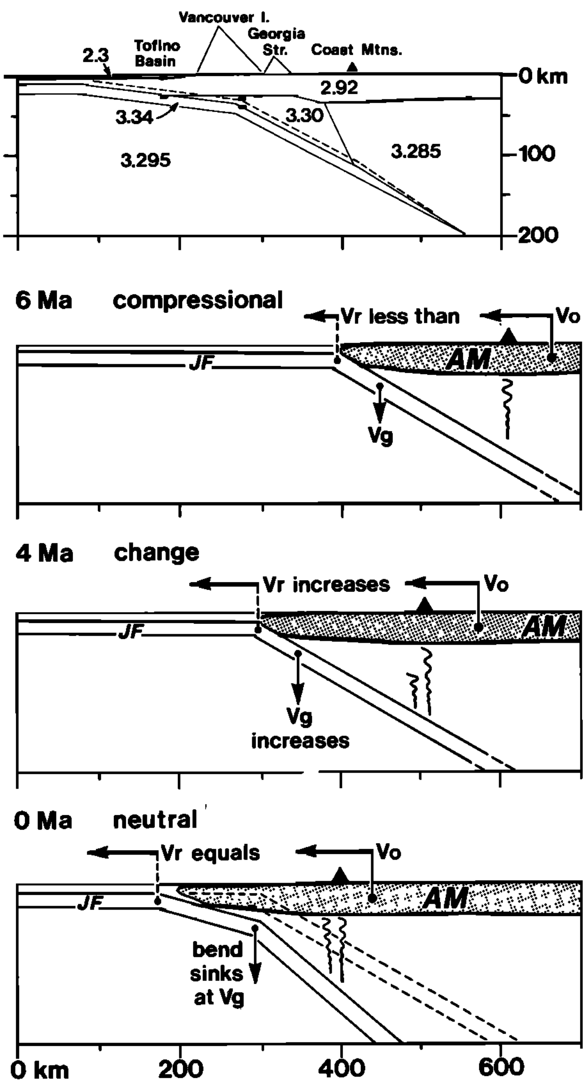

Fig. 14. (Top panel) Cross section across southern Vancouver Island [from *Riddihough*, 1979]. (Bottom three panels) Sequential mechanism for the possible production of an observed bend in the downgoing slab. Sections are fixed in relation to the mantle; America (AM) moves westward at absolute velocity V_o. At 6 Ma the trench rollback velocity V_r is less than V_o, and compressional convergence occurs. At 4 Ma, V_g increases. This results in an increase in V_r such that it equals V_o and a steepening of the downgoing slab. The tectonic style is now neutral [*Dewey*, 1980], and a bend is produced.

in negative buoyancy produced by the phase changes. Its location in the Juan de Fuca plate at a point which could infer changes in convergent style at around 4 Ma may thus be a coincidence.

Gorda South

As stressed at the outset, motions for the southern part of the Gorda plate which apparently moved independently from 3 Ma [*Riddihough*, 1980] have been calculated assuming rigid plate tectonics. The possibility of nonrigid, or at least imbricate, distortion within this southern plate section was suggested by *Silver* [1971] and has been more recently examined by *Carlson* [1976] and *Carlson and Stoddard* [1981]. Analysis of the 1980 Eureka earthquake [*Smith et al.*, 1981] shows that northeasterly oriented left-lateral shear does occur and strongly suggests that imbricate deformation is a probable explanation.

The reason for the timing of the independence of this part of the Gorda plate at 3 Ma is not clear. It was not the youngest portion of the subducting Juan de Fuca plate at that time, although the recent detachment of the Explorer plate may have precipitated a redistribution of stress such that this corner of the system between the margin and the Mendocino F.Z. became particularly vulnerable. Being small, once it had broken away, it would presumably have little or no self-driving force. It could be argued that the clockwise motion from 3 to 1 Ma was determined either by northwesterly Pacific absolute motion or by the northwesterly right-lateral shear applied by Pacific/America relative motion. The increase in absolute motion by 0.5 Ma and the rapid decrease in spreading on the southern Gorda ridge suggest that by this time at least, its motion was controlled by the northwesterly moving Pacific plate. Given the length of the Mendocino F.Z., this seems reasonable and may be part of the process of northward migration of the Mendocino triple junction as suggested by *Riddihough* [1980].

SUMMARY COMMENTS

Although there are undeniable uncertainties in the poles and rates of rotation determined for the Juan de Fuca plate system by the methods used here, the results compare well with other approaches to the problem and produce a coherent pattern of plate movements. This pattern is valuable in that it may show in detail how the movements of a small plate system are affected by a number of factors, notably by resistance at the convergence zone. It affirms that at least for small plates, *Menard*'s [1978] concept of pivoting subduction is valid. The behavior of the most resistive, Explorer plate portion of the system in eventually becoming detached and ceasing to move down into the mantle is physically reasonable and suggests that the dominant resistance to motion is in this case provided by the asthenosphere. The behavior of the remainder of the Juan de Fuca plate after the Explorer plate detachment suggests that vertical and horizontal plate movements relative to the mantle could be independent.

Recent work on the Winona Basin [*Davis and Riddihough*, 1982] and continuing debate on the southern part of the Gorda plate tend to confirm that close to the triple junctions, small fragments of plates become dominated by the movements of the larger, bounding plates. In the Juan de Fuca system it seems that an almost continuous succession from larger, self-driven plates to small, interplate fragments can be seen. The fact that the absolute pole of motion for the Juan de Fuca plate itself may now be almost within the subducted portion of this plate (Figure 5) suggests that it, too, is rapidly slowing and will soon be controlled by its larger neighbors. While it is a very small part of the global plate system, it may thus provide a graphic example of the end points of the plate tectonic process.

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