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Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of Western North America

ABSTRACT

Magnetic anomaly patterns in the northeast Pacific Ocean combined with plate theory indicate that a trench existed offshore from western North America during mid-Tertiary time and that the present episode of strike-slip motion in the San Andreas fault system originated after the cessation of subduction, not earlier than 30 m.y. ago. At present, the American and Pacific plates appear to be moving past one another parallel to the San Andreas fault at a rate of 6 cm/yr. Data concerning the late Cenozoic history of motions between these plates is inconclusive, and so 2 probable models are examined. One assumes a constant motion of 6 cm/yr throughout the late Cenozoic, whereas the other assumes that the 2 plates were fixed with respect to one another until 5 m.y. ago, at which time they broke along the San Andreas fault system and began moving at 6 cm/yr. The second model implies that the San Andreas fault took up all the motion at the boundary between the North American and Pacific plates, while the first model suggests the broader view that much of the late Cenozoic tectonic activity of western North America is related to this boundary deformation. The models make testable predictions for the distribution of igneous rocks and for the total amount and timing of deformation expected. Extrapolation of the model of constant motions to the early Cenozoic suggests an era of slightly compressional strike-slip at the edge of North America. A major change in plate motions in late Mesozoic time is suggested.

INTRODUCTION

The theories of sea-floor spreading and plate tectonics as described by Vine (1966), Morgan (1968a), and Isacks and others (1968), have had such great success in predicting large-scale phenomena in the oceans that they are almost universally accepted by marine earth scientists. On the other hand, their implications for continental work are more obscure and complex and are only beginning to be developed. It is likely that many of the larger scale features of continental geology are related to plate motions, the energy for tectonic activity being derived from the interactions of plates. Many modern examples exist to support this view: the uplift and volcanism in the Andes appear to be related to the destruction of an oceanic plate, the uplift and deformation of the Himalayas to the collision of two continental plates, the opening of the African rift valley to the breaking of a plate, and so on. Although these continental expressions of plate interactions are less straightforward than the oceanic expressions, they hold the key to the past. While the sea-floor spreading process has left ample evidence in the oceanic crust to reveal Cenozoic plate motions, the subduction of oceanic crust at the trenches has annihilated similar evidence for any plate motions that might have occurred before a few hundred million years ago. Thus, the main possibility for unraveling plate motions during most of geologic time lies in understanding the relationship of continental geology to plate interactions. It behooves us to study known Cenozoic examples of such interactions where oceanic evidence still exists to indicate the nature of the motions.

Of the presently active continental tectonic zones, western North America seems especially promising for study since a great deal is known about both onshore and offshore features, and discernible relationships presently exist between the 2 regimes. The purpose of this paper is to outline what is known about plate motions from marine geophysical data in this region and to discuss the possible relationships of these motions to continental tectonics. Although many of the conclusions reached have been previously expressed or implied by Vine

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(1966), Morgan (1968a), and McKenzie and Morgan (1969), their geologic implications have not been stressed.

IMPLICATIONS DRAWN FROM THE MAGNETIC ANOMALIES IN THE NORTHEAST PACIFIC OCEAN

Figure 1 shows the pattern of magnetic anomalies in the northeast Pacific. The numbering of the anomalies follows the time scale set up by Heirtzler and others (1968, Fig. 3). Although most of the ages in this time scale were highly speculative when they were proposed, dates from the Deep Sea Drilling Project and from an abyssal hill dredge haul indicate that they are approximately correct (Maxwell and others, 1970; McManus and Burns, 1969; Luyendyk and Fisher, 1969). All anomaly ages used in this paper were taken from the Heirtzler time scale, and the correlation of ages to geologic epochs follows Berggren (1969).

If we use the plate model for sea-floor spreading and continental drift developed by Morgan (1968a) and McKenzie and Parker (1967), and assume that the central Pacific Ocean floor acted as a rigid plate during the Cenozoic, then the locations of the anomalies and the fracture zones indicate the configurations through time of the ancient spreading ridge and its transform faults. For example, Figure 2 shows the configuration of the spreading system at the time when anomaly 21 was being created, the early Eocene.

A Mid-Cenozoic Trench off Western North America

A striking feature of Figure 1 is that the anomalies present represent only the western half of the symmetrical pattern expected. All presently known ridges spread approximately symmetrically, and so we might expect to find the other halves of these anomalies somewhere. In fact, the eastern halves and the ridge itself are for the most part missing. This geometry indicates that there once was another plate lying to the east of the ridge, the "Farallon plate" of McKenzie and Morgan (1969), which contained the missing anomalies, and since most of this plate no longer exists, there must have been a trench which consumed it at its boundary with the American plate. This trench apparently consumed the Farallon plate at a rate that was, on the average, faster than the rate at which it was being created at the ridge (5 cm/yr), so that eventually the ridge itself was overrun by the trench. At any point along the margin, the age of the youngest anomaly present in the oceanic plate indicates a time at which the ridge was still viable and spreading. Furthermore, since the symmetrical eastern anomaly is missing, the trench must also have been viable and consuming crust at least until that time.[1]

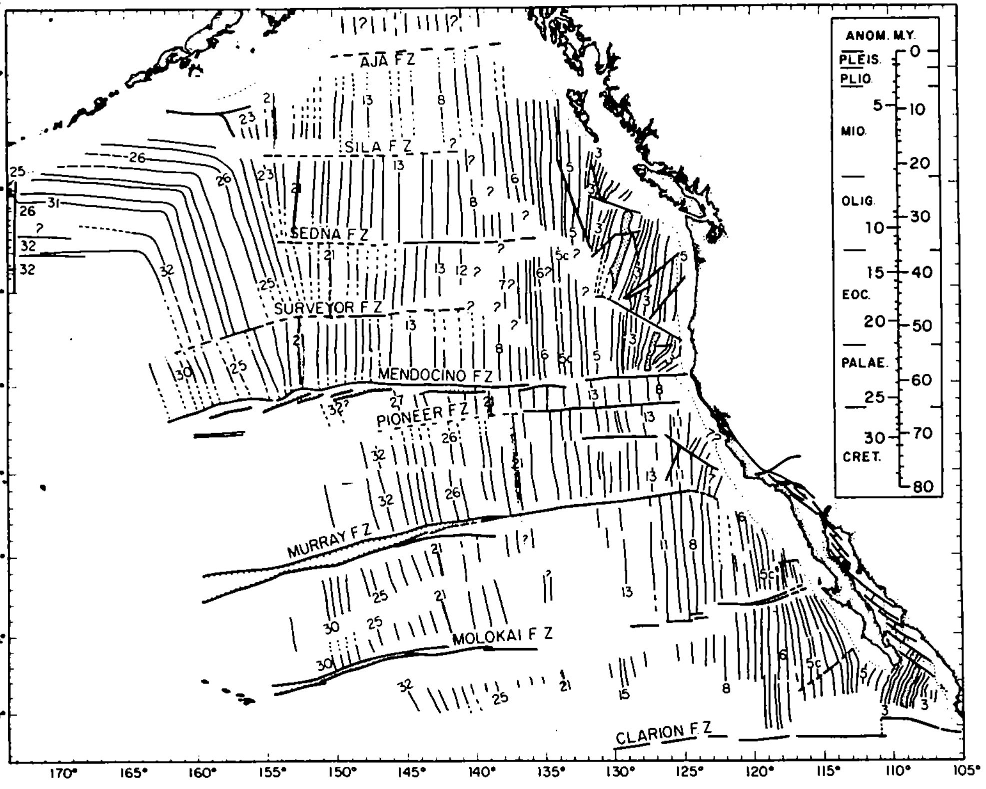

Figure 1. Magnetic anomalies in the northeast Pacific from Atwater and Menard (1970). Numbering of anomalies and their ages shown in the scale follow Heirtzler and others (1968); ages of geologic epochs follow Berggren (1969).

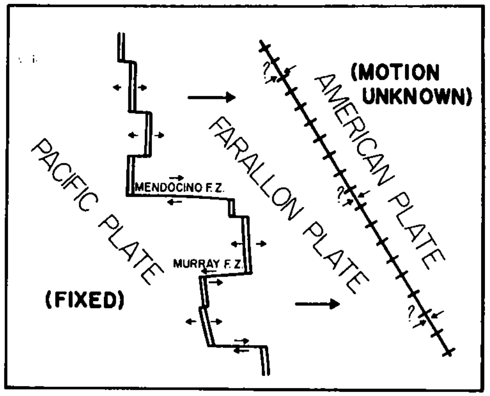

Figure 2. Configuration of plate boundaries at the time of anomaly 21, about 53 m.y. ago, as deduced from Figure 1. Magnetic anomalies and fracture zones are being created by the ridges and transform faults between 2 rigid oceanic plates. In this and subsequent figures, symbols follow McKenzie and Parker (1967): single lines are transform faults, double lines are spreading centers, and hatched lines are zones of subduction (usually trenches). Large arrows show motions of plates with respect to the Pacific plate which is arbitrarily held fixed. Small arrows show relative motions at points along plate boundaries.

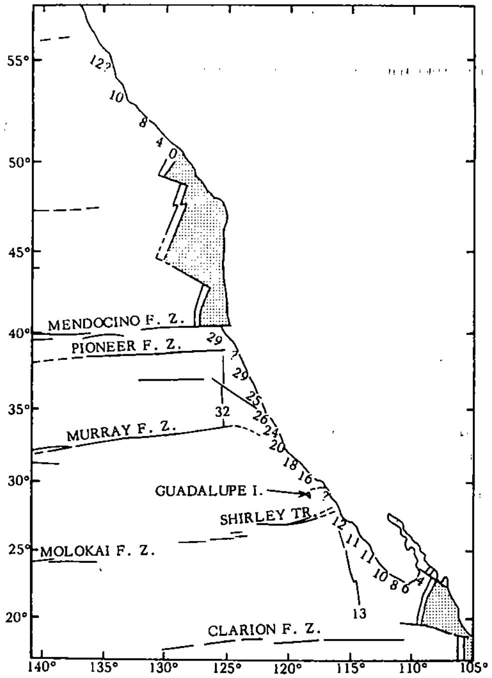

Figure 3. Ages (in millions of years before present) of easternmost recognizable anomalies in the Pacific plate. These ages indicate the earliest possible time that the ridge and trench collided and the Farallon plate was destroyed in a given region. Ceasing of trench activity and the starting of motion related to the San Andreas fault may be indicated by these ages. The coastline has been omitted to emphasize that the position of the North American plate during most of the collisions in unknown.

The numbers along the continental margin in Figure 3 show the ages of the youngest anomalies recognizable. They indicate that the trench was active until at least 29 m.y. ago just south of the Mendocino fracture zone. Between the Pioneer and Murray fracture zones, the Farallon plate broke up, and spreading slowed about 32 m.y. ago, so that rapid creation and consumption of crust ceased for this entire segment at that time. The trench continued to consume crust more slowly until at least as recently as 29 to 24 m.y. ago. South of the Murray fracture zone, the easternmost anomalies become younger southward from 20 m.y. Near Guadalupe Island, they lack distinctive character and thus remain unidentified except that they probably belong to the anomaly 5B-5A sequence (16 to 12 m.y.). South of the Shirley trough (the eastward extension of the Molokai fracture zone), the anomalies changed strike so that they are approximately parallel to the coast; thus anomaly 5A (11 m.y.) is the easternmost one along much

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[1] It is geometrically possible that the consumption of the Farallon plate occurred entirely after the formation of all anomalies, but this possibility seems highly unlikely.

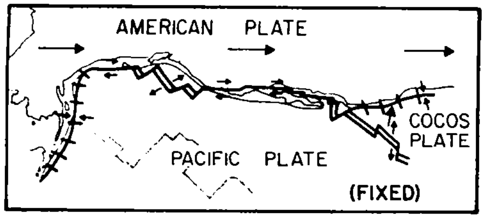

Figure 4. Present configuration of plate boundaries in the northeast Pacific and western North America, after Morgan (1968a). The map is a Mercator projection about the pole of relative motion between the Pacific and American plates, 53° N., 53° W., Morgan (1968a). Transform faults between the two plates lie on small circles about the pole of relative motion; thus, in this projection they form horizontal lines. Gray line marks the location of anomaly 21, used in Figure 2. Boundary symbols and arrows are as described in Figure 2.

of southern Baja California (Chase and others, 1970).

All of these ages supply only upper limits for the time when the trench ceased activity, for it is possible that younger anomalies once existed offshore and subsequently were overridden by the continent. It should also be emphasized that these anomalies lie within the Pacific plate and move with it. The geometrical relationship between the events they date and events on the continent cannot be deciphered until the relative motion of the North American plate is determined. Nevertheless, the anomalies do indicate that a trench existed along the western United States and Mexico in middle Tertiary times.

The character of the trench that consumed the Farallon plate may be guessed from the rate at which it consumed crust. This rate was, on the average, greater than 5 cm/yr, since the trench was able to overtake the ridge; the most likely models, discussed below, suggest consumption rates of 7 to 10 cm/yr. Thus, the trench may have been approximately equivalent to the more active trenches known today (Kurile, Japan, Tonga; *see* Le Pichon, 1968), having a well-developed Benioff zone, calc-alkaline volcanism, and associated vertical tectonics.

Limits on the Age of the San Andreas Fault

Some conclusions can also be drawn concerning the history of the San Andreas fault system. According to the plate tectonics model (Fig. 4), this fault system is simply part of the present boundary between the North American and Pacific plates and expresses their relative motion (Morgan, 1968a; McKenzie and Parker, 1967). In these terms, the San Andreas can exist only where the 2 plates are in direct contact. As long as the Farallon plate lay between the American and Pacific plates, the San Andreas system could not function as a strike-slip boundary. Thus, no part of the San Andreas system began movement in the present sense and rate before 30 m.y. ago, and the ages of the offshore anomalies discussed above give age limits not only for the ceasing of trench activity but also for the beginning of the various segments of the San Andreas system.

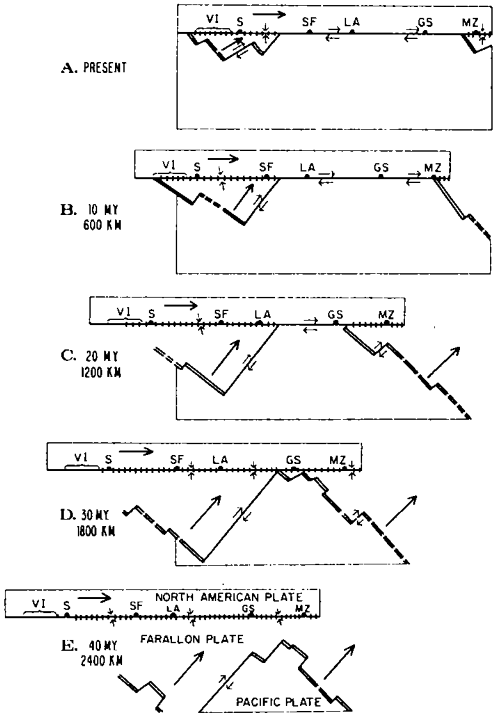

Figure 5. Schematic model of plate interactions assuming that the North American and Pacific plates moved with a constant relative motion of 6 cm/yr parallel to the San Andreas fault. The coast is approximated as parallel to the San Andreas. Farallon-Pacific plate motions are approximated from anomalies in Figure 1. Initials represent cities listed in Figure 6 and Vancouver Island. Boundaries and arrows are as in Figure 2, the Pacific plate being held fixed. Captions show the time represented by each sketch in millions of years before present and the distance that the North American plate must subsequently be displaced to reach its present position with respect to the Pacific plate.

This young age for the San Andreas system contradicts data which suggest a considerable amount of early and middle Tertiary slip: the post-Oligocene offset is about 350 km (Huffman, 1970), while the post-Cretaceous offset of the basement is about 500 km (Hill and Hobson, 1968). It is possible that a pre–San Andreas fault may have existed behind the middle Tertiary trench as a trench-related, strike-slip fault; such relationships are not uncommon behind presently active trenches (Allen, 1962; Burk and Moores, 1968). Another possibility, that older offsets on the San Andreas fault were related to a distinct, early Tertiary episode of oblique motion, is discussed in the last section of this paper.

CONCERNING THE MOTION OF NORTH AMERICA

To understand how the Eocene plate configuration (Fig. 2) evolved into the present one (Fig. 4), we must establish how the North American plate moved with respect to the oceanic plates during the intervening time span. As discussed below, evidence suggests that North America has been moving with respect to the Pacific plate at a rate of 6 cm/yr for at least the last 4 m.y. For the relative motions prior to 4 m.y. ago, 2 distinct models have been previously proposed and still others are possible. In the following sections, I shall first present the proposed models and then examine the data which concerns them.

A Model with Constant Relative Motion

If the Pacific-American motion is constant,[2] if all of it is taken up by a single transform fault, and if the coastline is parallel to the motion, then the simplified evolution described by McKenzie and Morgan (1969) results (Fig. 5). The ages of the easternmost anomalies in Figure 3 just predate the passage of a ridge-trench-transform triple junction (that is, a point where the ridge and trench collide and a transform fault emerges). Figure 6 is a plot of time versus distance along the coast of North America. It shows how the triple junctions migrated up and down the coast and which

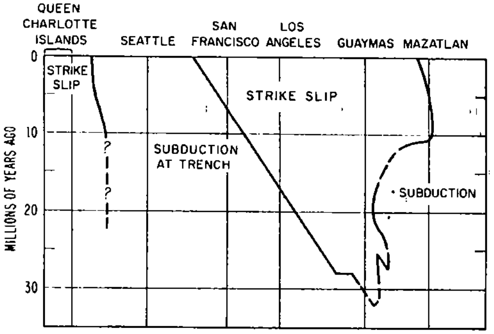

Figure 6. Evolution with time of boundary regimes along the coast of North America assuming the model of constant American-Pacific motion described in Figure 5. White areas denote times and coastal locations where the Pacific plate was touching North America and interacting with it. Gray area shows times and coastal locations where the Farallon plate lay offshore and was underthrusting North America.

plate was interacting with North America at any point along the coast at any time. For example, it shows that off San Francisco, the Farallon plate was impinging on North America at a trench until 6 m.y. ago, when the Mendocino fault migrated past and the North America-Pacific interactions (San Andreas fault) began in this region. As another example, it shows that 17 m.y. ago, a trench bordered North America from southern British Columbia to Los Angeles and south from central Baja California, while San Andreas-type interactions were taking place off southern California, northern Baja California, and northern British Columbia.

Models with Changing Motions

The interactions represented in Figures 5 and 6 are derived from the assumption of constant relative motions. If we assume instead that the relative motions changed, many other models are possible. One such model (Morgan, 1968b; Vine and Hess, 1970) is that the North American and Pacific plates were fixed with respect to one another until about 5 m.y. ago, at which time they broke and began to move past one another at a rate of 6 cm/yr. Figure 7 illustrates this possibility, and Figure 8 shows the evolution of boundary conditions for the North American plate. Figure 8 shows that off San Francisco in this model, the trench ceased its activity 30 m.y. ago, after which there were no plate interactions until the San Andreas began, 5 m.y. ago.

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[2] For this and all models of "constant motion" considered below, relative motion between the Pacific and North American plates is a rotation about a pole (fixed with respect to both plates) which presently lies at 53° N., 53° W. The rate of rotation used amounts to 6 cm/yr at the mouth of the Gulf of California. This geometry was derived by Morgan (1968a) from trends of faults in the San Andreas and Fairweather systems. A similar geometry was independently derived by McKenzie and Parker (1967) using the first motions of earthquakes on the San Andreas fault and in the Aleutian arc.

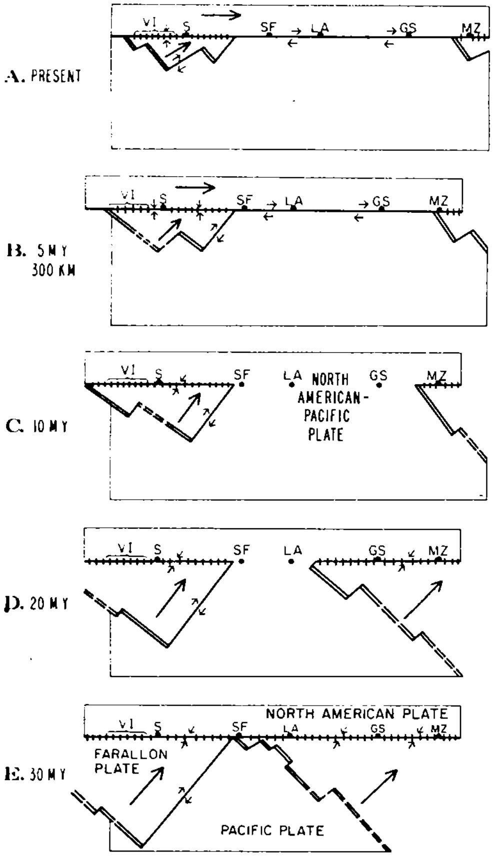

Figure 7. Schematic model of plate interactions assuming that the North American and Pacific plates were fixed to one another until 5 m.y. ago, at which time they broke apart and began to move at a rate of 6 cm/yr. Other assumptions and symbols are similar to those in Figure 5.

Other models postulating changes of motion are possible. However, models that include significant overthrusting of the Pacific by the North American plate are discounted by evidence (discussed below) that the coast was nearby at the time of the formation of anomalies that are now nearshore, and models that include significant southwest spreading of the Pacific away from the North American plate are ruled out by the lack of symmetrical anomalies near the coast. Thus, the other likely models lie between the two presented: prior to 4 m.y. ago, the rate of motion may have varied considerably, but the direction remained approximately parallel to the San Andreas and the coast.

The considerable differences between Figures 6 and 8 demonstrate how important it is to decipher the true relative motions between the Pacific and North American plates. Although this cannot be done unambiguously at the present time, considerable data exist which bear on the problem, and appropriate tests can be suggested.

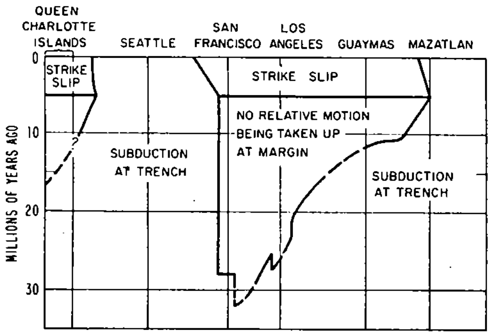

Figure 8. Evolution with time of boundary regimes along the coast of North America assuming the model of changing motions described in Figure 7. White areas denote times and locations of Pacific-North American interactions. Prior to 5 m.y. ago, these plates were locked so that no plate-related tectonics should be detected in the regions and during the times indicated by the white spaces marked "no relative motion. . . ." White areas from zero to 5 m.y. ago indicate a regime of strike slip. Gray areas show times and places where the Farallon plate lay offshore and was underthrusting North America.

Spreading at the Mouth of the Gulf of California

The magnetic anomalies at the mouth of the Gulf of California (Fig. 9A) indicate spreading at a half-rate of 3 cm/yr (6 cm/yr total) in a direction approximately parallel to the San Andreas system for the last 4 m.y. (Larson and others, 1968). According to Figure 4, Baja California is presently part of the Pacific plate and Mexico is part of the North American plate, and so spreading in the Gulf is a manifestation of the relative motion of these two plates, and the Gulf anomalies may be used to deduce the rate of this relative motion. Thus, it is crucial to discover how realistic Figure 4 is as a model for this region.

Seismicity provides one test. The lack of earthquakes west of the ridge (Fig. 9A) shows that it is probably safe to assume that Baja California moves with the Pacific plate. On the other hand, the continuation of the mid-America trench north of the Rivera fracture zone, the epicenters near the coast of Mexico in that region, and the distinct orientation of the

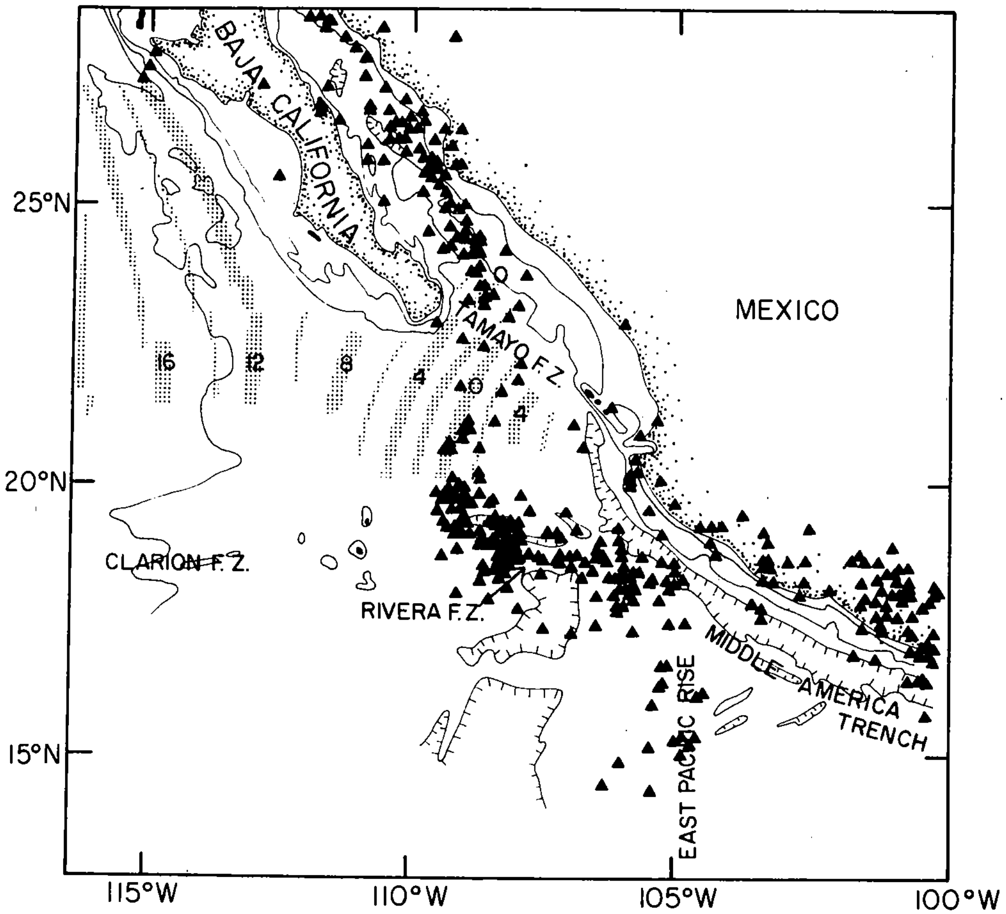

Figure 9A. Earthquake epicenters and sea-floor age near the mouth of the Gulf of California. Earthquakes (triangles) include all preliminary determinations of hypocenters of the USCGS, ESSA, between 1961 and 1967. Sea-floor ages (in millions of years before present) were deduced from anomalies as described in Larson and others (1968) and Chase and others (1970). Contours of 200, 1000, and 2000 fathoms are from Chase and Menard (1965).

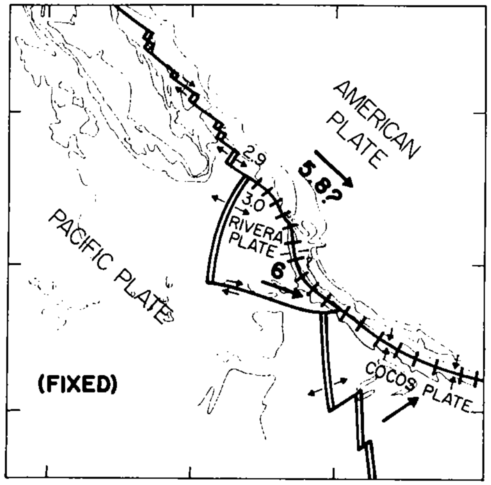

Figure 9B. Present plate configurations and motions near the mouth of the Gulf of California. Spreading rates and ridge orientation indicate that the Rivera plate may be moving approximately with the American plate; however, earthquakes, the topographic trench, and the difference in orientation of the fracture zones may be indications of compression between these two plates.

Rivera fracture zone may indicate that the ocean floor east of the ridge acts as an independent plate (the Rivera plate, Fig. 9B). This plate was once part of the Cocos plate (McKenzie and Morgan, 1969, p. 131), and although it now appears to be moving with the American plate, it may not be entirely coupled to it yet. A complicated motion for this small plate would not be surprising, since it is caught in a triple junction (East Pacific Rise, Mid-America Trench, and Gulf of California spreading system) and shares boundaries with 3 large plates (North American, Pacific, and Cocos). Unfortunately, most of the magnetic anomalies known in the Gulf were created at the boundary between the Pacific plate and this small wayward one, so that their relationship to the American plate is uncertain. On the other hand, 2 magnetic profiles northeast of the Tamayo fracture zone show rates of 2.9 cm/yr (5.8 cm/yr full rate) for the last 2 m.y. (Larson and others, 1968; R. L. Larson, 1969, personal commun.). These anomalies are not involved with the Rivera plate and appear to be truly a part of the Gulf spreading system. The similarity of rates across the Tamayo fracture zone suggests that the Rivera plate is nearly coupled to the American one. The spreading rate northeast of the Tamayo fracture zone is probably the strongest evidence we have concerning the Pacific-North American rate of relative motion. It is the principal source for the 6 cm/yr rate used in the models described above.

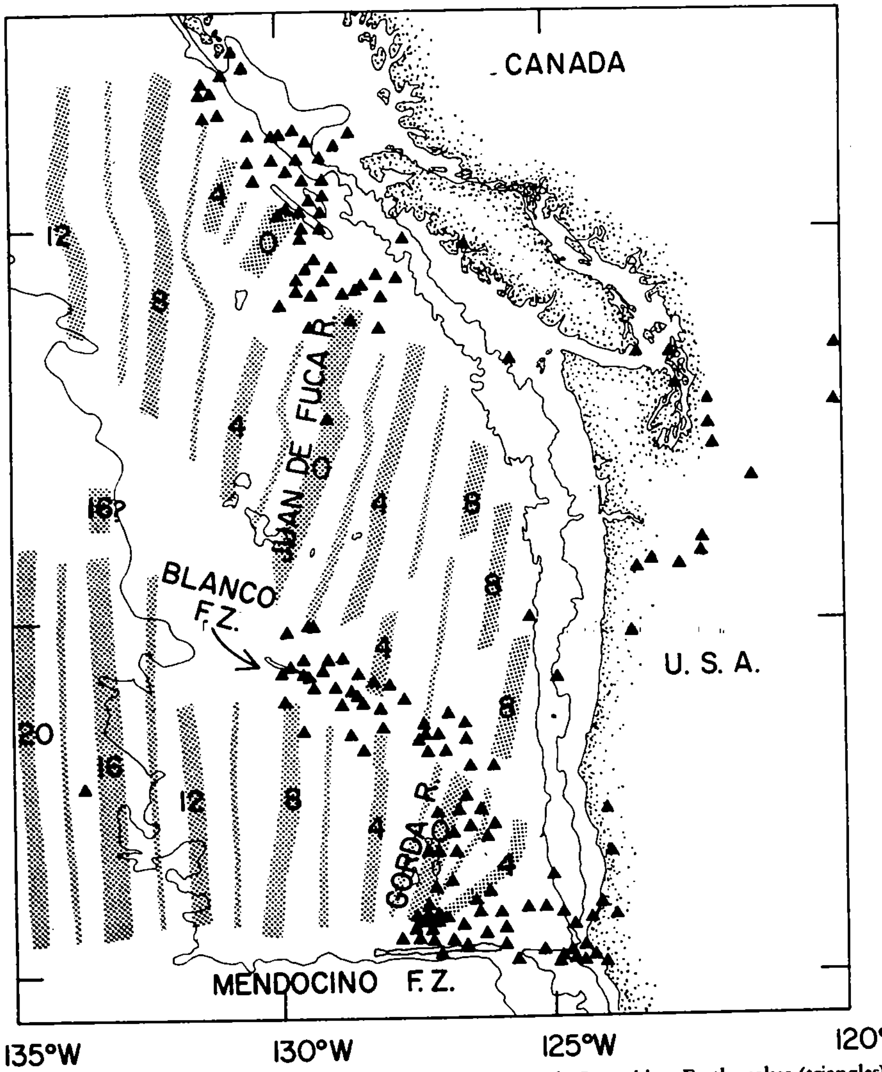

Figure 10A. Earthquake epicenters and sea-floor age near the Juan de Fuca ridge. Earthquakes (triangles) are from Tobin and Sykes (1968). Sea-floor ages (in millions of years before present) are deduced from anomalies of Raff and Mason (1961) and Atwater and Menard (1970). Contours of 200, 1000, and 2000 fathoms are from McManus (1967).

The onset of spreading of the Gulf 4 or perhaps 6 m.y. ago (Larson and others, 1968; Larson, 1970) may be interpreted as the onset of Pacific-North America motion in the model of changing motions, or it can be attributed to the southward migration of a triple junction in the model of constant motions. This second possibility will be discussed below.

Spreading at the Juan de Fuca Ridge

The magnetic anomalies at the Juan de Fuca Ridge (Fig. 10A) show that spreading is occurring there at a half-rate of about 2.9 cm/yr (5.8 cm/yr total), presumably in the direction parallel to the Blanco fracture zone. The northern Gorda Ridge is also spreading at this rate and direction. (Activity on the southern part of the Gorda Ridge and on the Mendocino fault may be disregarded for our purposes, since distorted anomalies and scattered earthquakes indicate that the sea floor is not acting as a rigid plate in this region.) The Juan de Fuca Ridge and Blanco fracture zone have been considered to be a continuation of the San Andreas system by Vine and Wilson (1965), Bolt and others (1968), and others. As such, it would be an indicator of the relative rate of motion between the American and Pacific plates. However, Figure 4 emphasizes a serious problem in this interpretation. Figure 4 is a Mercator projection which uses the North American-Pacific pole of relative motion as its north pole (similar to that of McKenzie and Parker, 1967, Fig. 1). In this projection, any fault which is acting as a transform fault between the Pacific and American plates will appear as a horizontal line. The strike of the Blanco fracture zone differs from this trend by about 25°. Either the Blanco is absorbing a large amount of compression, or else the ocean floor between the ridge and the continent is acting as a separate plate (the Juan de Fuca plate, Fig. 10B).

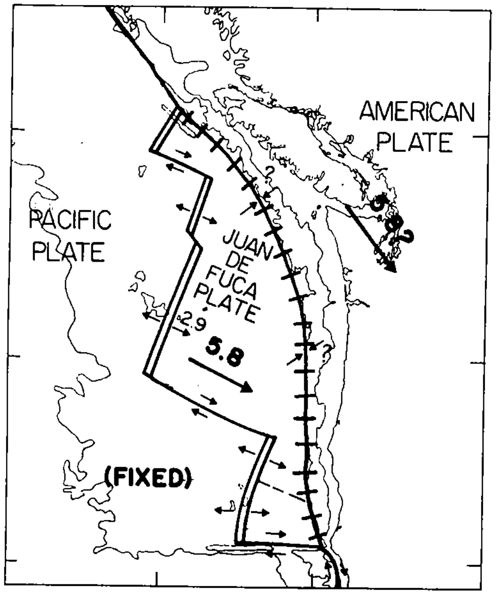

Figure 10B. Present plate configuration and motions near the Juan de Fuca ridge. The probability that the Juan de Fuca plate is underthrusting the North American plate makes spreading at the Juan de Fuca ridge unreliable as an indicator of North American-Pacific motion.

If the Juan de Fuca plate is a separate plate and is moving parallel to the Blanco fracture zone at 5.8 cm/yr while the American plate is moving parallel to the San Andreas fault at at 5.8 cm/yr, Figure 11A shows that the resulting motion between these 2 plates is a north-northeastward compression of about 2.5 cm/yr. If Oregon and Washington are moving at a rate less than 5.8 cm/yr (as in Fig. 16), then the compression is faster and is in a more easterly direction (Figure 11B). There is a considerable amount of evidence that the margin of North America is being underthrust by the ocean floor in this region (Silver, 1969a, 1969b; Byrne and others, 1966), and the andesitic volcanism of the Cascade mountains independently suggests the existence of a down-welling oceanic plate. The lack of a clear Benioff zone of earthquakes may be considered as evidence against downwelling; however, a few earthquakes of intermediate depth do occur (Tobin and Sykes, 1968), and boundaries where slow compression is predicted are noted for their low seismicity (southern Chile and the Macquarie ridge are examples; *see* Le Pichon, 1968). Furthermore, the Juan de Fuca plate is young and thus not very thick and cool, and so it may reheat very quickly, producing few deep earthquakes. The possibility of de-coupling of the Juan de Fuca and American plates renders the spreading rate at the Juan de Fuca ridge unreliable as a Pacific-American rate indicator.

A short discussion of the history of the Juan de Fuca ridge as shown by magnetic anomalies is in order. As stated above, the older anomalies were formed by spreading between the Pacific and Farallon plates (Fig. 2), and a trench existed which was consuming the eastern edge of the Farallon plate. After the ridge and trench collided south of the Mendocino fracture zone, a large piece of the Farallon plate remained to the north and continued to move eastward from the Pacific plate. Even though the spreading rate and direction changed (Vine, 1966; Menard and Atwater, 1968), and the manner by which the present spreading configuration evolved from the previous one is not understood, the Juan de Fuca plate is clearly a direct descendent of the Farallon plate. The fact that the anomaly sequence is complete just north of the Mendocino fracture zone and is very nearly complete near the Sila fracture zone shows that spreading has been continuous. If the Juan de Fuca plate is presently moving with the American plate, this coupling is relatively recent.

The direction of spreading changed at the Juan de Fuca ridge between 7 and 4 m.y. ago. This may be related to the onset of motion in the model of changing motions. However, it can be as easily explained using the model of constant motions by noting that the Farallon plate was steadily diminishing in size. Perhaps about 7 m.y. ago, it became too small to maintain its motion, and so it became partially coupled to the American plate.

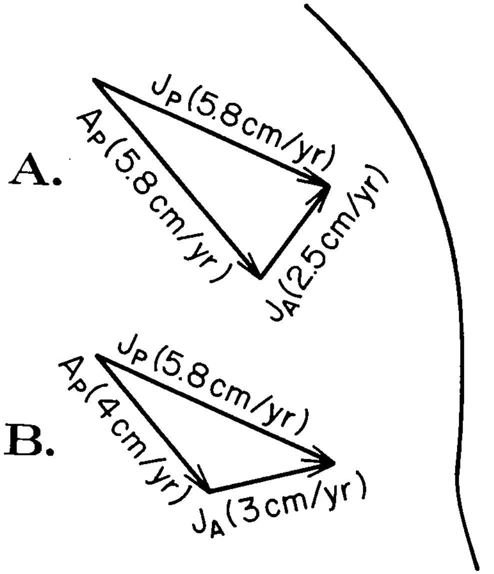

Figure 11. Vector diagrams for deducing relative motion between the Juan de Fuca and North American plates. Curved line shows trend of North American coast line. In both cases, the motion of the Juan de Fuca plate with respect to the Pacific plate (J_P) is assumed to be 5.8 cm/yr parallel to the Blanco fracture zone. A. The motion of the North American with respect to the Pacific plate (A_P) is assumed to be 5.8 cm/yr parallel to the San Andreas fault. The resultant motion of the Juan de Fuca with respect to the North American plate (J_A) is seen to be a compression in a north-northeast direction of 2.5 cm/yr. B. If the North American-Pacific rate of motion is assumed to be 4 cm/yr, then the Juan de Fuca-American motion (J_A) is seen to be an eastward compression of 3 cm/yr.

Evidence from the Sea Floor off Central California

Figure 12 shows the magnetic anomalies west of central California. The complicated broken geometry and the slowing of the spreading rate may be interpreted as an indication that the Farallon plate broke up about 32 m.y. ago, as the ridge neared the trench and this part of the plate became very narrow (McKenzie and Morgan, 1969; Atwater and Menard, 1970). If this is correct, the broken pattern indicates that some part of the continent was nearby. Further support for this conclusion comes from Deep Sea Drilling Project operations off San Francisco. Late Miocene abyssal fan deposits were recovered near the bottom of the section (more than 400 km from the coast; *see* McManus and Burns, 1969), indicating that the continent was nearby and that the trench had been destroyed or overfilled before this time.

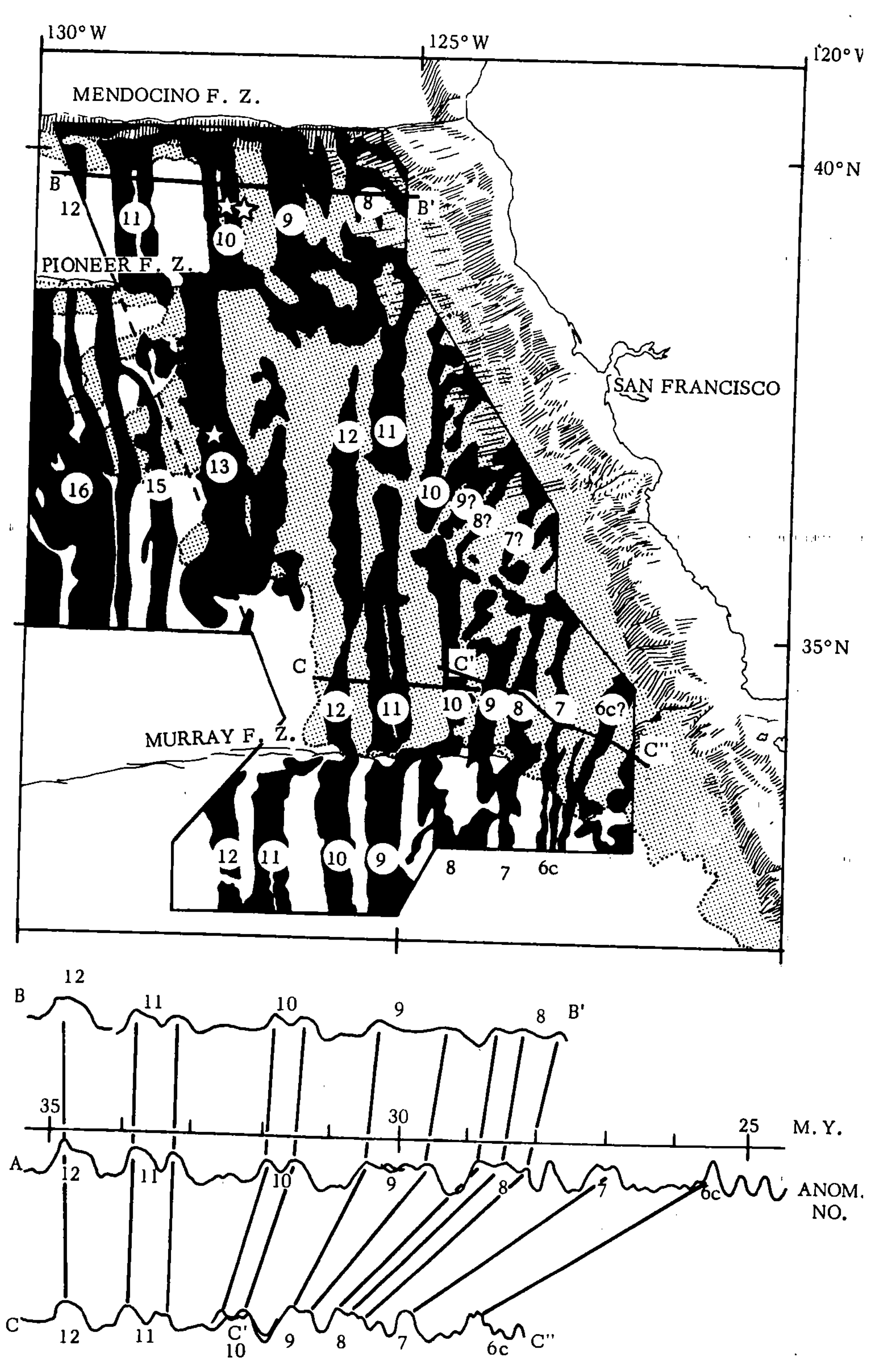

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Figure 12. Magnetic anomalies and sedimentation off central California. Positive magnetic anomalies are shown in black (*after* Mason and Raff, 1961; Bassinger and others, 1969). Distribution of fan deposits (gray) and topographic features are from Menard (1964, physiographic diagram). White stars show locations of Deep Sea Drilling holes 32 (southern star), 33 and 34 which bottomed in late Miocene fan deposits. Magnetic anomaly profiles show the basis for identification of certain anomalies. Profile A, for comparison, is from north of the Mendocino fracture zone. Profile C-C'-C'' shows slowing of spreading about 32.5 m.y. ago, presumably associated with disruption of the Farallon plate.

These lines of evidence support plate models in which North America either was moving approximately parallel to its own coastline or was fixed with respect to the Pacific for the last 30 m.y. In such models, the ages of near-coast anomalies of Figure 3 represent the actual times of the ridge-trench collisions. Both models presented above are of this type.

Evidence from the Aleutian Abyssal Plain and Island Arc

Grim and Naugler (1969) have reported a headless submarine channel on the Aleutian plain (Fig. 13), and E. L. Hamilton (1967) found that the plain consists of old turbidites from a northern source, overlain by a blanket of pelagic sediments. The underlying crust is part of the magnetic bight. After this part of the crust was created, ridges lay north and east of it, probably forming a barrier for turbidites. Thus the starting of turbidite sedimentation may mark the demise of these ridges, about 25 m.y. ago according to constant motions (described below; *see* Fig. 18), or about 60 m.y. ago according to the changing-motion model (Pitman and Hayes, 1968). The cessation of turbidite deposition marks the cutting of pathways leading to the source area either by the encroachment of the Aleutian trench or by formation of the trench, depending upon which model is assumed. Both possibilities require younger ages than those estimated from pelagic sediment thickness by Hamilton. Future deep-sea drilling will supply dates which may distinguish between the models.

The Aleutian trench and island arc are the result of the Pacific plate underthrusting the North American plate, so that clues about the history of motions between these plates might be found from a study of the continuity of activity in the Aleutian chain. The constant-motion model predicts a definite history for the Aleutian arc which includes a change in the rate and direction of underthrusting in the mid-Tertiary, and data available appear to be compatible with such a model (Grow and Atwater, 1970).

Separation of Cretaceous Paleomagnetic Poles

Another method of measuring the motion of large plates is to compare their paleomagnetic polar wandering curves. Paleo-pole positions for the Pacific are known from the magnetization of seamounts (Francheteau and others, 1970) and from comparative magnetization of the limbs of the magnetic bight (Vine, 1968; Vine and Hess, 1970). These data indicate that the Pacific plate has moved northward a considerable distance since Cretaceous (at least 25° in the last 70 m.y.; *see* Vine, 1968). The pole position for North America during the Cretaceous is fairly well known (Gromme and others, 1967). The discrepancy between it and the seamount pole is 50° to 60°. Farrell (1968) shows that these poles can be brought together by assuming the Pacific and American plates moved with a constant relative motion parallel to the present San Andreas and at a rate equivalent to about 6 cm/yr at the San Andreas since Cretaceous time. This solution is not unique, but the fit is encouraging for the constant-motion model. The model with changing motions presented above predicts only a few degrees of total relative motion, so that it does not fit unless an older period of extremely rapid motion is postulated.

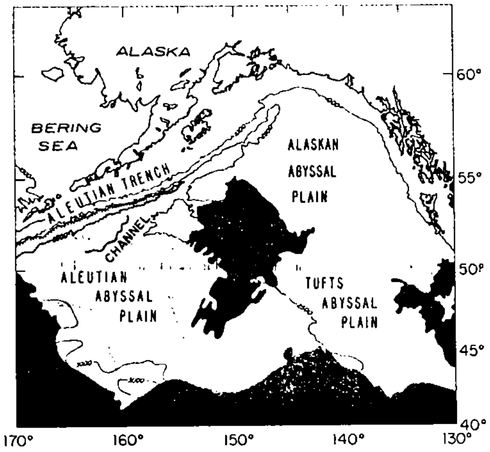

Figure 13. Location of sourceless sediments and beheaded deep-sea channel on the Aleutian abyssal plain, after Hamilton (1967) and Grim and Naugler (1969). Dark gray shows areas of abyssal hills and seamounts. Gray lines show location of anomalies 25 and 32 in the Great Magnetic Bight of Elvers and others (1967). Contours of 1000, 2500, and 3000 fathoms are generalized from U.S. Navy Hydrographic Office chart H.O. Misc. 15, 254-6 (1961). Ages of starting and ceasing of turbidite sedimentation may provide clues concerning the life time of the ridges which made the anomalies and the location of this plain on the Pacific plate with respect to possible source areas which lay in the North American plate.

CONTINENTAL PHENOMENA RELATED TO PLATE BOUNDARIES

Evidence concerning the evolution of the plate boundaries and triple junctions should be found within the continental geology of North America. Two active boundary regimes were predicted above for the edge of the North American plate: a trench and a strike-slip dominated regime.

Igneous Activity Related to an Offshore Trench

Probably the most easily detected continental indication of the existence of a presently active trench and associated Benioff zone is the eruption and intrusion of calc-alkaline magmas of predominantly intermediate and silicic compositions. Such activity should have existed above formerly active Benioff zones and should have ceased when subduction ceased. Thus, once the Pacific-North American motion is known, a figure similar to Figures 6 and 8 can be constructed and used to predict the type of igneous activity expected. Conversely, the distribution of igneous rocks may help to determine what the motions were. Lipman and others (1970) and Christiansen and Lipman (1970) report that intermediate volcanism was prevalent throughout the western United States in middle Cenozoic times and appears to have ceased in the southwest between 20 and 10 m.y. ago. This pattern is similar to that predicted by the models. Establishment of these relationships in time and space may provide the detail needed to choose the correct model of relative motion from among the possible ones described above.

The San Andreas System as a Transform Fault

The present boundary between the North American and Pacific plates is usually drawn as a single break following the San Andreas fault and Gulf of California rift system (Vine and Wilson, 1965; Morgan, 1968a; McKenzie and Parker, 1967). If this is a realistic description, a study of the history of offsets across it will yield a history of the Pacific-North American motions.

Geodetic measurements across the fault zone indicate average slips of 5 or 6 cm/yr in the San Francisco area (Meade and Small, 1966) and about 8 cm/yr in the Imperial Valley region (Whitten, 1955), and an estimate of the seismic moment for the San Andreas system since 1800 indicates an average slip rate of 6.6 cm/yr (Brune, 1968). These measurements may indicate that the San Andreas system is taking up all the motion, but any long-range conclusion is highly uncertain because of the short time span measured. For geologic time spans, offsets of the San Andreas can be measured by correlating and dating distinctive units which bridged the fault and since have been offset by it. Such studies have been summarized by Dickinson and Grantz (1968). They tend to favor a rate of offset of about 1.3 cm/yr in central California; however, the scatter in the points is great, and few of the correlations are sufficiently unique and well studied to stand alone. Three intensively studied ties suggest that while an offset of 350 km has occurred since the Oligocene (post-23.5 m.y.), much of it (about 275 km) is post-Miocene (Huffman, 1970; Turner and others, 1970).

These ties may be compatible with a model of changing motions like the one discussed above in which the San Andreas fault broke relatively recently and moved quickly, taking up all of the Pacific-North American motion (300 km in 5 m.y.), no offset occurring earlier. If the San Andreas fault took up all the American-Pacific motion, the constant motion model predicts that it would show 1400 km of offset since 23 m.y. ago. This obviously does not fit any of the measurements of offset. However, the constant model may fit reasonably well into a picture of broader deformation.

Western United States as a Broad Transform Fault Zone

The idea that the San Andreas fault constitutes a simple boundary between 2 large, perfectly rigid plates is almost certainly too simplistic a view. Other active and inactive faults in California lie parallel to the San Andreas and probably have taken up some motion, and the folding of the California Coast Ranges may be drag folding that has taken up some of it. We might take a still broader view and include the late Tertiary deformation of Oregon, Washington, Idaho, and the Basin and Range province, since this deformation has been described as a megashear in the San Andreas direction and sense. In other words, we might consider western North America to be a very wide, soft boundary between 2 rigid, moving plates. These unifying ideas for western U.S.A. tectonics have been suggested by Carey (1958), Wise (1963), and Hamilton and Myers (1966). It is especially enticing to include them here because it allows most of the late Tertiary tectonic activity of western North America to derive its driving energy from the interactions of moving plates. The concept of a wide, soft boundary is also suggested by the broad, diffuse seismicity pattern of the western United

States (Barazangi and Dorman, 1968). This pattern of earthquakes is entirely different from the narrow, linear belt of activity associated with oceanic transform faults.

Figure 14 contains some of the more prominent tectonic features from King (1969), plotted on the Mercator projection of Figure 4. The relationship of the Pacific-North American motion to features within the boundary can be visualized by moving the top of the map horizontally to the right. Faults running horizontally across the figure (San Andreas) show pure strike slip. Faults at other angles show opening (Basin and Range) and closing (Transverse Ranges). Rotations of small blocks will complicate the picture somewhat.

Relations of the Onset of Continental Deformation to Ridge-Trench Collisions

Before we can discuss the age of onset and the total amount of deformation expected within the continent, we must consider what occurs at a migrating ridge-trench-transform triple junction. Figure 15 is a sketch of plates in cross section as the ridge and trench approach. Figure 15A was constructed from McKenzie's (1967, 1969) models of ridges and trenches. The rigid plate has zero thickness at the ridge center and thickens as it moves away from the ridge and cools. At the trench, the down-going slab thins again as it is warmed by the surrounding mantle. In Figure 15B, the ridge is so near the trench that the plate is still very thin when it begins to descend into the mantle and to be thinned by heating. By the time the trench overruns the ridge, Figure 15C, the Farallon plate has practically ceased to exist.

In plate models, a spreading ridge is considered to be just the weakest place between 2 diverging plates; it is not especially related to a convective up-welling zone in the mantle. Thus, when the Farallon plate ceases to exist, the ridge also ceases. This idea is incompatible with hypotheses which relate continued activity of the overrun East Pacific Rise to rifting in the Gulf of California and the Basin and Range province. Those features are here regarded as weak places in the continental crust which broke and thereby became parts of the boundary between the obliquely diverging North American and Pacific plates.

Figure 15C is a sketch of the situation when the trench meets the ridge and the Pacific and North American plates first come into contact. The Pacific plate was still thin and hot at the juncture. In Figure 15D, the present situation, a piece of the continent has become attached to the Pacific plate and motion is taken up inland. This can occur only after the lithosphere at the juncture in Figure 15C has cooled and thickened. Thus, a cooling time must be introduced between the time that the triple junction passes a given point and the time when deformation related to the new boundary regime might be expected to be felt within the continent. For much of southern Baja California, there appears to have been a cooling time of 5 to 7 m.y., since the last anomaly offshore is 11 m.y. old, while spreading began inside the mouth of the Gulf 6 to 4 m.y. ago (Chase and others, 1970; Larson, 1970). During the cooling time, all American-Pacific motion was apparently taken up along the continental margin. If the margin is parallel to the motion, deformation will be pure strike slip, difficult to detect at a later time. If the margin lies at an angle to the motion, oblique spreading or compression will result. Much of the borderland rifting off southern California and Baja California may have occurred during these times before deformation jumped inland, and may be simply related to the slight nonalignment of the coast with the San Andreas trend. This possibility will be used in the reconstruction below (Fig. 16).

The fact that motion is presently taken up by deformation within the continent indicates that the continental lithosphere is very weak, weaker even than the continent-ocean interface, even after that interface was continually sheared and rifted during the cooling time.

A Reconstruction of Middle and Late Cenozoic Interactions

Using the concepts just discussed, a slightly more realistic version of Figure 5 can be constructed. In Figure 16, the North American plate is arbitrarily held fixed and, going backward in time, the Pacific plate is progressively moved horizontally to the right by the amount specified. The map projection is such that pieces may be moved horizontally across the page without changing size or shape. The offshore anomalies are used to delineate the Farallon plate. From zero to 20 m.y. ago, 2 continental boundaries are used. The wide, gray, inland zone schematically represents deformation in the Basin and Range province, while the coastal boundary represents offset on the San Andreas and other nearshore faults. Deformation is divided arbitrarily: one-third

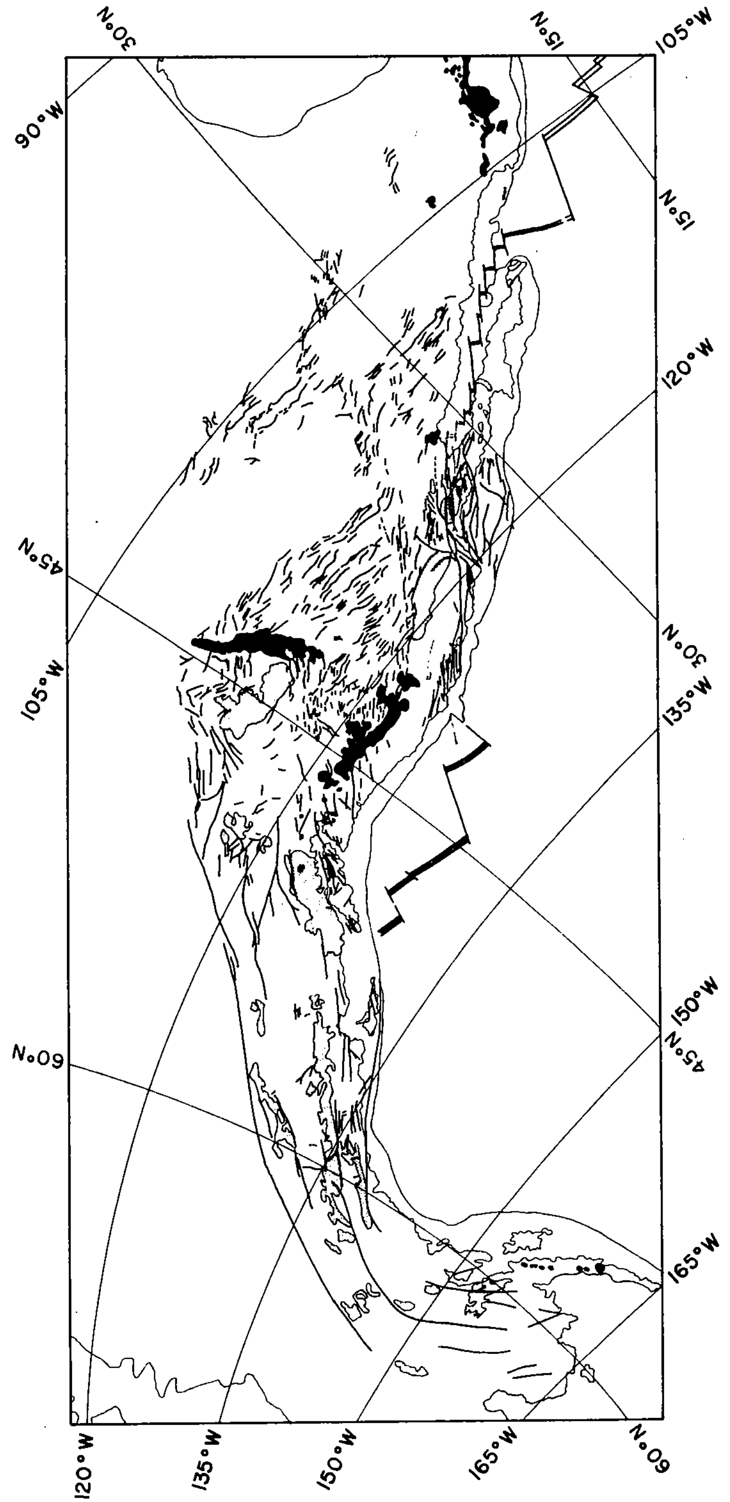

Figure 14. Some major tectonic features of western North America (*after* King, 1969). Quaternary volcanic rocks are black; granitic plutonic rocks are gray; most thrust faults have been omitted. Map projection is that used in Figure 4, so that deformation related to the motion between the American and Pacific plates can be imagined by keeping the ocean floor rigid and moving the rigid part of North America horizontally to the right. Horizontal faults experience pure strike slip while oblique faults have

on the inland boundary, two-thirds on the coastal one.

The black regions in Figures 16D, 16E, and 16F are overlaps of continental and oceanic crust which arise in the construction because the coast is not perfectly parallel to the direction of motion. These overlaps indicate some basic error in the assumptions, either the sea floor has been grossly misdated, or Mexico deformed much more than the amount accounted for by the rifting of the Gulf and borderland, or else the American-Pacific motion before 4 m.y. ago was not constant but changed and was more nearly parallel to the coastline. Minor, rather sudden changes in direction and rate of motion have been noted between other plates (Menard and Atwater, 1968; Heirtzler and others, 1968, Fig. 3) so that a small change would not be surprising. A change in direction 10 m.y. ago of about 20° would be adequate to avoid the overlap, for instance. Evidence cited above for the proximity of the coast to near-coast anomalies during their formation suggests that the change in direction was small. Assuming that the direction changed enough to resolve this conflict while the rate was about constant, a time-distance plot, Figure 17, can be constructed and the following history might be described.

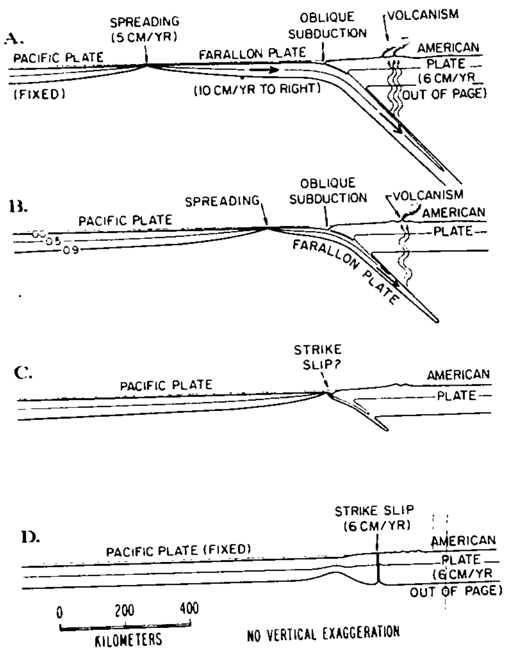

Figure 15. Sketch of plate cross sections during the collision of a ridge and trench. The Pacific plate is held fixed. The spreading center spreads at 5 cm/yr half-rate, accreting material onto both plates so that it moves to the right at 5 cm/yr and the Farallon plate moves to the right at 10 cm/yr. The American plate moves out of the page at 6 cm/yr. Consumption at the trench is oblique. As the Farallon plate moves away from the ridge, it thickens by cooling; as it moves down the Benioff zone, it is thinned by being heated. Plate thickness in *A* is sketched following the 0.9 isotherm of McKenzie (1967, 1969) (where 1.0 is the normalized potential temperature of material in the mantle beneath the plates and intruding at the ridge-crest). *A* represents the plates in early Tertiary, *C* represents the situation when the ridge and trench collided, and *D* represents the plate configuration in central California at the present time. The time which elapses during the evolution of the situation in *C* to that in *D* must be considered when origin times for the San Andreas fault are predicted.

About 32 m.y. ago, the Farallon plate broke up off Baja California between the Pioneer and Murray fracture zones, and thereafter, pieces of the ridge began colliding with the trench. By 24 m.y. ago, the Farallon plate between the Mendocino and Murray fracture zones had disappeared, and American-Pacific motion was being taken up at the young, hot, continent-ocean boundary. By 20 m.y. ago, this section lay off southern California and northern Baja California. Apparently the margin had cooled and strengthened sufficiently that American-Pacific motion began to be felt inland, on the San Andreas (Crowell, 1968), and perhaps in the Basin and Range province. Between 20 and 10 m.y. ago, more southerly sections of the ridge collided with the trench while the Mendocino continued to move northward so that the Pacific-American boundary was greatly lengthened. By 10 m.y. ago (Fig. 16C), the Farallon plate had disappeared along the full length of the present San Andreas-Gulf of California system. Opening of the lower Gulf of California does not appear to have begun until 4 or 5 m.y. ago. Apparently between 11 and 5 m.y. ago, the continent-ocean juncture off Baja California was still hot and weak so that motion was being taken up in the margin and borderland, perhaps causing the buried deformation of the margin noted by Normark and others (1969). In California, the ocean-continent coupling appears to have grown stronger so that more motion moved inland, accelerating the slip rate of the San Andreas (Huffman, 1970). Between 20 and 5 m.y. ago, the San Andreas and Basin-Range systems are assumed to have extended coastward to connect into the Baja margin system. The San Andreas apparently passed through the transverse Ranges while the Basin-Range deformation extended across southern California. Both systems pass into the borderland and southeastward along the coast. The trends of these extensions are such that movement in the San Andreas direction will cause them to open obliquely. In Figure 16C, this is schematically drawn as a rift-transform fault system, but a more realistic description would be a zone of northwest-southeast stretching of the crust, manifested by the formation of numerous basins and rifts. The timing of subsidence of the

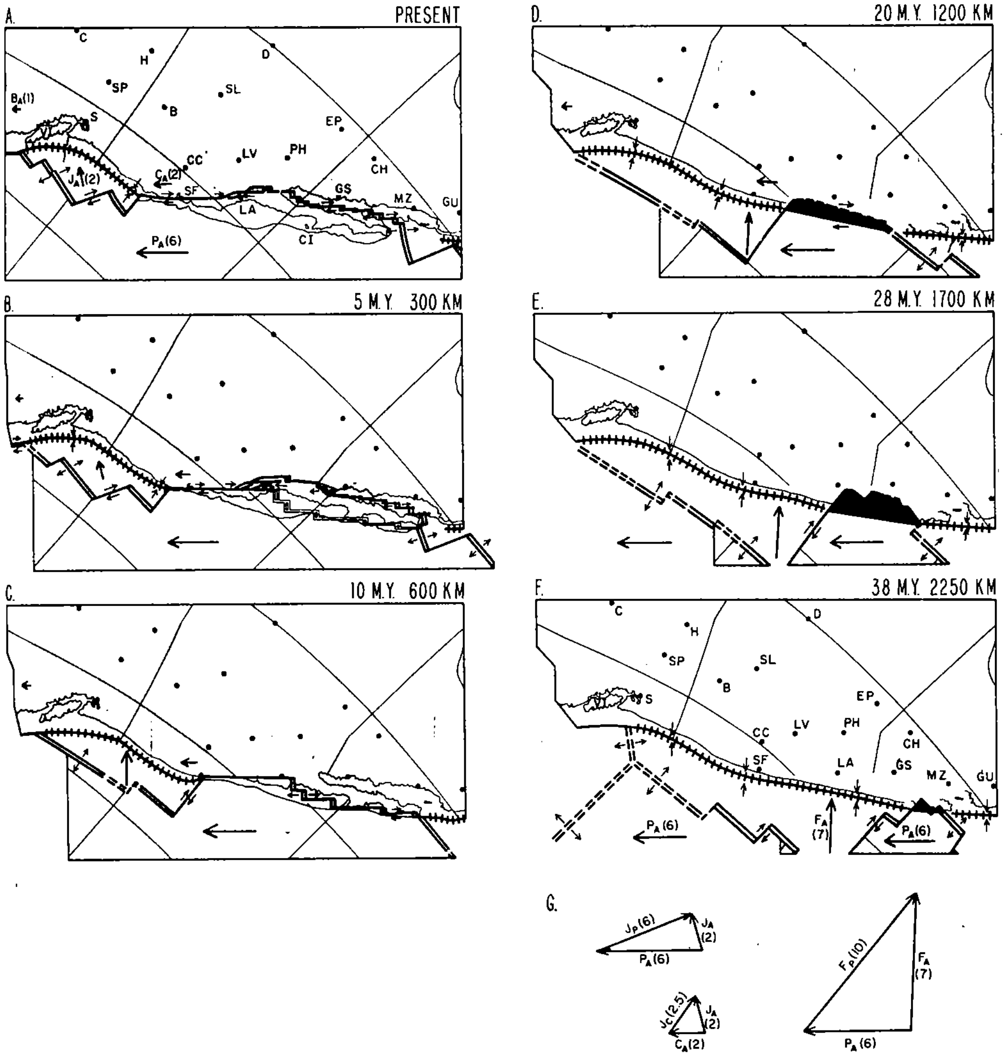

Figure 16. Reconstruction of plate evolution and deformation related to late Cenozoic interaction of the North American and Pacific plates. Initials are cities listed in Figure 17 and symbols and arrows follow Figure 2 except that North America is now arbitrarily held fixed and large arrows show motion relative to it. Diagrams in *G* show the derivation of various vectors. Captions give time in millions of years before present and amount of offset which must subsequently occur to bring the Pacific and inner North American plates back to their present relative positions. Pacific-North America motion (P_A) is assumed constant at 6 cm/yr in a horizontal direction (map projection as in Figures 14 and 4). For the last 20 m.y., 4 cm/yr is assumed to be taken up on near-coast faults, while 2 cm/yr is accommodated by inland faults (gray region). Thus, California was moving northwest at 2 cm/yr (C_A). City locations and coordinate lines are deformed accordingly. Prior to 20 m.y. ago, all motion is presumed to be taken up at the coast. Black regions are unacceptable overlaps of oceanic and continental crust, showing that the direction of Pacific-North American motion probably suffered at least a minor change sometime between 20 and 4 m.y. ago.

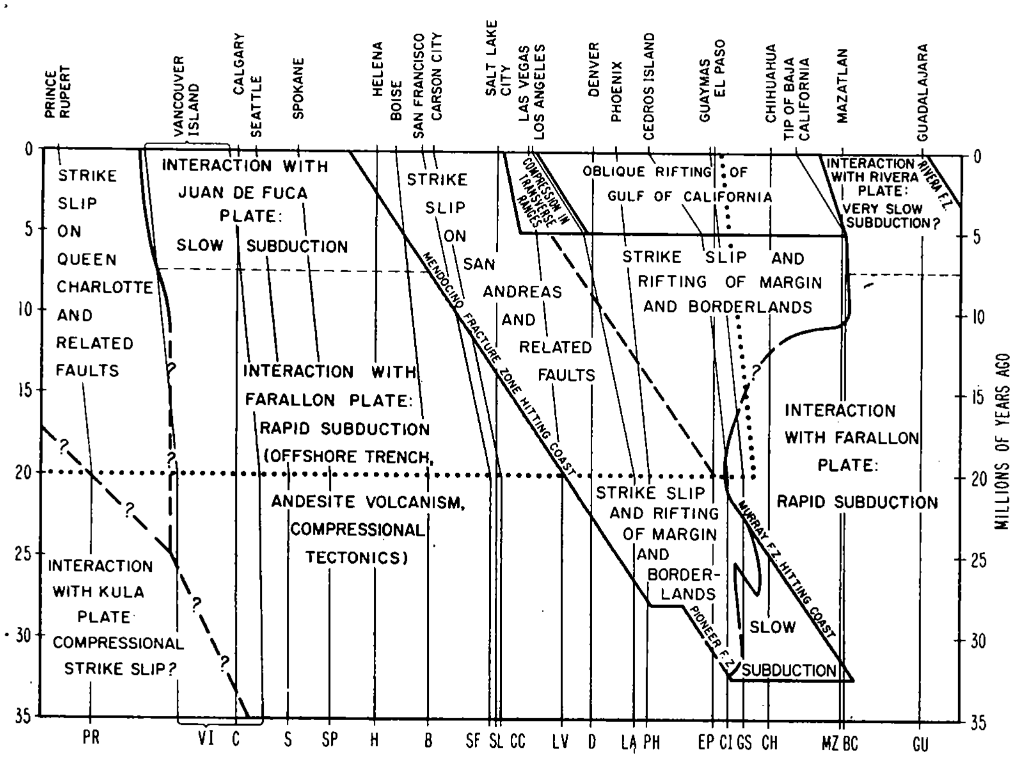

Figure 17. Location of plate boundary regimes with respect to points in western North America, assuming motions and deformations described for Figure 16. Inland cities are raised above the line. They have been projected to the coast vertically in the projection of Figure 16, roughly parallel to the direction of Farallon-North American underthrusting. Fine lines trace the shifting locations of the cities as the continent deforms. Gray areas show times and places where tectonic and igneous activity related to subduction are predicted. White areas show times and places where North America was in contact with the Pacific plate (or with the Kula plate, to be discussed below). The probable near-coast manifestations of these interactions are stated. The dotted line encloses the time and space included in the inland deformation zone of Figure 16. Although it is part of the North American-Pacific interaction, this zone overlaps the Farallon-Pacific field, so that effects of the 2 regimes may be superimposed. For example, around Carson City, andesite volcanism is predicted through the middle Tertiary until 11 m.y. ago, while strike-slip and basin-range rifting is predicted to have started 20 m.y. ago, lasting to the present day.

Los Angeles basin (Yerkes and others, 1965) fits this model well.

The configuration shown in 16C lasted until about 5 m.y. ago, when the margin apparently became stronger than an inland zone which broke to take up the motion (16B), opening the Gulf of California. In southern California, the San Andreas had to break its way inland to connect into the new Baja California boundary. The bend was in such a direction that oblique compression began in the Transverse Ranges (Crowell, 1968). The two-stage development of the San Andreas system with motion first taken up outboard and then inboard of the Baja peninsula has been suggested by Crowell (Dec. 1969, personal commun.) and developed by Suppe (1970b), although the suggested timing is different.

AN EXTRAPOLATION INTO THE EARLY CENOZOIC

When the model of constant motions is extended into the early Cenozoic, yet another triple junction is seen to have migrated along the coast of North America. This is the junction between the Farallon, North American, and Kula plates (Fig. 18).

The late Mesozoic existence of the Kula plate (Grow and Atwater, 1970) has been postulated to account for the formation of the east-west-trending magnetic anomalies which lie south of the Aleutian trench (Pitman and Hayes, 1968; Grim and Erickson, 1969). The rate and direction of spreading of the Kula and Farallon plates away from the Pacific plate can be determined from anomaly spacing and fracture zone trends near the magnetic bight. The 3 plates were all diverging so that a third ridge lay between the Kula and Farallon plates (Pitman and Hayes, 1968). The direction and rate of spreading of the third ridge can be deduced for the period from 75 to 63 m.y. ago, but the Aleutian trench has destroyed data concerning more recent motions of the Kula plate and spreading of the third ridge. The configuration of the third ridge and its transform faults cannot be determined, for the anomalies created by its spreading lay in the Kula and Farallon plates which have both subsequently been destroyed.

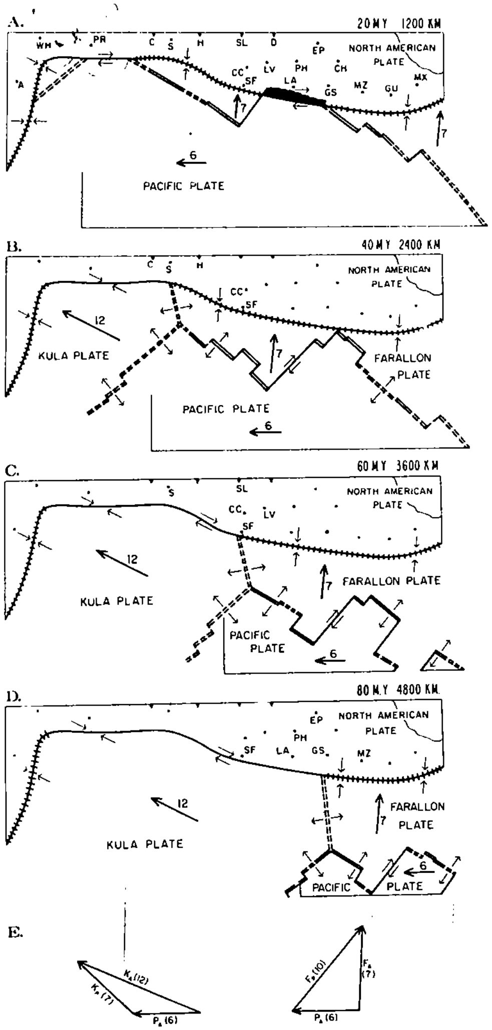

Figure 18. Plate relationships derived from extrapolation of Pacific-North American and Pacific-Kula motions through the Cenozoic. Conventions and assumptions are as in Figure 16.

If we take the Kula-Pacific motion of the late Mesozoic and the North American-Pacific motion of the last 4 m.y. and extrapolate them both throughout the Cenozoic, and if we assume that the third ridge had no transform faults, then the history shown in Figure 18 results. This extrapolation is very tenuous. The Kula-Pacific motion since 60 m.y. ago is unknown and no compelling reasons exist to suggest that it was constant. The North American-Pacific motion amounted to a large offset in the present direction (from paleomagnetic evidence), but it is almost certain that it suffered at least minor changes in direction and rate along the way. The crustal overlaps in Figures 16E and 16F seem to require such a change between 20 and 4 m.y. ago. The Farallon-Pacific motion is known to have had a minor change about 58 m.y. ago (Menard and Atwater, 1968; Atwater and Menard, 1970). In Figure 18, this was assumed to reflect a change only in the Farallon plate motion, but the Pacific plate motion may have changed as well. Furthermore, McKenzie and Morgan (1969, p. 131) show that 3 plates cannot all maintain constant relative motion in the sense that it is used here (rotation about a pole which is fixed with respect to the plates whose motions it describes); constant minor readjustment is required.

Another problem with the reconstruction in Figure 18 is that the pole for Kula-Pacific relative motion is difficult to establish since anomalies and fracture zones concerning it occupy such a small area. For the extrapolation the pole is assumed to be far away so that rate and direction of motion is uniform over the entire Kula plate. This uncertainty makes the Kula-North American vector, K_A, particularly unreliable. Yet another problem is that other oceanic plates may have once existed north and east of the Kula and Farallon plates. This could drastically change the predicted North American boundary regimes.

Despite these many uncertainties, the gross geometry of Figure 18 is probably correct. It is clear that at least 3 ridges existed in late Mesozoic and early Cenozoic times, and that their triple junction lay farther south than the present location of the magnetic bight. Unless other small plates intervened, the third ridg intersected North America, and this triple junction moved up the coast, the Farallon-North American trench developing south of it.

This geometry suggests possible relationships to some geologic problems. Although the Kula-North American vector is poorly known, it appears to have had a significant component of right lateral strike slip. A late Mesozoic-early Cenozoic era of Kula-North American interaction is indicated off the western United States. This suggests a possible early episode of slip on the San Andreas which could account for the pre-late-Oligocene offset of Mesozoic terrains discussed above. A late Mesozoic episode of San Andreas slip is also suggested by Wentworth (1968) to explain contrasting source areas and troughlike depositional characteristics for the Gualala basin. The geometry also shows that the mid-Tertiary trench discussed near the beginning of this paper can begin only after the passage northward of the third ridge triple junction. Dating of igneous rocks suggests the existence of a short-lived mid-Tertiary trench off California (McKee and others, 1970); however, it appears to have started in middle or late Eocene, somewhat later than predicted. Another implication of Figure 18 (and Fig. 17) is that the Farallon plate never extended farther north than Vancouver Island. Central British Columbia and southeast Alaska are presently interacting with the Pacific plate. The Kula and other unknown plates lay offshore in earlier times. No definite predictions can be made concerning plate interactions in this region.

A Mesozoic trench is often associated with Franciscan rocks (Dietz, 1963; Ernst, 1965, 1970; Hamilton, 1969a; and others) and with the emplacement of the Sierra Nevada batholith (Gilluly, 1969; Hamilton, 1969b). It appears to have been active until about 80 m.y. ago (Evernden and Kistler, 1970; Suppe, 1970a). According to Figure 18, the Kula or some other northern plate lay off western North America during the Mesozoic. The trench had nothing to do with the Darwin rise nor with the Pacific or Farallon plate. If the Tertiary motion of the Kula plate was approximately as shown, its relative motion must have changed about 80 m.y. ago from a more compressional motion to the nearly strike-slip one shown. Alternatively, another unknown plate may have lain between the Kula and American plates. A major change in motion seems likely since extrapolation of Farallon-Kula-Pacific motions backward in time shows that the ridge-ridge-ridge triple junction represented by the magnetic bight intersected the Surveyor and Mendocino fracture zones about 100 and 115 m.y. ago (about 1300 and 1950 km southwest of anomaly 31). Consideration of ridge-ridge-ridge triple junctions shows that the offsets on fracture zones must come into existence at or after this intersection time (Atwater and Menard, 1970). Thus, the huge offset of the Mendocino fracture zone indicates some major change between 115 and 77 m.y. ago. The variable spacing and trend of anomalies 32 to 31 south of the Aleutian trench (Hayes and Heirtzler, 1968; Grim and Erickson, 1969) may be an indication that until about 72 m.y. ago, the Kula-Pacific ridge was still getting adjusted to a large change or to its original formation.

Probably the most important contribution of Figure 18 is that it emphasizes the inconstant nature of plate tectonic boundary effects. The figure was constructed assuming constant relative motions of the plates, and yet, 3 different successive boundary regimes are predicted at many points along the coast.

DISCUSSION

The conclusions in the 3 main sections of this paper represent 3 different levels of uncertainty. All assume that the basic principles of sea-floor spreading and plate tectonics are approximately correct. Given this assumption, the conclusions in the first section—that a mid-Tertiary trench lay off western North America and that the San Andreas fault began activity in its present role not earlier than 30 m.y. ago—are nearly inescapable. The conclusions in the second section depend upon which model is assumed for the history of motions of the North American plate with respect to the oceanic plates. Most of the discussions and reconstructions (Figs. 5, 6, 16, and 17) in this section assume that the motions were approximately constant during the late Tertiary. Although this model appears to be the most probable one, it cannot be definitely established. The third section deals with an outrageous extrapolation of the constant motion model. Its value lies mainly in that it presents the most straightforward model for early Tertiary plate motions, and thus may serve as a starting point for discussions of plate reconstructions of that era.

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