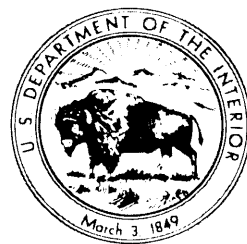


# Melanges and Their Bearing on Late Mesozoic and Tertiary Subduction and Interplate Translation at the West Edge of the North American Plate

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1198



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By KENNETH F. FOX, JR.

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## CONTENTS

	Page		Page
Abstract .....	1	Franciscan Complex .....	23
Introduction .....	2	Age of deformation resulting in the Franciscan Complex .....	23
Late Cretaceous and Tertiary plate-tectonic setting .....	2	Cause of allochthonous deformation that created the Franciscan Complex .....	24
Definition of melange, broken formation, and petrotectonic assemblage .....	3	Comparison of Cretaceous through early Eocene tectonic regimes as predicted by the triple-junction hypothesis with concepts suggested by other evidence .....	25
Origin of melange .....	3	Evidence from the Franciscan Complex contradictory to the triple-junction hypothesis .....	27
Objectives of present investigation .....	4	Oregon-Washington borderland .....	28
Geometry of Humboldt- and Mendocino-type triple junctions .....	5	Age, distribution, and plate-tectonic setting of the borderland .....	28
Age and distribution of melanges and related rocks .....	10	Origin of the borderland through plate collision .....	29
San Onofre Breccia .....	10	Reconciliation of the collision hypothesis with other tectonic features of the Pacific Northwest .....	32
Olympic Peninsula and Oregon-Washington borderland - Franciscan Complex, Franciscan assemblage, Great Valley sequence, and correlative rocks .....	15	Melanges of the Olympic Peninsula .....	33
Semantic distinction between Franciscan Complex and Franciscan assemblage and the relation of these rocks to the Great Valley sequence .....	15	The Aja Fracture Zone and the formation of a Humboldt-type triple junction .....	33
Hsu's (1969) concept of allochthonous, mesoallochthonous, autochthonous, and neoautochthonous rocks .....	18	Origin of melanges and broken formations .....	33
Evidence bearing on the age of formation of the Franciscan Complex .....	18	San Onofre Breccia .....	34
Morro Bay area .....	19	Conclusions .....	36
Clear Lake-Covelo area .....	20	References cited .....	36
Bandon area .....	21		
Main elements of melanges and their bearing on plate-tectonic history .....	23		

## ILLUSTRATIONS

	Page
FIGURE 1. Sketch map showing geometry west of the North American plate from 60 to 80 Ma derived through extrapolation of late Cenozoic plate motions .....	2
2. Schematic model of early and middle Tertiary evolution of the plate geometry of the northeastern Pacific .....	2
3. Sketch map showing relation of oceanic features of the north eastern Pacific to melange and other features of the western part of the North American plate .....	4
4. Cross section showing hypothetical formation of melanges through tectonic churning and accretion of trench deposits to underside of a subduction zone as postulated in subduction-complex theory .....	6
5-8. Diagrams showing:	
5. Vector circuit representing the relative movement of three plates in mutual contact at a ridge-transform fault-subduction zone triple junction .....	7
6. Evolution of plate geometry at a triple junction .....	8
7. Progressive advance of Humboldt-type triple junction along a continental plate and the volume of material that must be disposed of during this advance .....	9
8. Formation of fold belt, thrusts, gravity thrusts, and melanges at Humboldt-type triple junction .....	10
9. Geologic map of western Oregon and Washington .....	11
10. Sketch map showing tectonic classification of the Franciscan Complex and associated rocks of western California and southwestern Oregon .....	14
11. Diagram showing correlation of boundary regimes and petrotectonic features along the west side of the North American plate .....	17
12. Schematic view to northwest showing transit of Early Cretaceous Humboldt-type triple junction with accompanying formation of melange and a proto-Coast Range thrust to east .....	26
13. Paleomagnetic map of the floor of the northeastern Pacific Ocean .....	30
14. Diagram showing Late Cretaceous and early Tertiary plate geometry west of the North American plate .....	31
15. Sketch map showing successive positions of the Aja fracture zone relative to the North American plate .....	34
16. Schematic view to north showing deformation and generation of melanges and broken formations in early and middle Miocene time at the present site of the Olympic Peninsula .....	35

# MELANGES AND THEIR BEARING ON LATE MESOZOIC AND TERTIARY SUBDUCTION AND INTERPLATE TRANSLATION AT THE WEST EDGE OF THE NORTH AMERICAN PLATE

By KENNETH F. FOX, JR.

## ABSTRACT

Melanges are commonly considered to be material scraped off an oceanic plate descending at a subduction zone, tectonically churned, and accreted to the underside of the overriding plate. Yet the correlation of Late Cretaceous and Tertiary melanges of western North America with subduction zones of that age is poor. During much of the middle and late Tertiary, this area was continuously or discontinuously bordered by a subduction zone within which the Farallon plate and much of its successor, the Juan de Fuca plate, were consumed. Yet known melanges of this age that can reasonably be linked to this process are rare and limited to those of the Olympic Peninsula of Washington. Melanges are also present within the Franciscan Complex of western California and within the Otter Point Formation of southwestern Oregon, mostly Eocene or older.

An alternative to the subduction-complex theory is that melanges are material that was broken and sheared as it was plowed aside and either coasted or was rammed inland at a triple junction migrating along the edge of the continental plate. The required triple junction is of a singular dynamic type, referred to as a Humboldt-type, formed where an oceanic plate obliquely underthrusts a continental plate and advances laterally along the edge of that plate while following a retreating oceanic (or possibly continental) plate. The triple junction may be formed through the intersection of either (1) a spreading ridge, transform fault, and subduction zone or (2) two transform faults and a subduction zone.

The Franciscan Complex includes rocks that contain detritus eroded from preexisting melanges or detritus deposited by normal sedimentary processes on top of preexisting melange. These sequences were subsequently sheared, fragmented, and intermixed to form new melanges or broken formations, strata similar to melanges but containing no exotic blocks. The Franciscan in places contains a record of two or more distinct cycles of melange development. Evaluation of such constraints as are known on the ages of these cycles suggests three diachronous events, believed to represent the transit along the western margin of the continent of Humboldt-type triple junctions in Cretaceous and early Tertiary time. The youngest of these is fairly well bracketed by ages of nonpenetratively deformed rocks and penetratively deformed melange or broken formation near Morro Bay, Calif., and less satisfactorily in the Covelo-Clear Lake area of California. The ages suggest that the most recent period of formation of the Franciscan Complex and correlative rocks was during the Campanian at Morro Bay and early Eocene or perhaps later time near Covelo. Farther north, the age of the most recent overthrusting and imbrication of Franciscan-like rocks near Bandon, Oreg., also is bracketed within the early Eocene, but it is not certain that melange or broken formation formed contemporaneously with the thrusting.

In California, the final episode of allochthonous deformation was probably a diachronous upheaval producing melange and broken for-

mation that transited the continental margin at a rate of roughly 4 cm/yr, reaching northern California by the early Eocene. This timing nearly coincides with the transit of the Kula-Farallon-North American triple junction, as inferred by Tanya Atwater in her constant-motion model of Late Cretaceous and Tertiary plate geometry. In early Eocene time, however, this transit apparently evolved into an event in which coastal areas of southwestern Oregon and northwestern California were contemporaneously deformed and the allochthonous oceanic crust now underlying northwestern Oregon and western Washington was formed and accreted to the craton.

The basement rock of this Oregon-Washington borderland consists of oceanic tholeiitic basalt of early and middle Eocene age, which, from published paleomagnetic data, is believed to have been rotated clockwise as much as about 70° by middle Tertiary time. The contact of the oceanic crust with the craton to the east is apparently defined by a zone of steep negative gravity gradients. The angular to jagged outline of this contact as inferred from published gravity maps suggests that the borderland is an aggregation of variably rotated blocks, rather than a single elongate and coherent crustal block. The reported attitude of source fissures of the tholeiite suggests derivation in part in a stress system with a tensional direction comparable to that of the Kula-Pacific ridge rather than of the supposedly nearby Kula-Farallon ridge.

Prior to 56 Ma (million years before A.D. 1950), the paths of Pacific and North American plates may have been convergent rather than parallel to the trend of the Queen Charlotte and San Andreas faults, as they have been for the past 25-30 million years. If they were convergent, the allochthonous crust of the borderland could have been accreted to the North American plate during a collision between that plate and the Pacific plate.

It has been proposed that the Kula-Pacific spreading ridge vanished abruptly shortly after 56 Ma. The presence within the oceanic crust of the Oregon-Washington borderland of a tensional orientation comparable to that of this ridge suggests that the ridge, instead of vanishing, jumped northward, intersecting the North American plate northwest of the former Kula-Farallon-North American triple junction.

The Pacific plate, enlarged by the addition of part of the Kula plate, then sideswiped the North American plate, driving a widening wedge of recently formed oceanic crust inland while crunching and stacking adjacent rocks of the craton in Oregon and Washington. By the impact of this collision, the Pacific and North American plates were deflected into their present paths parallel to their bounding transforms as the allochthonous wedge of oceanic crust was sheared off, fragmented, and rotated clockwise to form the basement of the Oregon-Washington borderland.

The core rocks of the Olympic Peninsula consist of melange and broken formation, infaulted or imbricated with blocks of intact strata. Rocks peripheral to the core consist of the oceanic tholeiitic basement

of the Oregon-Washington borderland with interfingering clastic deposits, mainly overlain by shallow-water marine-shelf deposits. The core rocks are bathyal marine turbidite deposits. Melanges of the western core contain fossils whose reported ages are as young as early or middle Miocene. Published potassium-argon ages of the rocks of the eastern core suggest metamorphism after 29 Ma and cooling about 17 Ma.

Magnetic lineations of the northeastern Pacific step right laterally across the Aja fracture zone. From the age of these anomalies, it appears that north of the Aja, the spreading ridge system and coexisting subduction zone shrank, then vanished about 21½ Ma. The Aja would then intersect the Queen Charlotte fault and the subduction zone to the south and, with continued right-lateral movement of the Pacific plate, would form a Humboldt-type triple junction. That triple junction would then persist through about 5½ m.y., finally dying 16 Ma as the ridge system south of the Aja stepped eastward and intersected the subduction zone. This timing nearly coincides with potassium-argon ages of cooling of the youngest melanges in the eastern core of the Olympic Peninsula. To account for the structural fabric and geographic extent of the Olympic melanges of Miocene age through the tectonism associated with this triple junction, the junction must have been situated immediately west of the Olympic Peninsula. If this spatial and temporal relation is valid, northwestward movement of the Pacific plate relative to the North American plate has averaged about 6 cm/yr at least since middle Miocene time, a rate comparable to accepted estimates of the rate of movement of these plates averaged over the past 2 m.y.

## INTRODUCTION

### LATE CRETACEOUS AND TERTIARY PLATE-TECTONIC SETTING

In Late Cretaceous and early Tertiary time, the North American plate was flanked to the west by the Kula plate (Grow and Atwater, 1970, p. 3717) and the Farallon plate (McKenzie and Morgan, 1969). Still farther west, the Kula and Farallon plates joined the Pacific plate (fig. 1) at spreading ridges from which all three plates grew. During this time, the oceanic plates, though moving in various directions with respect to each

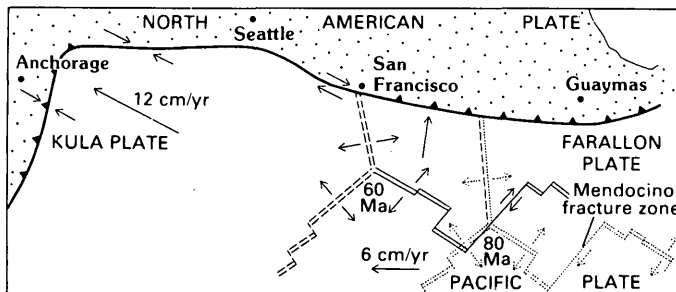
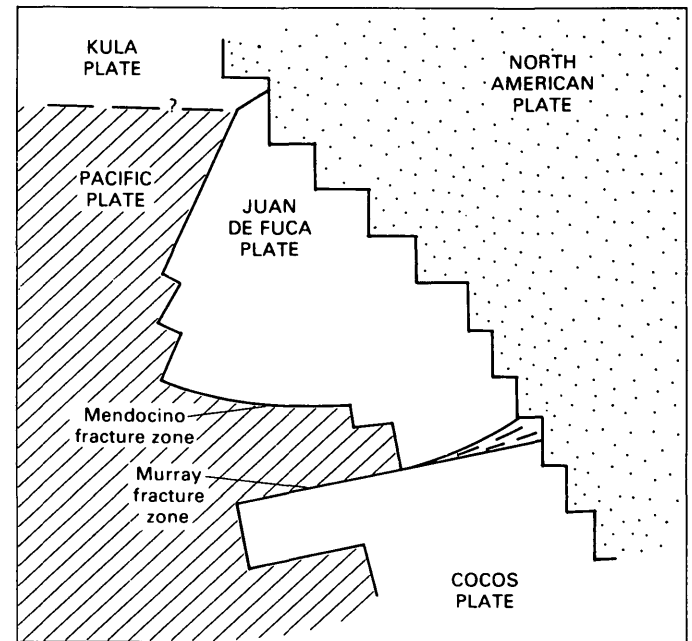


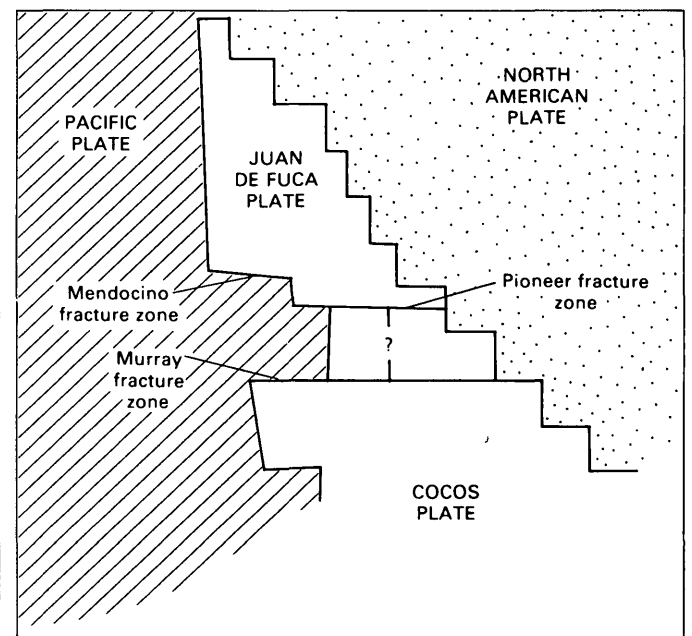
FIGURE 1.—Plate geometry west of North American plate from 60–80 Ma (million years before A.D. 1950) (derived by Atwater, 1970, p. 3531, through extrapolation of late Cenozoic plate motions). Arrows show directions of spreading and plate movements relative to the North American plate, arbitrarily held fixed. Pacific plate is assumed to be moving at a constant 6 cm/yr parallel to transform faults that later (in late Cenozoic) developed between it and the North American plate. Model explained by Atwater (1970, p. 3531) as one of numerous alternatives permitted by her data.

other, collectively moved right laterally past the North American plate (Atwater, 1970). Consequently, the subduction zone down which the Farallon plate plunged obliquely below the overriding North American plate gradually lengthened to the northwest.

The spreading direction between Pacific and Farallon plates changed abruptly in early Tertiary time



A



B

FIGURE 2.—Early to middle Tertiary evolution of plate geometry of northeastern Pacific (modified from Menard, 1978, p. 105). A, Early Tertiary (50 Ma). B, Middle Tertiary (36 Ma).

(Menard and Atwater, 1968). Magnetic anomalies formed after this change radiate slightly fanwise about a distant pole (Menard, 1978, p. 104), suggesting that the Farallon plate gradually pivoted counterclockwise with respect to the Pacific plate. Menard (1978, p. 104) has postulated that about the time anomaly 21 was formed (50 Ma)<sup>1</sup> the Farallon plate broke along the eastward projection of the Murray fracture zone into two parts, cutting the Juan de Fuca plate on the north away from the main part of the Farallon plate on the south, here referred to as the Cocos plate (fig. 2).

At about the time of formation of anomaly 13 (36 Ma), the Pioneer fracture zone also broke eastward to the edge of the North American plate, forming a small plate between the Pioneer and Murray fracture zones (Menard, 1978, p. 104). Shortly after about 30 Ma, the eastward projection of the Pacific plate between the Pioneer and Murray fracture zones contacted the North American plate. After 27 Ma, some 3 to 4 m.y. later, the segment of Pacific plate between the Mendocino and Pioneer fracture zones also contacted the North American plate. Subsequently, through northward advance of the Juan de Fuca-Pacific-North American triple junction (now at Cape Mendocino) and southward retreat of the Cocos-Pacific-North American triple junction, the plate geometry evolved into its present configuration (fig. 3)<sup>2</sup>.

The evolution of plate geometry outlined here is based on the history of spreading of the northeastern Pacific, deduced chiefly from the magnetic lineations and morphology of its basaltic floor, and extrapolation of the present rate (roughly 6 cm/yr) and direction of relative movement between the Pacific plate and North American plate back to Late Cretaceous time. Although the gross geometry is probably correct, the model becomes progressively weaker proceeding back in time because of the cumulative effect of errors in the assumptions and because much of the pre-Tertiary spreading record has been eradicated by consumption of oceanic crust at converging plate margins.

*Acknowledgments.*—I appreciate the penetrating yet constructive criticisms of the manuscript by J. C. Matti, R. W. Tabor, M. C. Blake, Jr., D. L. Jones, and P. D. Snively, Jr. Continuing dialogs with R. J. McLaughlin and M. C. Blake, Jr., on problems of the Franciscan Complex were very helpful, as were discussions with R. W. Kopf on the distinction between rock-stratigraphic units and lithotectonic units, and distinc-

tion between the terms "Franciscan Complex" and "Franciscan assemblage."

#### DEFINITION OF MELANGE, BROKEN FORMATION, AND PETROTECTONIC ASSEMBLAGE

Geologic features indicative of particular plate-tectonic regimes of the past (petrotectonic assemblages of Dickinson, 1971) include ophiolites, paired metamorphic belts, old volcanic arcs, thrust belts, and melanges. Following Hsu (1968, p. 1065), "melange" refers to those enigmatic, though "mappable bodies of deformed rocks characterized by the inclusion of tectonically mixed fragments or blocks, which may range up to several miles long, in a pervasively sheared, fine-grained, and commonly pelitic matrix." The melanges include both exotic and native blocks. Again quoting Hsu (1968, p. 1065), "*Native blocks* are disrupted brittle layers which were once interbedded with the ductilely deformed matrix. *Exotic blocks* are tectonic inclusions detached from some rock-stratigraphic units foreign to the main body of the melange." A body of broken strata containing no exotic blocks but otherwise similar to a melange is defined as a "broken formation" (Hsu, 1968, p. 1065-1066).

These and analogous features are major guides to past plate geometries. Even where correctly identified, the precision with which they can be applied is reduced because (1) the features are inherently difficult to date; or (2) their genetic correlation with a particular plate-tectonic regime is tenuous; or (3) the spatial relation is diffused because the petrotectonic feature forms over a broad area at a considerable or indefinite distance away from the causal plate boundary regime; or (4) the spatial relation is confused by lateral translation of unknown magnitude before final accretion to the craton. Attempts to verify, calibrate, and rigorously extend Atwater's (1970) model by dating the petrotectonic features of the continental plate have generally been frustrated.

#### ORIGIN OF MELANGE

The recognition of the loose association of melanges with presumed consuming plate boundaries, the internal tectonic disruption of the melanges, and the incorporation of trench deposits and ophiolitic bodies within them suggested to many workers that the melanges formed through scraping off and tectonic churning of the upper surface of the oceanic plate as it was being subducted (Hamilton, 1969, p. 2415-2416). By this concept, melanges were considered to be imbricated slices of material scraped off the descending oceanic plate and accreted to the underside of the overriding plate during the subduction process (fig. 4). Indeed, the presence of melanges within a geologic terrane is now the single most important indicator of the subduction complex.

<sup>1</sup>Ages assigned to magnetic anomalies in this report are based on the time scale of La Brecque and others (1977).

<sup>2</sup>The Juan de Fuca plate was called the Vancouver plate by Menard (1978). At the risk of some slight loss in precision, this plate and other fragments of the Farallon plate, such as the Cocos plate, are here referred to by the commonly accepted name of their major surviving remnant.

One of the inadequacies of this subduction complex theory is that, in detail, the correlation between the location and age of melanges and the inferred location and duration of past subduction regimes is poor. For example, according to Atwater's (1970) model, during much of the middle and late Tertiary, the western side of the North American plate was continuously or discontinuously bordered by a subduction zone within which the Farallon plate and much of its successor, the Juan de Fuca plate, were consumed. Yet known melanges or melangelike rocks of this age that could possibly be related to this subduction process are rare, being limited to those of the Olympic Peninsula (Stewart, 1971; Tabor and Cady, 1978a). Perhaps the subduction process is inherently occult, its products concealed from observation except when unusual circumstances not now understood intervene. If it is, the subduction-complex hypothesis in its present form makes no verifiable predictions.

An alternative hypothesis to explain the origin of the melanges of the Franciscan Complex was recently

advanced by Fox (1976). According to this hypothesis, melanges form as a series of coalescing and imbricated gravity slides and thrust slices at a triple junction as it migrates along the edge of the continental plate. Further, the required triple junction is of a singular dynamic type referred to as a "Humboldt" triple junction. At a Humboldt-type triple junction, a transform fault bounding the continental plate is converted to a subduction zone through lateral transport of the two adjacent oceanic plates. Melanges, then, represent a chronological and spatial tie between the point on the continental plate where it joins with two adjacent oceanic plates and one at which there is a transition from a strike-slip tectonic regime to a subduction regime.

#### OBJECTIVES OF PRESENT INVESTIGATION

One of the objectives of this paper is to test the subduction-complex and triple-junction hypotheses by com-

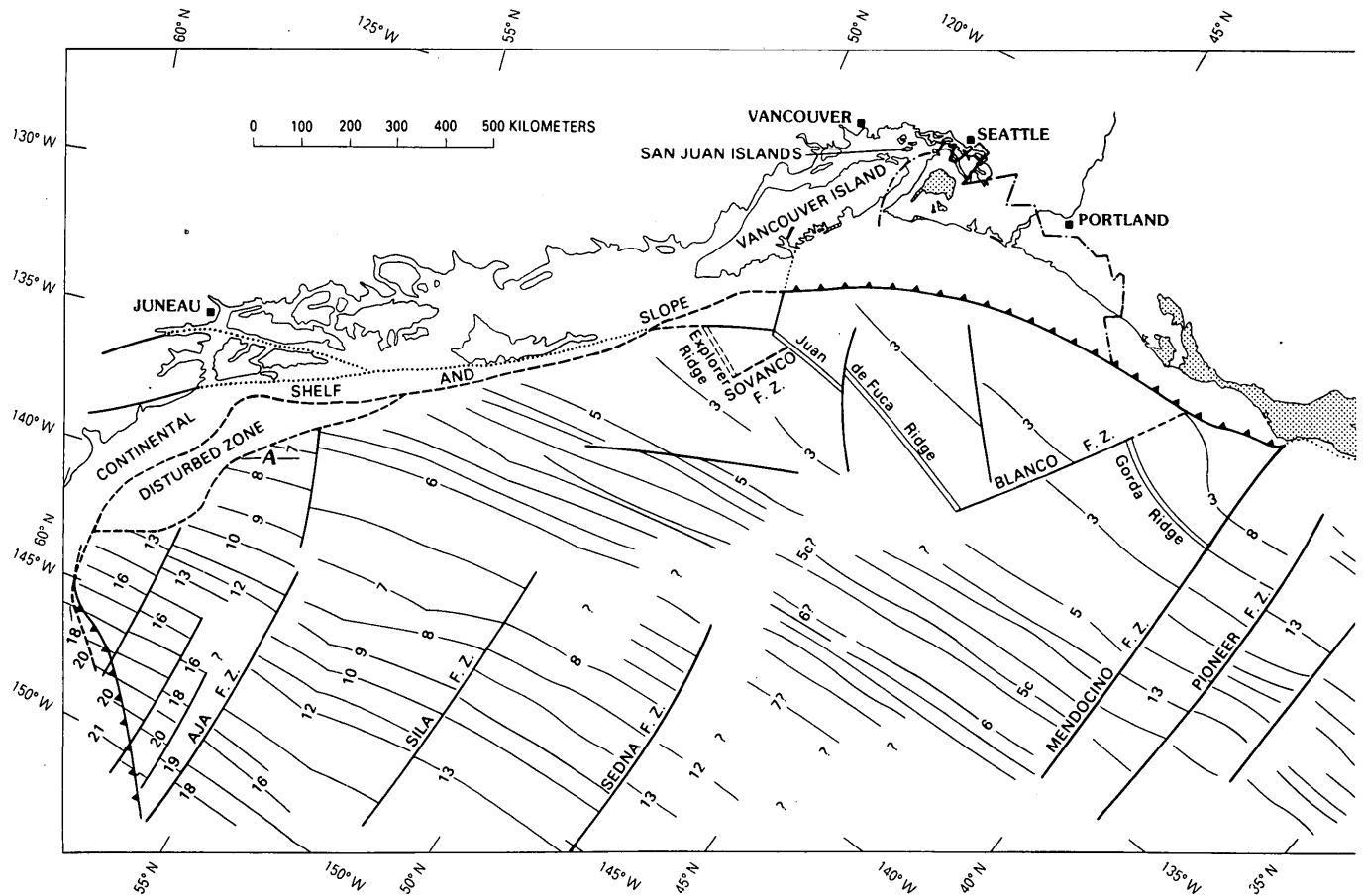


FIGURE 3.—Relation of oceanic features of northeastern Pacific to melange and other features of western part of North American plate. Oblique Mercator projection about late Cenozoic pole of rotation between Pacific and North American plates at lat 52° N., long 73° W. (Chase, 1972). Melange terranes too small to show located in San Juan Islands (S.J.I.) and at Cedros Island (C.I.). Oceanic features after Atwater and Menard (1970), Naugler and Wageman (1973), Vine (1968), Raff and Mason (1961), Barr and Chase (1974), Moore (1973), and Larson (1972).



paring the timing and locus of melange formation with that suggested by the known or inferred evolution of plate geometry along the western margin of the North American plate. Except for the Neogene, however, neither the evolutionary history of plate geometry nor the age of formation of the melanges is known with sufficient exactitude to provide a very sensitive test. Meaningful comparisons can indeed be made for the Neogene, but only very crude comparisons for the early Tertiary and Cretaceous. For that part of the geologic record, the recognition of an association of melanges with specific triple junctions could potentially improve both perception of past tectonic regimes and precision in their correlation with particular plate configurations. This leads to the second objective of this paper; to summarize evidence now available concerning the ages of the melanges and, by interpreting them as records of the existence and passage of Humboldt-type triple junctions, to modify and amplify the Late Cretaceous and early Tertiary plate-tectonic history of western North America.

**GEOMETRY OF HUMBOLDT- AND MENDOCINO-TYPE TRIPLE JUNCTIONS**

Triple junctions have been classified into 16 types according to the nature of the intersecting plate boundaries, that is ridge-ridge-ridge, ridge-transform-subduction zone, transform-transform-subduction zone, and so on, and the conditions under which they are stable defined (McKenzie and Morgan, 1969). In this discussion, my interest is focused chiefly on understanding the tectonic processes at the margin of a continental plate. I therefore restrict my inquiry to the dynamics of those stable ridge-transform-subduction zone and transform-transform-subduction zone triple junctions in which the edge of a continental plate is a transform fault on one side of the triple junction and a subduction zone on the other side.

The subduction zone is presumed to dip continentward at an angle within the range of dip of modern Benioff zones, approximately 20°-65° (Turcotte and

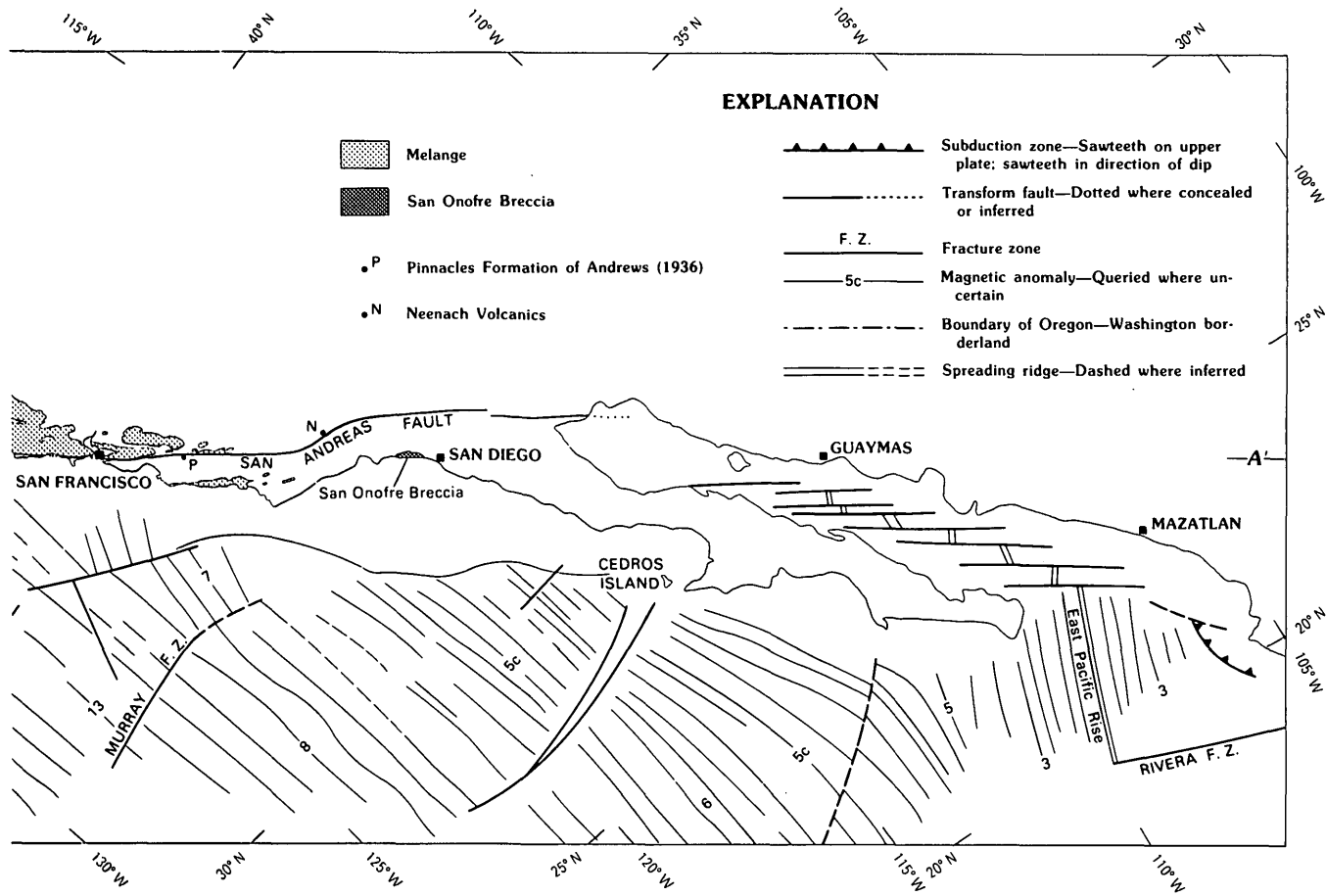


FIGURE 3.—Continued

Schubert, 1973, p. 5880), whereas the transform fault is presumed to be nearly vertical, also in accordance with seismic studies of modern transform faults such as the San Andreas fault. The triple junction marks, then, the point at the surface of the Earth where the inclined plane of the subduction zone intersects the nearly vertical plane of the transform. The third leg of the triple junction is either a spreading ridge or transform separating two oceanic plates.

The rate and direction of lateral migration of triple junctions at which a continental plate contacts two adjacent oceanic plates depends on the relative motion of the three plates with respect to each other. Although that fact will seem self-evident, the details of the geometric relation between the movement of the triple junction and that of the three plates may seem obscure except to those who closely followed the development of plate-tectonic theory. The geometric details may be clarified by considering the following hypothetical example of relative movement between three plates, A, B, and C, as depicted in figures 5 and 6.

I define the triple junction between plates A, B, and C to be stable in the sense of McKenzie and Morgan (1969); that is, the relative movement between these plates sums to zero and can therefore be represented by the vector triangle shown in figure 5. In this example, spreading at the ridge between plates B and C is orthogonal to the ridge and is symmetrical; that is, equal in-

crements of new oceanic crust are accreted to plates B and C during any given interval of time, and so plates B and C move away from the ridge at equal rates. That being the case, all points on the ridge and its imaginary prolongations at either end must lie on the perpendicular bisector of line B-C (fig. 5).

The triple junction must lie both on the perpendicular bisector of line B-C and also on the line of which the vector between C and A is a segment, hence must be located at J in figure 5. The vector  $J_A$  thus represents the direction and velocity of movement of the triple junction J with respect to plate A, that is, 1 cm/yr N. 40° W. if the spreading direction is N. 87° E.

In this example, plate B moves N. 40° W. at 6 cm/yr relative to plate A, and plate C moves N. 80° E. at 6 cm/yr relative to plate B. Were these rates the same, but the spreading direction N. 80° E. rather than N. 87° E. (fig. 5), the triple junction would plot at  $J^2$ , coincident with the apex of the triangle at A. In this situation, the triple junction would not move relative to plate A. Were the spreading direction N. 75° E. (fig. 5), the triple junction would plot at  $J^3$  in figure 5, hence would move 1 cm/yr S. 40° E. relative to plate A. In this example, the direction and rate of movement of the triple junction relative to plate A is very sensitive to minor differences in spreading direction. Differences in spreading rate, angle of intersection of ridge and the margin of the continental plate, or in rate of offset of the continental plate with re-

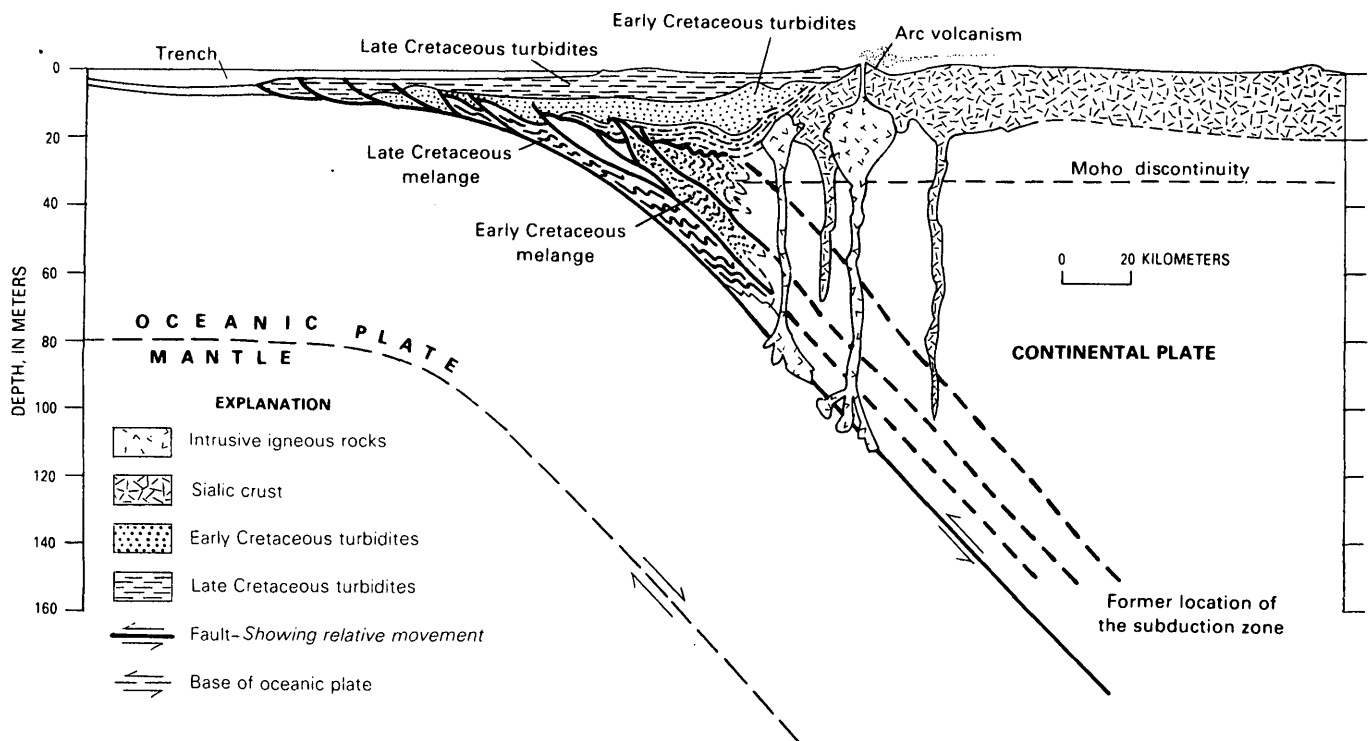


FIGURE 4.—Cross section showing hypothetical formation of melanges through tectonic churning and accretion of trench deposits to underside of a subduction zone, as postulated in subduction-complex theory.

spect to the oceanic plates could similarly affect the movement of the triple junction.

Relative to the continental plate, then, the triple junction could (1) move in the same direction as the transform-fault-bounded oceanic plate but at the same or a lesser rate, thereby extending the length of the subduction zone; or (2) not move; or (3) move in the direction opposite (1), thereby extending the length of the transform fault.

Returning to our example (fig. 6) and its vectorial representation (fig. 5), it is convenient to consider the spreading ridge as simply a crack along which upwelling magma is plastered to plates B and C. From the vector diagram (fig. 5), we see that a point on this crack (P) must move 4 cm/yr toward N. 3° W., that is, toward triple junction  $J^5$  (fig. 6). Hence the crack, or spreading ridge, is being shortened at a rate of 4 cm/yr.

The vector  $C_J$ , which represents the direction and rate that plate C moves with respect to the triple junction J, trends N. 34° E. Hence the edge of the subducted slab (dotted line in fig. 6A) must also trend N. 34° E. (ignoring the effects that curvature, dip, partial melting, deformation, and other processes might have on the outline of the subducted slab as projected to the surface). To clarify this picture, we define three points that initially are superimposed on triple junction  $J^5$  in figure 6A. Point R is attached to plate B, point S to plate C, and point Q is fixed with respect to the crack (spreading ridge). At this instant in time, a brief magnetic polarity change is recorded in the cooling basalt along the ridge system, forming anomaly 5.

After an interval of time, the plate geometry will have evolved to that portrayed in figure 6B. Relative to plate A, point R has moved 6 cm/yr to N. 40° W., point S has been subducted and moved 5.4 cm/yr to N. 24° E., where it lies on the N. 34° E.-trending edge of the subducted part of plate C. The triple junction has moved from  $J^5$  to  $J^4$ , and point Q now lies on an imaginary prolongation of the crack (spreading ridge), which has been shortened at the rate of 4 cm/yr. Anomaly 5 is visible alongside the spreading ridges. The length of that anomaly in plate C, including the part that has been subducted, equals its length in plate B.

The evolution of this plate geometry is followed through four more time periods, assuming no changes in spreading rates, in figures 6C, 6D, 6E, and 6F. Note that the triple junction and the leading edge of the subducted slab move steadily northwest, until the ridge-ridge transform fault forming part of the boundary between plates B and C intersects the margin of plate A. At that time, the velocity of the triple junction with respect to plate A abruptly accelerates from 1 cm/yr to 6 cm/yr, and there is a concomitant acceleration and change in outline of the leading edge of the subducted slab.

Consider now the space problems that arise if the triple junction and leading edge of the subducted slab are forced to migrate laterally along the margin of the continental plate. If, as in the example given, the subduction zone is extended at the expense of the transform fault bounding the continental plate, the descending plate must incrementally displace the wedge-shaped volume of lithospheric material partly bounded by the transform, the base of the continental plate, and the laterally projected surface of the subduction zone (fig. 7). As shown in figures 6 and 7, the space problem may be exacerbated while a ridge-ridge transform fault is subducted.

Because of its buoyancy, the displacement of the volume of crustal material involved must be accomplished by the plowing up and ramming back of the lip of the continental plate above and ahead of the advancing prow of the subducting slab (fig. 8). Thus elevated,

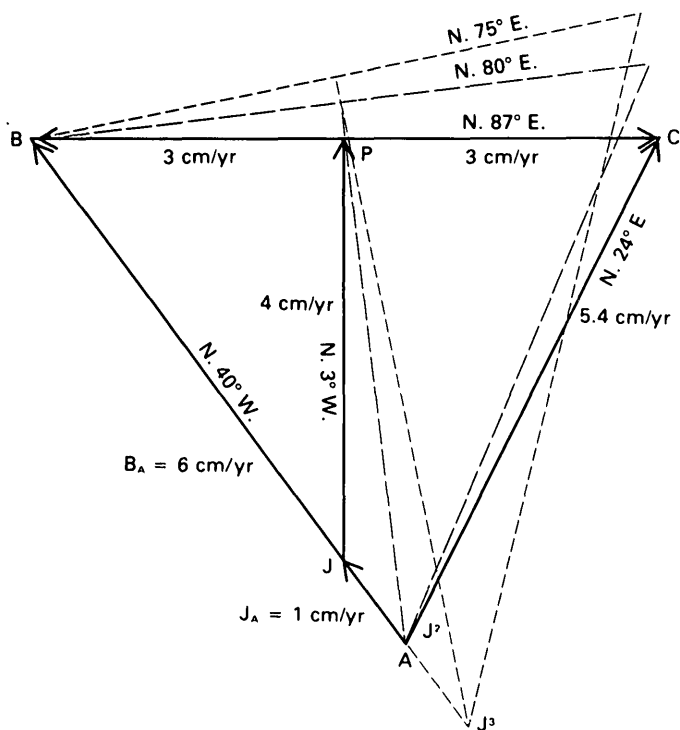


FIGURE 5.—Vector circuit representing the relative movement of three plates, A, B, and C, at a ridge-transform fault-subduction zone triple junction (J) that is stable in the sense of McKenzie and Morgan (1969) and at which the three plates are in mutual contact. A point on the spreading ridge is represented by P. The direction of spreading is orthogonal to the ridge, and the rate of spreading symmetrical with respect to the ridge. Three cases are represented; in all, plate B moves N. 40° W. at 6 cm/yr with respect to plate A, and the spreading rate at the ridge is also 6 cm/yr. Case 1 (solid lines): plate C moves N. 87° E. with respect to plate B; case 2 (long-dashed lines): plate C moves N. 80° E. with respect to plate B; case 3 (short-dashed lines): plate C moves N. 75° E. with respect to plate B.

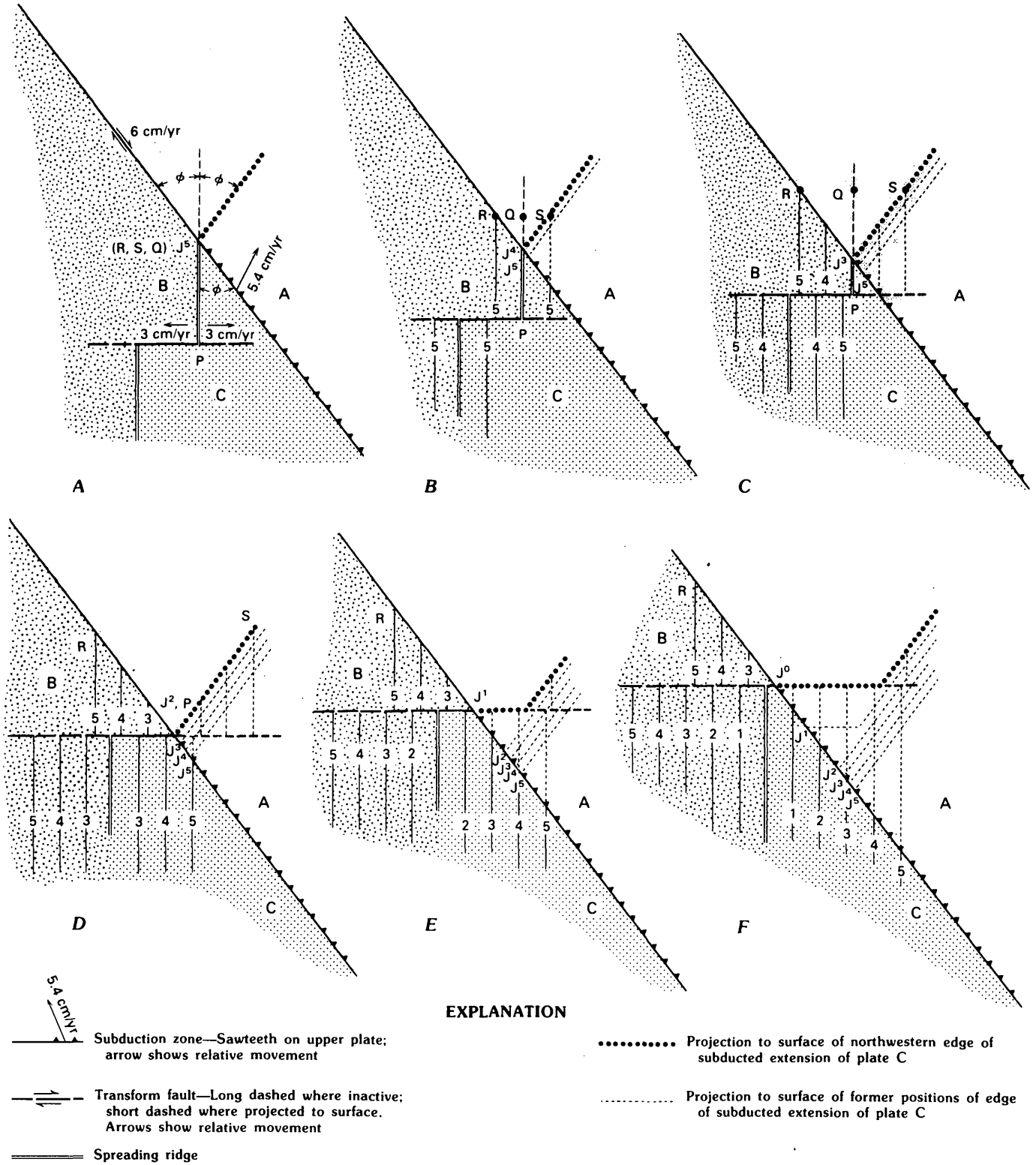


FIGURE 6.—Evolution of plate geometry at a triple junction between three plates A, B, and C. Spreading rates, nomenclature, and assumptions are same as those in figure 5 (case 1). A, Initial configuration of the three plates. B, C, D, E, and F, Configuration after lapse of successive and equal increments of time. Movement and growth of plates B and C are shown with respect to plate A, arbitrarily held fixed. Dotted line, projection to surface of northwest edge of subducted extension of plate C. Former positions of this edge are shown in B through F by fine-dotted lines. Numbered lines 5, 4, 3, 2, and 1 represent magnetic anomalies formed at the time of frames A, B, C, D, and E, respectively, shown as solid lines at surface of plates B and C; dotted lines, where subducted beneath plate A.  $J^5$ ,  $J^4$ ,  $J^3$ ,  $J^2$ ,  $J^1$ , and  $J^0$  represent location of triple junction at time of successive frames A, B, C, D, E, and F, respectively. R, Q, S, points mentioned in text.

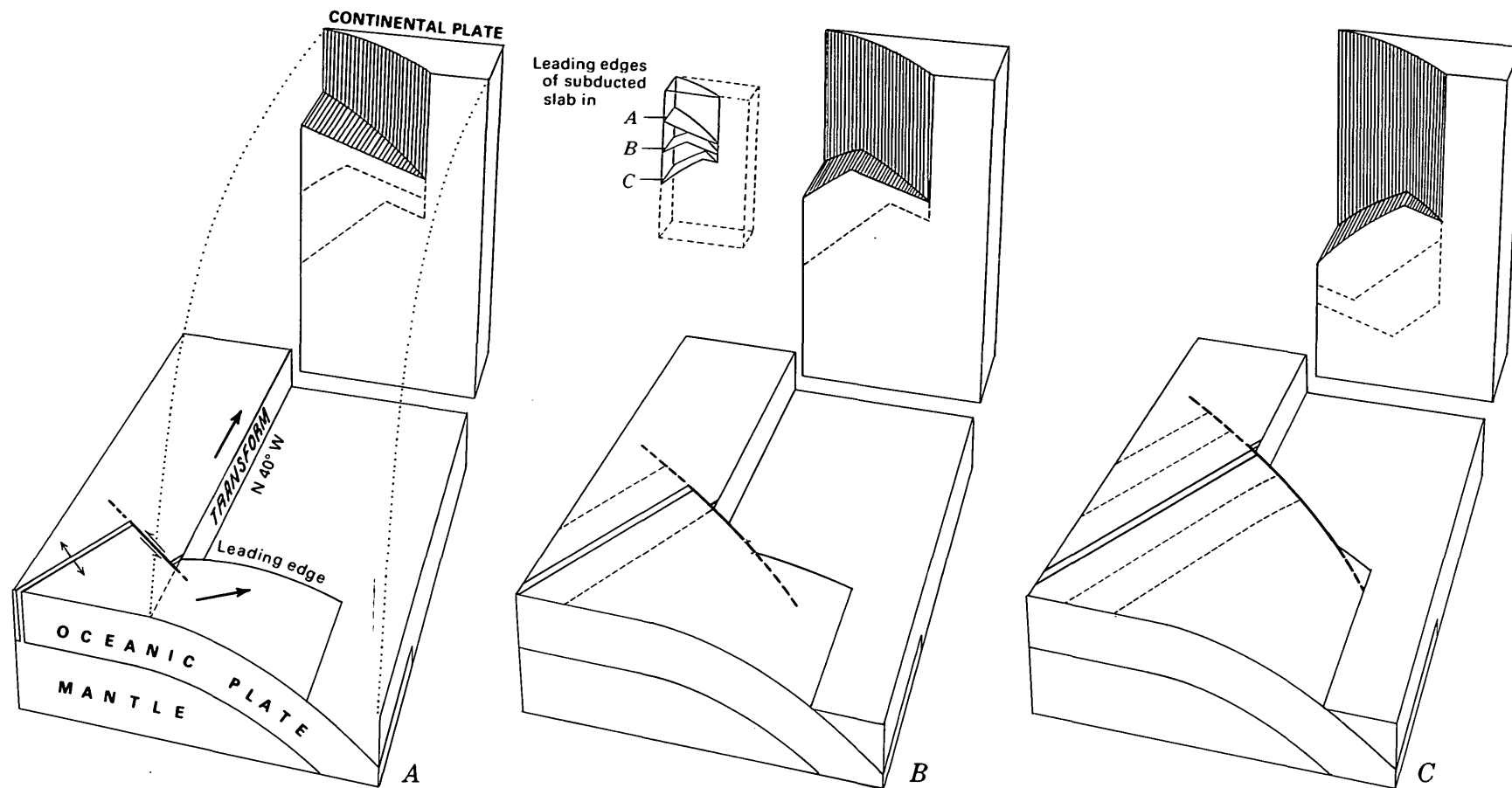


FIGURE 7.—Diagram showing progressive advance of Humboldt-type triple junction along a continental plate (tilted back) and volume of material that must be displaced during this advance. Although rates of spreading, subduction, and right-lateral movement are constant, intersection of ridge-ridge transform with transform fault between oceanic and continental plates exacerbates space problem. *A*, Tiny segment of spreading ridge north of ridge-ridge transform will vanish as spreading continues. Dashed lines on underside of continental plate show position of leading edge of subducted slab reached in *B* and *C*. Thin arrows show spreading directions, thick arrows direction of movement of oceanic plates relative to continental plate; *B*, Truncation of subsurface part of continental plate accelerates as triple junction evolves to transform-transform-subduction zone configuration. Magnetic anomalies generated at *A* shown by long-dashed lines in oceanic plates; *C*, Ridge again intersects transform boundary with continental plate. Dotted lines on underside of continental plate show successive positions of leading edge of subducted slab at future time intervals equivalent to those between *A*, *B*, and *C*.

the lip of crustal material will probably slough away as subhorizontal gravity slides, imbricated thrust fault slices, and intercalated melange and broken formation (Fox, 1976).

A triple junction whose movement is associated with the lateral advance and impingement of the subducted slab on space occupied by the continental plate, resulting in the displacement of parts of the continental plate by the subducted slab, has been defined as a Humboldt-type triple junction (Fox, 1976). Two other situations can be visualized. In one, the triple junction does not perceptibly move relative to the continental plate. With time, the tectonic situation at the margin of that plate will stabilize, with a strike-slip regime to one side of the triple junction and a subduction regime to the other side.

Alternatively, if the triple junction moves in such a way that the transform fault bounding the continental plate is extended at the expense of the subduction zone, then the wedge-shaped space formerly occupied by the obliquely descending lithospheric plate must be filled through upwelling of mantle or by accordion-folding of lithospheric material. This type of triple junction has been defined as a Mendocino-type (Fox, 1976).

#### AGE AND DISTRIBUTION OF MELANGES AND RELATED ROCKS

Melanges of late Mesozoic and possible early Tertiary age recognized along the western margin of the North American plate (fig. 3) have been cataloged by Jones and others (1978). Exclusive of melanges in Alaska, which are outside the scope of the present study, the melanges include those of the Franciscan Complex in California and its presumed correlatives in Oregon and the Baja Peninsula of Mexico and melanges on both the San Juan Islands of Washington and the west coast of Vancouver Island, British Columbia. To

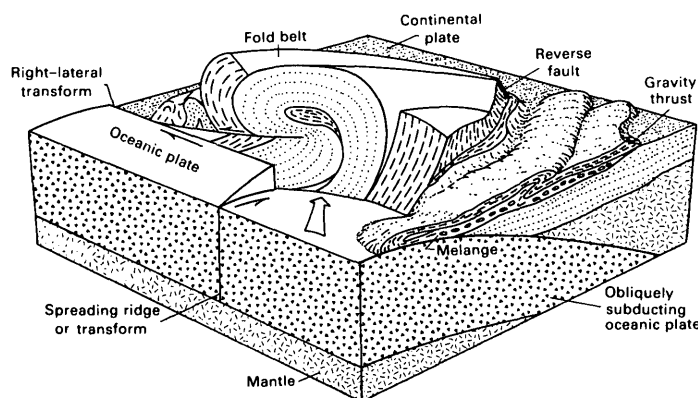


FIGURE 8.—Diagram showing formation of fold belt, thrusts, gravity thrusts, and melanges at Humboldt-type triple junction.

these must be added the melanges of the Olympic Peninsula of Washington, reported to be of Eocene (Snively and Pearl, 1975; Snively and others, 1977), and Miocene age (Rau, 1975). The melanges of the Olympic Peninsula, because of their relative youthfulness, permit comparison of the plate-tectonic situation that prevailed at the time of their formation, as deduced from the magnetic lineations of the northeastern Pacific, with that predicted by the subduction-complex and triple-junction theories.

The Olympic melanges occupy part of the northern end of a 640-km-long coastal strip apparently underlain by oceanic crust composed chiefly of tholeiitic basalt and subordinate volcanoclastic sediments (Snively and others, 1977, p. 9). The oceanic crust is early and middle Eocene and was probably accreted to the craton in middle Eocene or later time (MacLeod and others, 1977, p. 226). Melanges are not found outside the Olympic Peninsula within this volcanogenic borderland, but because its history forms an important link in the story of interaction between oceanic and continental plates, its geology is briefly outlined below.

The San Onofre Breccia (Woodford, 1925), though not a melange, is briefly mentioned because its origin may be related to the plate interactions that are the main concern of this paper. Correlation of these rocks with a particular tectonic setting is deferred to the section below entitled "Main Elements of Melanges and \*\*\*."

#### SAN ONOFRE BRECCIA

The San Onofre Breccia consists of sandstone, conglomerate, and breccia, together aggregating at least 795 m in thickness (Woodford, 1925, p. 185). The deposit is unusual in two respects, first because it contains angular blocks of blueschist and other crystalline rocks as much as 4.6 m long (Woodford, 1925, p. 186); second, because, though interlayered with marine deposits derived entirely from the craton to the east, the breccia itself was derived through erosion of a briefly emergent submarine source area to the west (Woodford, 1925 p. 236-239). The deposit formed as a subaerial alluvial fan and bordering shallow-water marine-fan and delta complex in late Saucian, Relizian, and Luisian(?) stages of the Miocene (Stuart, 1976).

#### OLYMPIC PENINSULA AND OREGON-WASHINGTON BORDERLAND

Between Bandon, Oreg., and Vancouver Island, British Columbia (fig. 9), the continent is bordered by a 200- to 300-km-wide strip in which the apparent basement rock is chiefly tholeiitic basalt of early and middle Eocene age, overlain by younger volcanic and volcanoclastic strata (Snively and others, 1966). This area, here

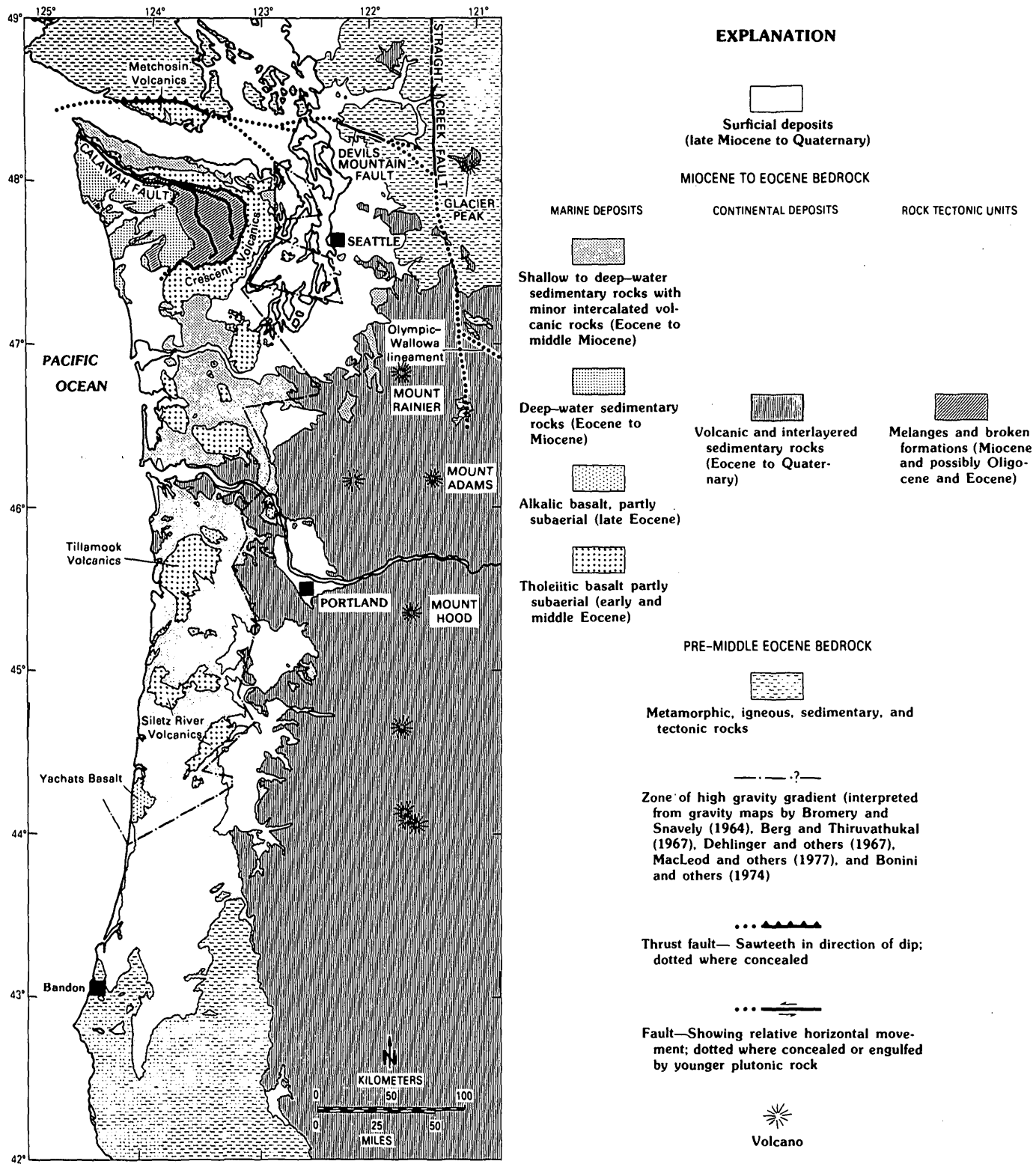


FIGURE 9.—Geologic map of western Oregon and Washington. Chiefly from Hunting and others (1961), Wells and Peck (1961), Bromery and Snavely (1964), MacLeod and others (1977), and Tabor and Cady (1978b).

referred to as the Oregon-Washington borderland, underlies only the western part of an early and middle Tertiary eugeosyncline (Snively and Wagner, 1963) that also included the area to the east underlain by fringing shelf deposits of eugeosynclinal aspect.

As pointed out by Bromery and Snively (1964, p. N-1), the contrast between the high density of the basement rock and the lower density of the superjacent sedimentary rocks makes feasible the mapping of the basement surface through gravity surveys. Gravity maps by Bromery and Snively (1964), Bonini and others (1974) and MacLeod and others (1977) confirm the coincidence of positive gravity anomalies with areas in which the tholeiitic basement rocks crop out. These anomalies are bounded on the east by zones of steep negative gradients, here assumed to represent the contact in the subsurface of oceanic crust with less dense crustal material of the craton (fig. 9). The zones of high gradient appear to be segmented, though linear within individual segments. Considering the smoothing effect of the gravity-measurement and map-contouring process, the actual contact is probably angular and in some areas jagged.

The Eocene basalt includes, from south to north, the Siletz River Volcanics (Snively and others, 1968), the Crescent Formation (Arnold, 1906), and the Metchosin Volcanics of Clapp (1910) (Snively and others, 1966, p. 456). These volcanic rocks apparently are chiefly Ulatisian (late early and early middle Eocene) in age (Rau, 1964, p. G-4; Snively and others, 1968, p. 467). The Siletz River Volcanics has been dated at 49.3 to 54.7 m.y. by potassium-argon methods (Duncan, 1977).

The volcanic rocks generally include a thick lower member of marine pillow basalt and interbedded deep-marine sediments, locally overlain by an upper member of shallow-water to subaerial tholeiitic or alkalic basalt, the whole aggregating as much as 15 km in thickness (Cady, 1975, p. 575). According to Snively and others (1968, p. 480), the lower part of the Siletz River Volcanics rose from the mantle along north-trending fissures.

Sedimentary rocks interlayered with basalt of the Crescent Formation contain clasts of continental provenance including boulders of quartz diorite as much as 3 m in diameter, suggesting proximity of the basalts to the North American continent at the time of their extrusion (Cady, 1975, p. 579). In Washington, the Crescent basalt is conformably overlain by, or intertongues with, a sequence of deep-marine clastic sediments mapped as the Aldwell and overlying Lyre Formations (Olympic Peninsula) or McIntosh and overlying Northcraft Formations (southwestern Washington) of upper Ulatisian to middle Narizian (middle and early late Eocene) age (Rau, 1964, p. G-4; Snively and others, 1958, p. 17-22).

These units are unconformably overlain by shelf deposits, the unconformity marking a significant orogenic episode in the opinion of Snively and others (1977, p. 7, 20).

In Oregon, the Siletz River Volcanics underlies the Tyee Formation, a 3,000-m-thick sequence of rhythmically interbedded sandstone and siltstone of continental provenance deposited by northward-flowing turbidity currents (Snively and Wagner, 1963, p. 7). The Tyee is in turn overlain by the late Eocene Yachats Basalt (Snively and McLeod, 1974).

The pre-Pliocene bedrock of the Olympic Peninsula (fig. 9) is broadly composed (Tabor and Cady, 1978a) of peripheral rocks and core rocks. The peripheral rocks consist of a thick stratiform sequence of Eocene to Miocene age, which, though folded and faulted, is essentially stratigraphically intact (compare Glassley, 1974, p. 786). In contrast, the core rocks, though also of Eocene to Miocene age, consist of rocks that have been tectonically disrupted, forming a mass in which melanges and broken formations are imbricated and infolded with fault-bounded blocks and slivers of intact strata.

The peripheral rocks consist of tholeiitic basalt of the Crescent Formation and interfingering deep-water clastic deposits. Except for the northwestern part of the peninsula, these rocks are overlain by a succession of shallow-water marine shelf deposits. In contrast, the core rocks consist of bathyal marine turbidite deposits.

Melanges of the northwestern core are "composed of sheared middle Eocene basalt, large infolded blocks of turbidite sandstone, and broken formation" according to Snively and Pearl (1975). These rocks are positionally overlain by deep-water marine siltstone and sandstone of latest Eocene to middle Miocene age, and the sequence is itself strongly deformed and unconformably overlain by tilted strata of latest Miocene and Pliocene age (Snively and Pearl, 1975).

Melanges in the west-central part of the core zone are described by Rau (1973, p. 5) as part of the Hoh rock assemblage, which, in addition to melange, contains much-deformed turbidite deposits, chiefly rhythmically interbedded and graded sequences of siltstone, sandstone, graywacke, and conglomerate. Most of the foraminiferal assemblages contained within these deposits indicate deposition at no less than upper bathyal depths (Rau, 1975). The melanges typically are composed of blocks or slabs of sandstone, graywacke, or conglomerate embedded in a matrix of much-sheared siltstone. The blocks commonly are as much as a meter or more in length; and Rau (1973, p. 8), in his excellent descriptions and photographs of the melanges, noted that the blocks include some as large as houses and some even larger ones that form sea stacks, promontories,



and small islands. The slabs range to several kilometers in length and appear to be "floating" in melange (Snively and others, 1977, p. 21).

At the seacliff exposures to which the I was directed by W. W. Rau, the blocks are angular to nearly equant and faceted. Outer surfaces are polished and commonly striated, and the blocks, though essentially intact, are crisscrossed by fractures. The melange locally contains zones composed predominantly of sandstone or graywacke that is sheared ubiquitously but not penetratively at hand-specimen scale. Exotic clasts of greenstone are present in the melange, but blueschist and eclogite have not been reported.

The foraminifers of the Hoh rock assemblage have been extensively collected and studied by W. W. Rau. The following paragraph summarizes his findings (in Rau, 1975):

Foraminifers, though rare, have been collected from 50 localities within the Hoh rock assemblage. Most of these fossils suggest either an early or middle Miocene age (Saucesian or Relizian Stages of Kleinpell, 1938) of deposition; a middle Eocene assemblage was found at one locality and a late Eocene at two. Some of the youngest assemblages (five localities) suggest a Relizian age, and one very poorly preserved assemblage tentatively suggests an age as young as late Miocene. Collections from the melanges themselves suggest upper Saucesian to possibly Relizian (middle Miocene) age. The single significant megafossil assemblage found indicates an early or middle Miocene age, according to W. O. Addicott (cited by Rau, 1975).

The Hoh rock assemblage is beveled by an angular unconformity and on land is overlain by the late Miocene(?) and Pliocene Quinault Formation, flat-lying siltstone, sandstone, and conglomerate (Rau, 1975). Offshore, according to Rau (1975), late Miocene strata are at least in places present between the structurally complex rocks of early and middle Miocene age and the strata of Pliocene age.

The eastern core rocks have recently been described by Tabor and Cady (1978a) as consisting of shale, siltstone, sandstone, and minor conglomerate, basalt, basaltic volcanoclastic rock, diabase, and gabbro, varying metamorphosed to slate, semischist, phyllite, greenstone, and greenschist. These rocks range from faulted or shear-zone bounded, but intact, bedded sequences to completely disrupted broken formations composed of sandstone or semischist clasts embedded in a matrix of slate or phyllite. Exotic clasts such as blueschist or eclogite have not been found. The rocks are multiply cleaved and lineated, and both bedding and cleavage have been folded and refolded.

Fossils are very rare; those found range from early Eocene to early Oligocene. An intensive investigation of

the potassium-argon geochronology of the northeastern core led Tabor (1972) to conclude that the age of regional metamorphism was about 29 Ma and the age of a later episode of faulting and quartz veining about 17 Ma. Measured ages (66 reported determinations) range from 16.2 to 227.4 m.y. (Tabor, 1972, table 1), with an apparent inverse correlation between metamorphic grade and age. Potassium-argon ages of graywacke and semischist range downward to about 29 m.y. This lower limit was defined by three samples from which separates of matrix material yielded ages of  $31.2 \pm 0.6$ ,  $29.1 \pm 0.9$ , and  $29.0 \pm 0.7$  m.y.; separates of coexisting clast material yielded corresponding ages of  $35.2 \pm 0.7$ ,  $36.2 \pm 0.9$ , and  $39.1 \pm 1.3$  m.y. Considering the possibility of imperfect separation and consequent cross-contamination of matrix and clast material, noted by Tabor (1972, p. 1810), it seems probable that the age of pure metamorphic matrix material is significantly less than 29 Ma.

The potassium-argon age of slate and phyllite ranged down to 27 Ma. The 10 determinations of the age of phyllite breccia, however, clustered at about 17 Ma and ranged from 16.2 to 19.9 Ma. The samples of breccia are from widely scattered localities, some adjacent to outcrops of rocks giving much older ages (Tabor, 1972, p. 1811, fig. 10).

Core rocks are separated from peripheral rocks by a curving system of observed and inferred faults and shear zones following or splaying away to the inside of the Olympic horseshoe (fig. 9). On the north, the system includes the Calawah fault, which diverges westward from the inferred shear system between peripheral and core rocks, cutting through the core rocks as a zone locally more than a kilometer and a half wide (Gower, 1960; Tabor and Cady, 1978a). Gower (1960) inferred that the zone was a left-lateral strike-slip fault. MacLeod and others (1977, p. 227) concurred in this opinion, noting that major differences in lithology and provenance of Eocene deep-water marine sandstone north and south of the fault suggest strike-slip offset. They concluded that because of this lithologic contrast and the wide zone of shearing, offset was probably substantial.

Tabor and Cady (1978a), after analyzing the structural fabric, concluded that the parental rocks of the core were isoclinally folded, then faulted, imbricated, overturned westward, and pressed by east-west compression into the basaltic horseshoe. The horseshoe could have formed by this deformation, or it could have been already in existence. Continued compression caused the core rocks to yield upward and outward by shear folding, forming a "mushroom-like dome" (Tabor and Cady, 1978a).

The age, or ages, of the deformation of the core, zone rocks is critical to any understanding of their origin. In the eastern core, the age of some or all of the

broken formation and of the most recent tectonism must be late Oligocene or younger, on the basis of Tabor's (1972) potassium-argon age study. Tabor's work establishes a strong presumption that these rocks were metamorphosed after 29 Ma and finally cooled through the blocking temperature of fine-grained mica about 17 Ma. In Tabor's opinion, the potassium-argon age data suggest two events, the ages of which are closely approximated by the clusters of potassium-argon ages at 29 Ma (late Oligocene) and 17 Ma (early Miocene).

The melanges of the Hoh rock assemblage of the western core must be entirely or in part at least as young as the youngest fossils found within them, that is, possibly Relizian. This age would imply a maximum age of about 16 m.y. (time scale of Van Eysinga, 1975). The presence of little-deformed late Miocene sediments unconformably resting on the western core rocks similarly places a younger age limit of at least 5 m.y. on the age

of the most recent deformation. That there was at least one previous episode of major deformation is indicated by the presence of latest Eocene sediments depositionally overlying melange containing middle and early Eocene rocks (Snively and Pearl, 1975).

In summary, the deformation of the core-zone rocks was apparently episodic, not continuous. Snively and Pearl (1975) had suggested that the core rocks reflected two major orogenic events, the first of which was in late middle or early late Eocene, the last in middle Miocene. Their conclusion, insofar as it applies to the western core, seems amply sustained by the available evidence. Tabor's age data suggest that deformation of the eastern core during the last orogenic event ended in latest early Miocene time and further may point to the existence of a third major event of late Oligocene age. Confirmation of the late Oligocene event should be sought in the stratigraphic record.

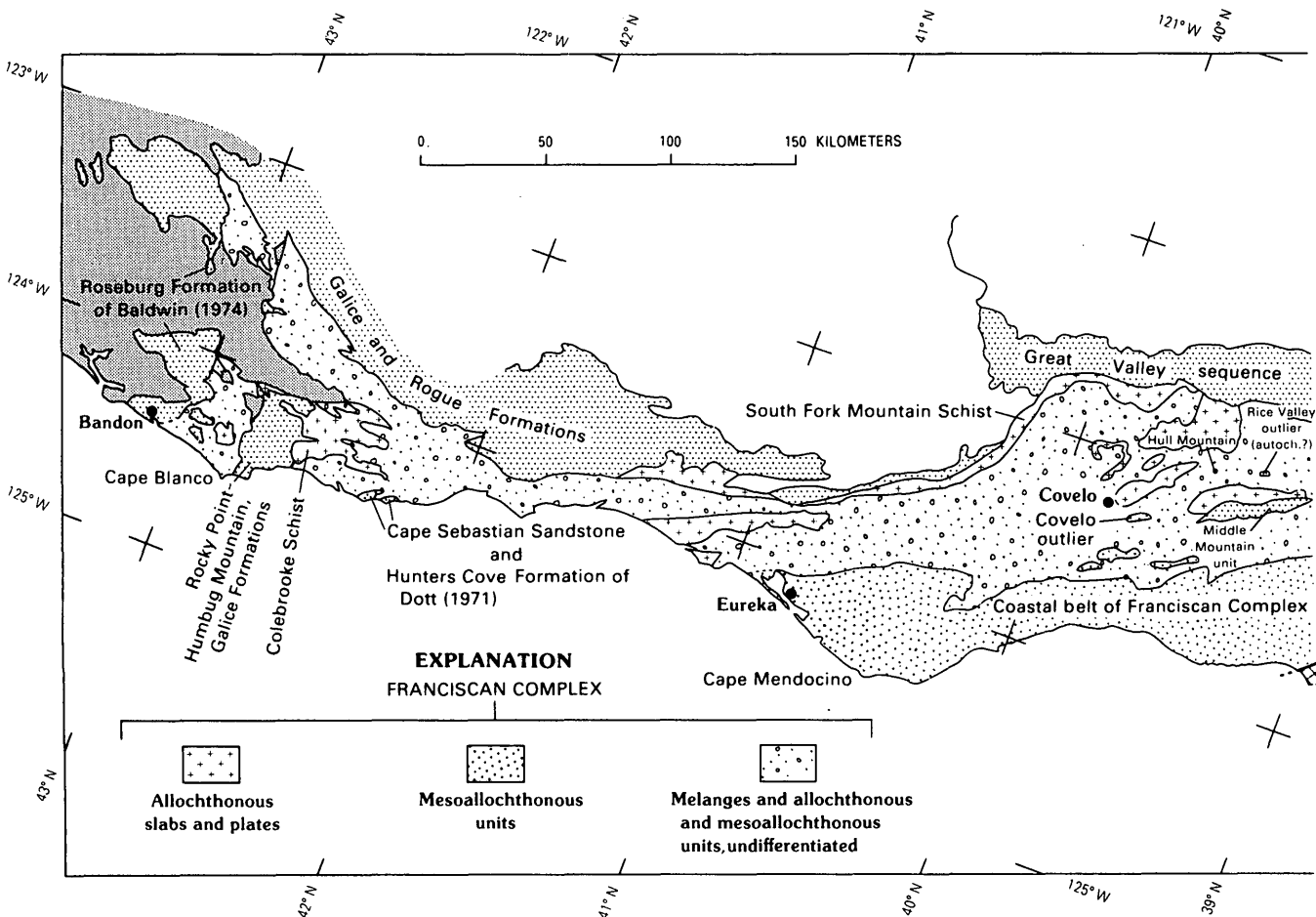


FIGURE 10.—Sketch map showing tectonic classification following Hsu (1969) (see also Hsu and Ohrbom, 1969) of the Franciscan Complex and associated rocks of western California and southwestern Oregon. Modified chiefly from Jennings (1977) with additions from Coleman (1972), Baldwin (1974), Dott (1971), and Beaulieu and Hughes (1976).

**FRANCISCAN COMPLEX, FRANCISCAN ASSEMBLAGE,  
GREAT VALLEY SEQUENCE,  
AND CORRELATIVE ROCKS**

**SEMANTIC DISTINCTION  
BETWEEN FRANCISCAN COMPLEX  
AND FRANCISCAN ASSEMBLAGE  
AND THE RELATION OF THESE ROCKS  
TO THE GREAT VALLEY SEQUENCE**

The late Mesozoic and early Tertiary rocks underlying much of the western seaboard of central and northern California are collectively referred to as the Franciscan assemblage (Bailey and others, 1964, p. 11) or Franciscan Complex (Berkland and others, 1972). Although these names are applied to nearly the same rocks, the Franciscan assemblage and the Franciscan Complex embody different stratigraphic concepts and are therefore not synonymous. The Great Valley sequence borders

the Franciscan Complex on the east, and similar rocks are found in isolated areas surrounded by the Franciscan Complex (fig. 10).

The semantic distinction between the age of the assemblage and that of the complex is like that between the age of the trees in a forest or several forests and a house built from those trees. The trees might be of various ages within a discrete range; after cutting, sawing, planing, assembling, and nailing, the result is a new entity, a house, whose age is less than that of any of its components. Thus when we refer to the Franciscan Complex, we refer to the "house"; when we refer to the Franciscan assemblage, we refer to the "trees" from which the house was built. The problem is more complicated than this, in that like a house to which various wings have been added at various times, the Franciscan Complex has been built in various stages, places, and times.

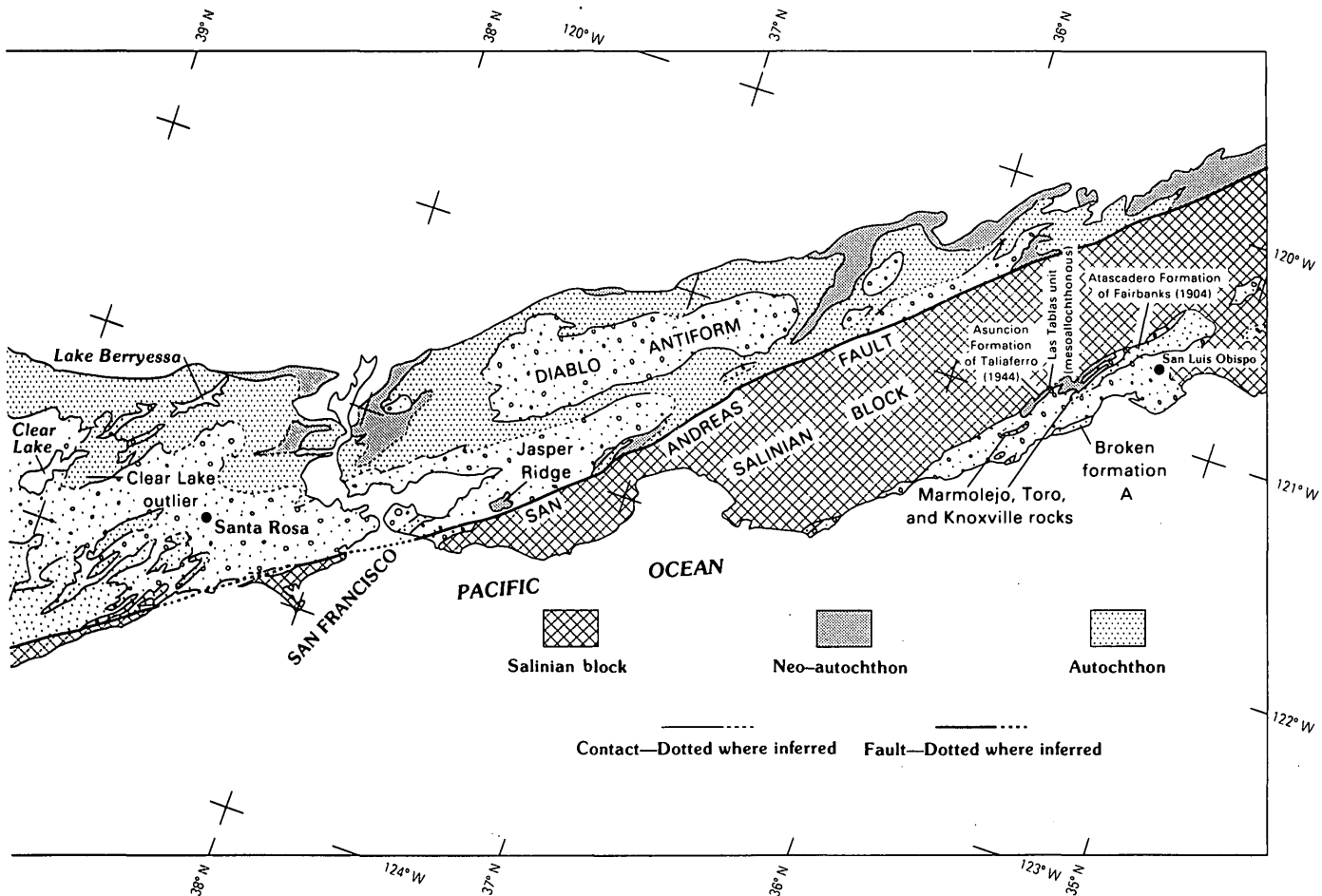


FIGURE 10.—Continued

The Franciscan Complex is a structural aggregation of rocks in which fault slices and blocks of relatively intact bedded deposits are imbricated and interwoven with shear zones, melanges, and broken formations. The structural fabric of the unit, dominated by subparallel to anastomosing fracture surfaces, closely spaced in the melanges and broken formations and widely spaced in the tectonic slabs and blocks, along with accompanying fragmentation and granulation, is the chief diagnostic feature of the complex. Berkland and others (1972, p. 2297) stipulated that the Franciscan Complex was the *basement* terrane of the California Coast Ranges, and their assignment of some rock units to the complex was partly based on an interpretation of whether or not they constituted part of the local basement (1972, p. 2299). As noted in an earlier paper (Fox, 1976, p. 740), the Franciscan Complex is probably not basement in some, and perhaps much, of its area of outcrop. Except for that element requiring it to be a basement terrane, Berkland and others' (1972, p. 2297) name "Franciscan Complex," with their definition of it, is here adopted in place of the name "Franciscan Formation."

The parental rocks were chiefly massive graywacke interbedded or interlayered with siltstone, conglomerate, bedded chert, greenstone, and locally limestone. During their structural disruption, slabs of serpentine, greenstone, and ophiolitic rocks were tectonically introduced into the complex. These rocks were zeolitized and locally metamorphosed to low-grade blueschist, greenschist, or amphibolite. In addition, high-grade blueschist and eclogite of enigmatic origin is present in the melanges as ubiquitous, though commonly widely scattered, exotic clasts.

The term "Franciscan assemblage" (Bailey and others, 1964, p. 11) is an informal designation collectively applied to various lithologies that make up the Franciscan Complex as defined above. Bailey and others (1964, p. 148) stressed that their so-called Franciscan rocks are sheared, disrupted, and deformed, but did not imply that the resulting structural fabric is a diagnostic part of their concept of the lithologic entity they designated an assemblage. Though only sparsely fossiliferous, the assemblage does contain scattered fossils of Late Jurassic, Cretaceous, and early Tertiary age (Irwin, 1957; Bailey and others, 1964; Blake and Jones, 1974). It is therefore correct to say that the Franciscan assemblage, as indicated by the available fossil evidence, ranges in age from Late Jurassic to early Tertiary, since by "age" we mean depositional age of the various parts of the assemblage.

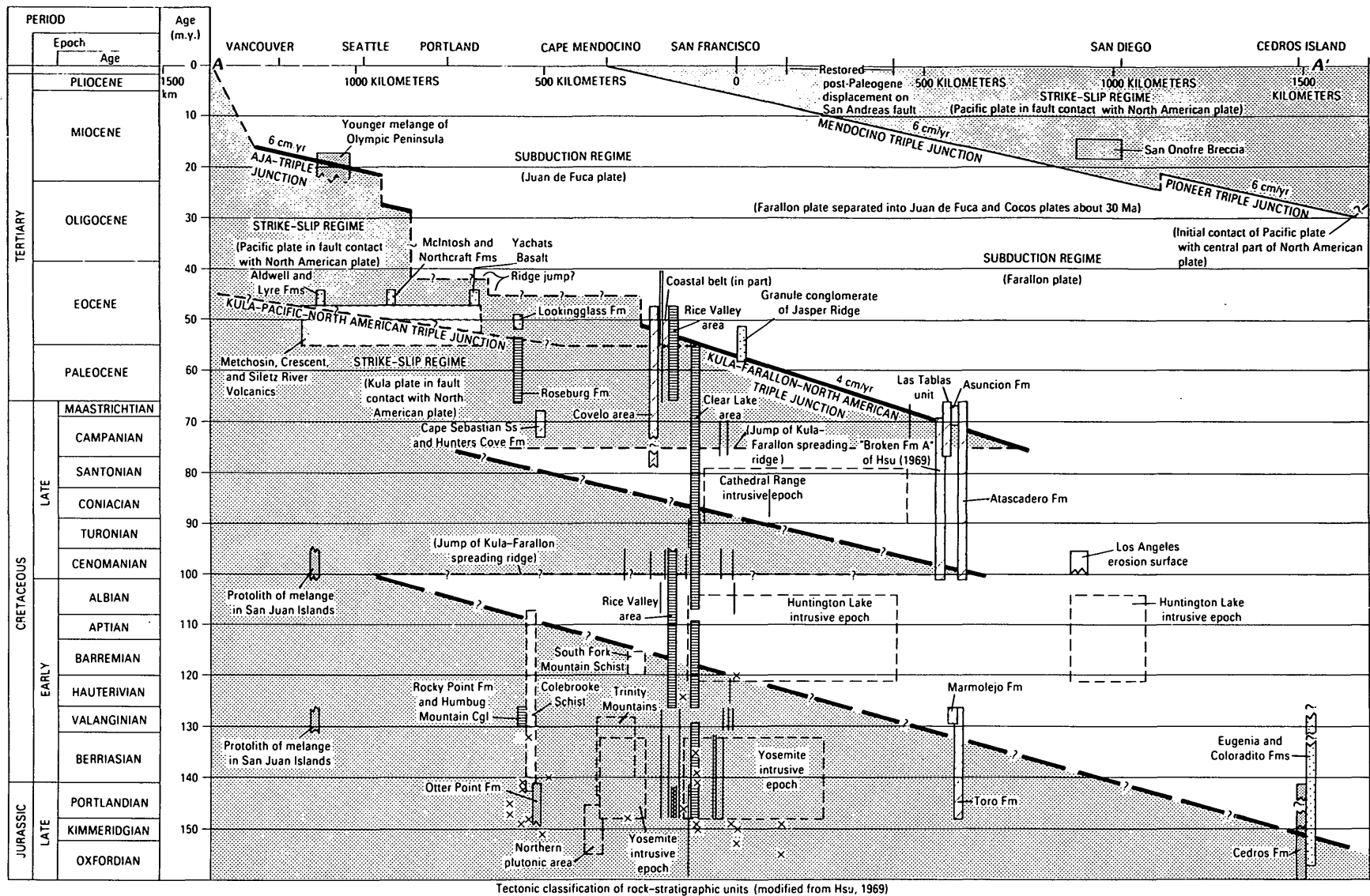
The Franciscan Complex is defined as a structural complex, a rock-stratigraphic unit according to Article 6j of the "Code of Stratigraphic Nomenclature" (American Commission on Stratigraphic Nomenclature, 1974)

though there seems to be a difference of opinion on this point (compare Berkland and others, 1972, p. 2299), and its age is that of its diagnostic structural fabric; its age at any given place is that of the deformation that produced the melanges and tectonic disruption characteristic of the complex. The older limit of that age is the age of the youngest fossils locally present (R. W. Kopf, written commun., 1976). Contrary to the opinion of Berkland and others (1972, p. 2300), the presence of fossils of Late Jurassic to early Tertiary age does not necessarily mean that the complex has a comparable range in age (melange rule three of Hsu, 1968, p. 1067). The deformation is penetrative with respect to the complex as a whole, though not necessarily at hand-specimen or even outcrop scale, a feature that could lead to difficulties in the practical application of this definition. More recent faulting and folding without this grossly penetrative aspect may displace the Franciscan Complex but is not considered part of its distinguishing structural fabric.

As defined by Berkland and others (1972, p. 2299) the Franciscan Complex geographically occupies three belts, an eastern belt, a central belt, and a coastal belt. In the eastern belt, the rocks are dominantly metaclastic and have a strong to barely perceptible schistosity. In the central belt, the dominant lithology is melange. The coastal belt, originally recognized and roughly delineated by Bailey and others (1964), contains graywacke, shale, and conglomerate but only a little greenstone, chert, serpentine, and blueschist and is structurally deformed in a manner analogous to other parts of the Franciscan Complex (see Bailey and others, 1964, p. 13).

The ages given by Blake and Jones (1974, p. 351) for fossils and fossil assemblages from the Franciscan assemblage of northern California (fig. 11) range from Late Jurassic to Eocene. Except for those of Late Cretaceous and early Tertiary age, most of which were found in the coastal belt, the fossils were found either in the matrix of the melange or within allochthonous blocks and slabs.

Rocks included within the Great Valley sequence range in age from Late Jurassic (Tithonian) to Late Cretaceous, making them equivalent in age to some of the lithologic elements incorporated within the Franciscan Complex (Irwin, 1957; Bailey and others, 1964, p. 123-139; Berkland, 1973, p. 2396-2399). The Franciscan Complex and Great Valley sequence are not found in depositional contact with each other. Rather, the two units are faulted together, or are faulted against folded sheet-like bodies of serpentine and variably serpentized ultramafic rocks that separate the two units. In places, the basal part of the Great Valley sequence depositionally overlies these ultramafic rocks (Bezore, 1969; Bailey and others, 1970). Curiously, the metamorphic grade of



AGE AND DISTRIBUTION OF MELANGES AND RELATED ROCKS

Tectonic classification of rock-stratigraphic units (modified from Hsu, 1969)

**EXPLANATION**

- Allochthonous slabs and plates
- Mesoallochthonous unit
- Protolith of melange (age marks maximum age of episode of allochthonous deformation)
- Autochthonous unit put in contact with melange during episode of allochthonous deformation
- Neo-autochthonous unit

**FIGURE 11.**—Correlation of boundary regimes and petro-tectonic features along west side of North American plate. All features are projected vertically to reference meridian of oblique Mercator projection shown as line A-A' in figure 3. Note that the 315-km displacement postulated by Turner and others (1970) and Matthews (1973) between the Pinnacles Formation of Andrews (1936) and the Neenach Volcanics (P and N in fig. 3) along San Andreas fault has been restored. Boundaries between tectonic regimes defined as follows: heavy line (queried where very speculative), represents transit of Humboldt-type triple junction; thin line (queried where very speculative), transit of Mendocino-type triple junction; short-dashed line, other types of transitions. Light vertical lines represent age range of fossils found in the Franciscan Complex, chiefly from Blake and Jones (1974). Crosses represent potassium-argon ages of exotic clasts composed of eclogite or high-grade blueschist and found in Franciscan Complex, as reported by Coleman and Lanphere (1971). Stratigraphic nomenclature is taken from several sources and does not necessarily follow that of U.S. Geological Survey. Age range of rock units and other features discussed individually in text is shown by vertical bars or blocks (boundaries short-dashed where established by potassium-argon or rubidium-strontium dating). Correlation of periods, epochs, and ages with geologic time follows Van Eysinga (1975).

the Franciscan assemblage increases toward the contact with the ultramafic rocks, and in places so does the metamorphic grade of the Great Valley sequence (Blake and others, 1967, p. 3-6). These age and contact relations hypothetically result from underthrusting of the Franciscan Complex below the Great Valley sequence (Bailey and others, 1964, p. 163-165; Irwin, 1964; Blake and others, 1967, p. 6-7; Bailey and Blake, 1969, p. 148).

**HSU'S (1969) CONCEPT OF ALLOCHTHONOUS, MESOALLOCHTHONOUS, AUTOCHTHONOUS, AND NEOAUTOCHTHONOUS ROCKS**

Rarely, the conglomerates within the Franciscan Complex contain scattered pebbles of blueschist similar to the blueschist found as exotic blocks within the melange, indicating that these deposits were derived through erosion of a preexisting part of the Franciscan Complex (Cowan and Page, 1975). Also rarely, shelf deposits that appear locally to unconformably overlie the deformed rocks of the complex elsewhere have been broken, disrupted, and imbricated with melange and broken formation, thereby assuming the same structural fabric as the complex as a whole (Hsu, 1969). The Franciscan Complex, in some places, then, contains a record of at least two episode(s) of deformation and melange formation. The earlier episode(s) was in places followed by cannibalization of the structural complex and deposition of detritus from it on a surface eroded across it. This cycle was followed by another cycle of deformation and melange formation. The Franciscan Complex is in places the product of two and possibly more distinct cycles of sedimentation and deformation.

The concept of tectonic cycles was first articulated by Hsu (1969), who classified the rocks in the Morro Bay area as allochthonous, mesoallochthonous, autochthonous, and neoautochthonous. According to Hsu (1969, p. 12-13):

(1) Allochthonous rocks are those that have been deformed by overthrusting or by gravity sliding and have been transported for a considerable distance from their original site of deposition.

(2) Mesoallochthonous rocks are those rocks that were deposited upon an allochthonous basement and transported for a considerable distance from their original site of deposition during a later episode of allochthonous deformation. A mesoallochthonous slab may include only mesoallochthonous sediments, or it may include both the mesoallochthonous sediments and some of the basement that has been deformed by two or more episodes of allochthonous movements.

(3) Autochthonous rocks are those rocks that have not been transported from their original site of deposition.

(4) Neoautochthonous rocks are those rocks that were deposited upon allochthonous rocks after all allochthonous deformations had taken place.

**EVIDENCE BEARING ON THE AGE OF FORMATION OF THE FRANCISCAN COMPLEX**

In applying Hsu's (1969) concepts of allochthonous, mesoallochthonous, autochthonous, and neoautochthonous rocks to the Franciscan Complex (fig. 10), it is stipulated that: (1) the craton to the east be regarded as a fixed reference frame; (2) tectonic dislocations, lateral translation, and accretion as tectonostratigraphic terranes (Beck and others, 1980) of the lithospheric crust underlying or including the Franciscan Complex and Great Valley sequence before the Cretaceous be ignored; and (3) the mode of deformation of the allochthonous rocks include overthrusting, gravity sliding, and (or) any other process capable of forming the penetrative fabric of the Franciscan Complex.

The ages of the "allochthonous deformations" are bracketed by the ages of neoautochthonous and mesoallochthonous deposits and by the ages of mesoallochthonous and the parental autochthonous deposits.

Hsu's classification appears to be relevant to the lithologic contrast between rocks of the coastal belt and the blueschist-bearing melange of the central belt. The coastal belt contains fossils as young as late early Eocene (Orchard, 1978), yet is imbricated, penetratively deformed, and includes broken formations, evidence of one or more episodes of allochthonous deformation (Blake and Jones, 1974, p. 347).

The nature of the contact of coastal-belt rocks with the central belt is controversial. Kleist (1974) concluded that melange near Laytonville in the central belt was deposited on the coastal belt, but Kramer (1976, p. 4) found that the contact in the Fort Bragg-Willits area was a high-angle reverse fault. Kramer (1976, p. 4, 5) also found isolated remnants of the coastal belt depositionally overlying central-belt rock and speculated that the reverse relations reported by Kleist (1974) might have resulted from Tertiary and Quaternary landsliding.

Detailed mapping of the coastal belt is incomplete; it may be found that some of the Eocene rocks are neoautochthonous. Nonetheless, exotic tectonic blocks of blueschist and eclogite are absent or very rare except at the margins of the belt. The coastal belt was probably deposited after conclusion of the tectonic event or events that stirred the exotic blocks into the melange of the central belt and, assuming that the coastal-belt rocks depositionally overlie central-belt rocks at least locally, must be chiefly mesoallochthonous.

Blocks of foraminiferal limestone attributed to the coastal belt that contain Cenomanian fossils have been

tectonically mixed with central-belt melange (Blake and Jones, 1974, p. 350–351). Cenomanian fossils have been reported from "Franciscan" sandstone and questionable Cenomanian fossils from a metagraywacke unit (Hull Mountain belt) enveloped by melange (Blake and Jones, 1974). By these findings, fossils as young as Cenomanian are locally present along with blueschist blocks in the melanges of northern California. The episode of deformation during which these rocks were mixed together, then, occurred in Cenomanian or later time but probably before deposition of the bulk of the coastal belt.

Farther south, near Jasper Ridge, 50 km southeast of San Francisco (fig. 10), rocks comparable in age to those in the coastal belt appear to be neautochthonous. At this locality, greenstone and chert of the Franciscan Complex, along with serpentine that contains pods or blocks of blueschist, is overlain by a thick sequence of sandstone and siltstone, containing fossils of middle and late Eocene age (Pampeyan, 1970; Page and Tabor, 1967). The Franciscan rocks form the core of an appressed west-northwest-trending anticline defined by steeply dipping and locally overturned Eocene rocks that form the limbs of the fold. The Eocene rocks of the south limb include a conglomerate as much as 60 m thick that positionally overlies the Franciscan rocks (Pampeyan, 1970). A conglomerate is also present at the base of the middle and upper Eocene sandstone on the north side, but there it is much thinner, being only about 3 to 9 m thick (Pampeyan, 1970), and measurably older, for it contains a fauna suggesting a late Paleocene or early Eocene age (Graham, 1967). This conglomerate positionally overlies the nearby serpentine, and is composed of packed granule-sized Franciscan detritus, mainly greenstone, in a calcium carbonate cement (Page and Tabor, 1967; Graham, 1967).

Page and Tabor (1967, p. 5–8) observed that the superjacent middle and upper Eocene beds contain unusual chaotic zones consisting of "disordered mudstone containing isolated sandstone bodies which have been detached from formerly continuous beds and have been more or less haphazardly distributed in the mudstone matrix." They concluded that the chaotic beds probably formed through submarine sliding in the late Eocene but that the steep folding of the Eocene beds and their close proximity to the San Andreas fault might be suggestive of a tectonic origin. Because neither the granule conglomerate nor the overlying Eocene beds are penetratively sheared, these rocks are here tentatively considered neautochthonous (fig. 10). In this area, it appears that the Franciscan Complex had been tectonically formed, then exposed to erosion by early Eocene at the latest.

Search of the literature reveals three areas where Hsu's (1969) classification either has been applied or

could be applied on the basis of published descriptions: the Morro Bay area of central California, the Clear Lake-Covelo area of northern California, and the Bandon area of southern Oregon.

#### MORRO BAY AREA

In the Morro Bay area, Hsu (1969, p. 17–18) mapped a slab of broken formation ("broken formation A") composed in part of graywacke containing about 10–20 percent K-feldspar, a few granite clasts, and abundant Franciscan debris. Blocks of similar graywacke were found in a melange below this slab, justifying Hsu's designation of the unit as mesoallochthonous (Hsu, 1969, fig. 2, p. 13; Smith and Ingeroll, 1978). Two palynomorphs from two samples of shale interbedded with the graywacke in this slab were identified by W. R. Evitt (in Hsu, 1969, p. 18) and considered by him to be Late Cretaceous, most likely Campanian or older.

Approximately 15 km inland, Cowan and Page (1975, p. 1089) found recycled Franciscan detritus, including glaucophane-lawsonite schist, as clasts in a mass of sandstone, the Las Tablas unit, about 2.0 by 0.75 km in area, tectonically enveloped in Franciscan melange. Three palynomorphs (including the two species found in broken formation A) from three samples of shale intercalated with the sandstone were identified by W. R. Evitt (in Cowan and Page, 1975, p. 1093) and considered by him to be Late Cretaceous and, quite possibly but not necessarily, Campanian.

Rocks about 25 km southeast of the Las Tablas unit, mapped as the Atascadero Formation by Hart (1976), are composed of massive sandstone and conglomerate, along with bedded sandstone, siltstone, and mudstone. In this unit, according to Hart (1976, p. 15):

Internal deformation is widespread and locally intense. This includes: (1) pervasive shears in sandstone subparallel to the bedding; (2) pinched-off sandstone beds, including occasional boudins; and (3) pinching and swelling of mudstone beds. Some of the deformation may be of "soft rock" type (for example, slumping and sliding contemporaneous with deposition), but much of it is "hard rock" (as indicated by common microscopic shears and deformed grains in sandstone) and probably is the result of large-scale overthrusting or gravity sliding.

It appears, then, that these rocks have been affected by one or more episodes of allochthonous deformation. According to Hart (1976, p. 16), the Atascadero is probably Cenomanian or Turonian to late Campanian or Maestrichtian.

The oldest rocks in this area that are neither disrupted by penetrative shearing nor found as tectonic inclusions in the melanges make up the arkosic Asuncion

Formation of Taliaferro (1944), according to Hsu (1969, p. 25). Campanian and Maestrichtian fossils found in the upper part of this unit indicate the age of deposition (Taliaferro, 1944; Popenoe and others, 1960; Hsu, 1969, p. 25).

The most recent period of melange formation in this part of California appears to have been in Campanian time. The presence of mesoallochthonous deposits implies that there was at least one earlier period of melange formation.

The rocks of central California classified by Hsu (1969) as mesoallochthonous include rock units of Early Cretaceous age, mapped as part of the Marmolejo Formation by Taliaferro (1944). Fossils reported by Taliaferro (1944, p. 469) from the Marmolejo were assigned to the late Valanginian by Popenoe and others (1960, chart 10e, annotation no. 12, p. 1520), but according to Hsu (1969, p. 18), specimens of *Buchia* from the formation include both Late Jurassic and Early Cretaceous species. Hsu (1969) described these rocks as being evenly bedded siltstone and shale characterized by the preservation of stratal continuity, occurring both as large mappable slabs and tectonic inclusions too small to map. Hsu (1969, p. 16) correlated broken formation B, composed in part of graywacke commonly containing 2–5 percent detrital K-feldspar and conglomerate and sedimentary breccia containing clasts of glaucophane schist, with the rocks mapped as the Marmolejo by Taliaferro (1944) on the basis of their K-feldspar content. The designation of the fossiliferous Marmolejo as mesoallochthonous, rather than simply allochthonous, hinges on this correlation. Fossils were not found in broken formation B. If truly mesoallochthonous, an episode of tectonism in which blueschist exotics were incorporated in melange occurred prior to the deposition of the Marmolejo.

About 100 km southeast, the latest Jurassic and early Cretaceous (Valanginian) Toro Formation, as described by Hart (1976), seems to grade into melange. While evidence for a pre-Marmolejo and pre-Toro episode of melange formation is somewhat tenuous, there can be no doubt of one after deposition of these rocks.

#### CLEAR LAKE-COVELO AREA

Near Clear Lake, Swe and Dickinson (1970) described a succession of clastic sedimentary deposits, ranging in age from Late Jurassic to Late Cretaceous, that they correlated with the Great Valley sequence to the east. They postulated that these deposits, aggregating 10,700 m (35,000 ft) in thickness, along with lower Tertiary beds, represented outliers of imbricated sheets that were overthrust to the west onto the Franciscan assemblage, or that the Franciscan was underthrust to

the east below Great Valley rocks, and that these imbricated sheets were subsequently infolded with the Franciscan. The rocks correlated with the Great Valley sequence form four fault-bounded segments within which the strata appear to be conformable.

The lower Tertiary strata consist of a lower unit of sandstone and shale aggregating 1,300 m (4,230 ft) in thickness and an upper unit of conglomeratic sandstone aggregating 335–365 m (1,100–1,200 ft) in thickness (Brice, 1953, p. 28–30). These two units had originally been assigned to the Martinez (early Paleocene) and Tejon (late Eocene) Stages, respectively, by Dickerson (1914, 1916), but as Berkland (1973, p. 2391) reminds us, the “Tejon” beds were subsequently reassigned to the Meganos (late Paleocene) Stage by Clark and Vokes (1936, p. 856, fig. 2). The basal contact of the Paleocene beds was given careful attention by Swe and Dickinson (1970, p. 183). They found that the Paleocene strata are in thrust contact with underlying rocks correlative with the lower part of the Great Valley sequence. On this basis, they inferred that the Great Valley and Tertiary rocks were tectonically emplaced against Franciscan rocks after deposition of the lower Tertiary beds.

The thrusting may have produced a certain degree of mixing of Franciscan and Great Valley rocks, for Swe and Dickinson (1970, p. 171) observed such mixing in several areas. In one area, small fossiliferous thrust slices of the Great Valley sequence were caught up in the underlying Franciscan tectonic breccia. In another (1970, p. 169) the Great Valley is extensively sheared and intricately mingled with serpentinite breccia. In a third, highly deformed massive graywacke and pebble conglomerate mapped as the Franciscan assemblage lie on the strike of a 6½-km (4 mi)-long belt of graywacke and conglomerate in the adjacent Great Valley sequence (1970, p. 168–169); these Franciscan and Great Valley rocks had previously been mapped as a continuous belt of the Knoxville Formation by Brice (1953, p. 13–14, pl. 1).

The preservation of the Cretaceous and Paleocene depositional sequence suggests that the Great Valley sequence found within the Clear Lake outlier has not been grossly dismembered and therefore probably has not been transported great distances from its original depositional site. These rocks are probably autochthonous. However, their deformation and local incorporation in Franciscan tectonic breccia imply that here the Franciscan Complex includes rocks that were tectonically detached from the Great valley sequence. The episode of allochthonous deformation during which these rocks were mixed necessarily occurred in Paleocene or later time.

At Rice Valley, Cretaceous strata correlated with the Great Valley sequence and overlying Paleocene and Eocene(?) strata form an elongate slab 0.7 km by 3 km



in plan that is tectonically enclosed by ultramafic rock and chaotic rocks of the Franciscan Complex (Berkland, 1973). The Cretaceous rocks consist of greenish-gray shale with thin-bedded K-feldspar-bearing sandstone interlayers aggregating 915 m (3,000 ft) in thickness, overlain by biotitic arkosic K-feldspar-rich sandstone about 150 m (500 ft) thick. The Paleocene strata overlie the Cretaceous strata with slight angular discordance (Berkland, 1973, p. 2396) and in ascending order consist of an unfossiliferous massive sandstone at the base, overlain by polished pebble conglomerate, also unfossiliferous but containing abundant reworked Franciscan detritus; quartz grit; fossiliferous concretionary sandstone containing a rich fauna of Meganos (upper Paleocene) age; and an uppermost unit of glauconitic sandstone containing a sparse fauna that could represent a horizon "possibly as young as Eocene" according to W. O. Addicott (in Berkland, 1973, p. 2398).

According to Berkland (1973), the Cretaceous part of the Rice Valley outlier is a conformable sequence, 965 m (3,500 ft) thick, that ranges in age from Hauterivian to Cenomanian on the basis of fossils from two horizons. As Berkland (1973) suggested, the difference in thickness between this section and the 12,000-m (40,000 ft) section of the Great Valley sequence at the western edge of the Sacramento Valley is in part due to erosion prior to deposition of the overlying Paleocene rocks. The Hauterivian to Albian part of the autochthonous Great Valley sequence in the Wilber Springs area (fig. 10), 50 km southeast of the Rice Valley outlier, is itself 5,100 m (17,000 ft) thick (Bailey and others, 1964, p. 132). Hence the thinness of the Rice Valley sequence implies extreme primary depositional thinning of the Great Valley sequence toward the west.

Berkland's (1973, fig. 2) map shows that the slab is folded into an appressed syncline with the dip of both limbs approaching the vertical near the bounding faults. Berkland presumed that the Rice Valley sequence is a remnant of an upper-plate underthrust by an oceanic plate of Franciscan materials (Berkland, 1973, p. 2400-2402). He suggested that the melange characteristic of the Franciscan Complex in this area may represent a tectonic mixture of adjacent thrust plates. In support of this concept, Berkland mentioned the presence along the east side of Rice Valley of a slab of unmetamorphosed K-feldspar-bearing graywacke and minor chert-pebble conglomerate similar to the Lower Cretaceous part of the Great Valley sequence.

The structural relations of the Rice Valley outlier to surrounding ultramafic rock and melange of the Franciscan Complex are equivocal. The actual contacts are chiefly high-angle faults, according to Berkland's (1973) map and cross sections. There is little direct evidence to support the conventional view that the slab is a down-faulted block or an erosional remnant of a once-contin-

uous sheet of Great Valley sequence thrust over the Franciscan. On the basis of structural relations described by Berkland (1973), the possibility cannot be ruled out that the slab is (1) an upfaulted block of the autochthonous basement on which the Franciscan rests, or (2) a large rip-up of that basement engulfed in melange, or (3) a mesoallochthonous deposit.

In the Covelo area, irregular "islands" formed by intact sequences of Upper Cretaceous, Paleocene, and Eocene strata are surrounded by a "sea" of broken and sheared rocks of the Franciscan Complex (Clark, 1940). The Franciscan Complex here consists of layers of melange and coherent sequences of mudstone and feldspathic arenite or graywacke; the melange contains fossils as young as Late Cretaceous (Albian through Cenomanian) according to Gucwa (1975, p. 107). Gucwa (1975) noted that one of the coherent units—the White Rock unit of Late Cretaceous age—is *depositionally* overlain by melange. He attributes this contact relationship to emplacement of the melange as a gravity mass flow during Late Cretaceous time or later.

The Upper Cretaceous strata forming the islands consist of sandstone, shale, and minor conglomerate that is in places conformably or disconformably overlain by Martinez (lower Paleocene), Meganos (upper Paleocene), and Capay (lower Eocene) sandstone (Clark, 1940). Locally this sequence of sediments *depositionally* overlies the Franciscan Complex (Gucwa, 1974, p. 39, 66).

We ask, then, are these Cretaceous and early Tertiary sequences mesoallochthonous or neoautochthonous? The field evidence bearing on this question seems to be somewhat equivocal. Gucwa (1974, p. 39) noted that one small outlier consisting of strata similar to the fossiliferous Upper Cretaceous rocks is overturned. He suggested that this section was deposited on melange and then partly incorporated into the melange. However, other sections of the Upper Cretaceous and Tertiary rocks do not give any indication of substantial postdepositional displacement, hence in Gucwa's opinion were probably deposited after formation of the subjacent melange. Probably additional field evidence will be needed to resolve this question. However, on the basis of the map and contact relations depicted and described by Clark (1940) and Gucwa (1974, 1975), it seems likely that the Late Cretaceous strata were deposited on melange, then dismembered and engulfed within melange in early Tertiary, hence are probably mesoallochthonous.

#### BANDON AREA

In southern Oregon, the closest lithologic correlative of the Franciscan Complex is the Otter Point For-

mation. The Otter Point consists of interstratified mudstone, graded sandstone (arkosic to lithic wacke), pebbly mudstone, volcanic breccia, bedded chert, conglomerate, and pillowed lava flows (Koch, 1966, p. 36–43). The presence of numerous detached garnetiferous blueschist blocks, universal shearing, and the absence of preserved bedding (Beaulieu, 1971, p. 30) imply that the Otter Point is in fact a melange (Dott, 1971, p. 27; Baldwin and Beaulieu, 1973, p. 13), hence should be considered a northern continuation of the Franciscan Complex.

The Otter Point Formation is regarded as Late Jurassic by the presence within it of a sparse fauna that includes *Buchia piochii* (Gabb) (Koch, 1966, p. 42–43). Cretaceous fossils have been found in other formations in the area, for example, the Upper Cretaceous Cape Sebastian Sandstone and Hunters Cove Formation of Dott (1971, p. 31–42) and the Lower Cretaceous Rocky Point Formation and underlying Humbug Mountain Conglomerate (Koch, 1966, p. 43–48). The Cape Sebastian Sandstone unconformably overlies the sheared Otter Point Formation (M. C. Blake, Jr., written commun., 1979). But as the contact between the Humbug Mountain and Rocky Point Formations and Otter Point melange is apparently tectonic (Koch, 1966, p. 43; Dott, 1971, p. 57), the episode or episodes of deformation that produced the Otter Point melange must be pre-Cape Sebastian Sandstone and could be post-Rocky Point Formation in age.

Along the coast, the type Humbug Mountain Conglomerate is gradationally overlain by the Rocky Point Formation; here the two formations are composed of interbedded conglomerate, mudstone, and sandstone, and aggregate about 2,750 m (9,000 ft) in thickness (Koch, 1966, p. 43–50). The two formations appear to be Valanginian in age (Koch, 1966, p. 44–45). The Humbug Mountain unconformably overlies the Upper Jurassic Galice Formation, composed of black argillite, slaty or phyllitic mudstone, and gray sandstone (Dott, 1971, p. 11, 21–23). Overthrusting of the Humbug Mountain and Rocky Point Formations by the Colebrooke Schist (Coleman, 1972, pl. 1) shows that their deposition was followed by one and possibly more than one episode of allochthonous deformation.

The youngest rocks in the Bandon area that have been penetratively deformed (at least locally) and tectonically juxtaposed against the Otter Point melange are those of the Roseburg Formation of Baldwin and Beaulieu (1973) and Baldwin (1974, p. 60), of early Tertiary age. Their Roseburg includes strata classified by Turner (1938, p. 5) as the lower member of Diller's (1898) Umpqua Formation. As defined, their Roseburg consists of a lower member of basaltic flows, pillow lavas, volcanic breccias and interflow sediments, chiefly conglomerate and tuffaceous sandstone, and an upper

member of tuffaceous siltstone and rhythmically bedded sandstone. The formation could aggregate 3,700 to 4,600 m (12,000 to 15,000 ft) in thickness (Baldwin, 1974, p. 6–8).

According to Baldwin (1974, p. 8–10), the Roseburg includes strata that at various localities have yielded a fauna of Paleocene, early Eocene, and rarely, Late Cretaceous age. In his opinion, rocks containing the Late Cretaceous fossils may have been tectonically introduced into the Roseburg.

The Roseburg is isoclinally folded and thrust over severely deformed strata in part considered to be the sedimentary upper member of the formation (Baldwin and Beaulieu, 1973, p. 20), and in places, as at Coos Bay, the Roseburg (nee lower Umpqua) "displays several melange features" (Beaulieu, 1971, p. 30). Steeply folded Roseburg strata also appear to be overthrust by the Colebrooke Schist (Baldwin and Lent, 1972, p. 125; Beaulieu and Hughes, 1976, p. 13). The Roseburg is herein considered to be autochthonous (fig. 9), although it is apparent from the descriptions given that parts of the formation might be allochthonous.

The Colebrooke Schist is composed of thin-bedded shale, sandstone, and associated minor pillow lavas, tuff, and chert metamorphosed at temperatures and pressures intermediate between those of the blueschist facies and greenschist facies (Coleman, 1972, p. 29, 43). This formation occupies an area of about 260 km<sup>2</sup> (100 mi<sup>2</sup>) in southwestern Oregon, much of which, according to Coleman (1972, p. 56), represents an allochthonous sheet thrust eastward over the Otter Point, Dothan, and other pre-Tertiary formations in the area.

The folded and beveled Roseburg and pre-Tertiary rocks are unconformably overlain by a mildly deformed conglomerate, sandstone, and siltstone, the Lookingglass Formation of Baldwin (1974), which contains a Penutian (late early Eocene) fauna (Baldwin, 1974, p. 12–16). Strata assigned to the Lookingglass by Baldwin (1974, p. 16, and geologic map) were considered by Turner (1938, p. 5) to be the upper member of the Umpqua. They also include the beds at one locality (Boulder Creek) mapped as Umpqua by Coleman (1972, p. 19, 28, pl. 1) that Baldwin (1974, geologic map) shows depositionally overlying the Colebrooke Schist, its basal decollement, and part of the subjacent imbricated serpentinite sheet.

The structural fabric of the Colebrooke Schist suggests multiple episodes of penetrative deformation, the most recent of which Coleman believed to be Late Cretaceous (1972, p. 19, 29, 56). However, the field relations of the Colebrooke to the Roseburg and Lookingglass appear to bracket the age of final tectonic emplacement of the Colebrooke Schist as early Eocene, as suggested by Baldwin and Lent (1972, p. 125) and Beaulieu and Hughes (1976, p. 13).

## MAIN ELEMENTS OF MELANGES AND THEIR BEARING ON PLATE-TECTONIC HISTORY

The origin of the melanges of the western part of the North American plate and their bearing on plate-tectonic history from Cretaceous through Tertiary time involves the formation of three main elements: (1) Cretaceous through early Tertiary melanges of the Franciscan Complex, (2) the Eocene Oregon-Washington borderland, and (3) middle(?) Tertiary melanges of the Olympic Peninsula of Washington. Here, attention is focused on whether the age of the most recent episode of allochthonous deformation during which part of the Franciscan Complex was formed coincides with the conversion of a transform boundary to a subduction zone at a northwestward-migrating triple junction, or spans the entire time during which the subduction zone was active.

The topic of the Oregon-Washington borderland represents a departure from the main subject of this paper, that is, the tectonic implications of the melanges. Yet an understanding of the origin of the borderland is necessary in order to link the Cretaceous through early Tertiary history of the Franciscan Complex with the middle(?) Tertiary history of the Olympic Peninsula.

In the third section of the discussion, attention is focused on whether the age of deformation of the Olympic Peninsula coincides with the age or ages of momentary formation and transit of a Humboldt-type triple junction between the Pacific, Juan de Fuca, and North American plates, as deduced from the magnetic record of the ocean floor.

### FRANCISCAN COMPLEX

#### AGE OF DEFORMATION RESULTING IN THE FRANCISCAN COMPLEX

The internal disruption and deformation characteristic of the Franciscan Complex has been attributed to (1) processes occurring at or above an active subduction zone (Hamilton, 1969) and, alternatively, to (2) processes occurring at or near a triple junction whose migration is associated with conversion of a transform plate boundary to a subduction zone (Fox, 1976). According to the subduction-zone hypothesis, deformation continues along the entire extent of the subduction zone for its life. According to the triple-junction hypothesis, deformation is episodic, occurring only in the immediate vicinity of the triple junction. Further, because of the migration of this triple junction, the age of formation is progressively younger along its course. We ask, then, was the formation of the Franciscan Complex a continuous process or was it an episodic process? If episodic, was all or most of the complex synchronously formed, or

was the deformation that produced the complex diachronous, becoming younger northwestward?

The fact that units within the Franciscan Complex can be classified as allochthonous, mesoallochthonous, autochthonous, and neoautochthonous strata, a division made by Hsu (1969), implies that deformation was an episodic process, interrupted at least locally by periods of erosion and sedimentation.

The age of the terminal episode of deformation is closely bracketed within Late Cretaceous (Campanian) in the Morro Bay area and early Eocene in the Bandon area. The youngest deposits presumed to be mesoallochthonous in the Covelo-Clear Lake area are late Paleocene, and possibly early Eocene at Rice Valley, and late Paleocene and early Eocene at Covelo. The coastal-belt rocks immediately to the west also are at least locally as young as Early Eocene.

The age of this terminal episode of allochthonous deformation varies from place to place and apparently becomes progressively younger to the northwest (fig. 11). The simplest history consistent with the data (fig. 11) is as follows: beginning in Late Cretaceous, a diachronous upheaval producing melange or broken formation and the younger part of the Franciscan Complex progressed northwest along the margin of the continental plate at about 4 cm/yr, reaching central California in early Eocene time.

The age of the deformation of the Eocene coastal belt and rocks in the Covelo area and Eocene(?) rocks in Rice Valley is not narrowly limited by the ages of younger neoautochthonous deposits. Conceivably, in these areas this event could be younger than early Eocene, implying that its rate of northwestward migration was less. On the other hand, the velocity could be greater if the Franciscan Complex in the Morro Bay area has been telescoped by right-lateral movement exceeding the 315 km of Neogene and later offset recognized by Matthews (1973) on the San Andreas fault.

The Campanian and early Tertiary event probably did not extend southeastward to the Los Angeles lowland. Crystalline rocks forming the basement of the Los Angeles lowland were beveled in middle Cretaceous time, forming the "Los Angeles erosion surface" (fig. 11), and were unconformably overlain, beginning in the Cenomanian, by a sequence of strata that, though folded and faulted, have apparently not been affected by a regional episode of penetrative allochthonous deformation (Woodford and Gander, 1977).

The continental borderland west of the Los Angeles lowland is underlain in places by the Catalina Schist (Bailey and others, 1964, p. 93), in other places by Cretaceous (Maestrichtian?, Campanian, Coniacian, and Cenomanian) and younger strata (Paul and others, 1976, p. 16). Neither the contact relation of the schist to the Cretaceous sediments nor the relation of the basement

rocks of the borderland to those of the Los Angeles lowland has been established with certainty (Howell and Vedder, 1981).

According to Howell and Vedder (1981), the borderland is composed of four terranes, probably representing large structural blocks. By northwest-directed lateral movement, the blocks have been individually dislocated with respect to each other and collectively dislocated with respect to the Los Angeles lowland. Hence, deformational episodes affecting the borderland may not be synchronous with those affecting the Los Angeles lowland. Howell and Vedder (1979, 1982) noted that "middle Cretaceous and late Paleocene hiatuses in sedimentation and concurrent regional lapses in magmatism may represent times of transform faulting that interrupted subduction." Until the movement history of the borderland is accurately reconstructed, the transitions from transform faulting to subduction implied by this statement cannot be placed in context with episodes of allochthonous deformation sensed in the Morro Bay area to the north.

That there were episodes of allochthonous deformation preceding the Campanian and early Tertiary event is implicit in the characterization of the Las Tablas unit of Cowan and Page (1975), the "broken formation A" of Hsu (1969), the Atascadero Formation of Hart (1976), and similar units as mesoallochthonous. Although accurate definition of these earlier deformational episodes is not yet feasible, available information is sufficient to at least suggest their existence and place rough limits on their age and extent.

In northern California, the latest Cretaceous and early Tertiary coastal belt is presumed to be chiefly mesoallochthonous and deposited after an episode of penetrative deformation that occurred in Cenomanian and Maestrichtian time. This Late Cretaceous episode (fig. 11) probably postdates the Hauterivian to Cenomanian sequence at Rice Valley and the Late Jurassic to Early Cretaceous (Valanginian) Marmolejo Formation of Taliaferro (1944) and the Toro Formation of the Morro Bay area. It must predate the early Tertiary Roseburg Formation and Covelo outlier, the Paleocene rocks at Rice Valley, the "broken formation A" of Hsu (1969), the Las Tablas unit, and the Atascadero Formation. At Rice Valley, this episode of allochthonous deformation probably occurred during the time represented by the unconformity between Cenomanian and Paleocene rocks.

A middle Early Cretaceous episode of melange formation in northern California also seems required, for most of the melanges there contain only a comparatively abundant Tithonian through Valanginian fauna without admixture of younger fossils (Blake and Jones, 1974, p. 350).

The middle Early Cretaceous event could also account for pre-Marmolejo development of melange in central California and perhaps at Baja, Calif. (fig. 11). The age of melange at Baja is not known with any certainty, however. At one locality on Cedros Island in Baja, Calif., the latest Jurassic through Early Cretaceous Eugenia Formation reportedly includes blueschist detritus believed to have been derived from the nearby melangelike Cedros Formation of probable Late Jurassic age (Kilmer, 1977). Potassium-argon ages of white mica and blue amphibole from blueschist at Cedros Island, however, range from  $94.4 \pm 4$  to  $110 \pm 2$  m.y. (Suppe and Armstrong, 1972). If not thermally retrograded, these ages indicate metamorphism and possibly formation of melange in or after Turonian time, that is, after deposition of the Eugenia Formation.

This middle Early Cretaceous episode could also be responsible for some of the structural disruption of the allochthonous terranes of the San Juan Islands. The age or ages of these rocks has not been firmly established. Some parts contain fossils as young as Cenomanian and Valanginian age (J. T. Whetten, written commun., 1977).

In summary, the development of the Franciscan Complex and allied rocks was apparently an episodic process. In some areas, such as the Morro Bay area, the evidence suggests that there were several episodes of deformation. The final episode was apparently diachronous; earlier events may have also been diachronous, but the data for them is less compelling. The age of much of the complex probably decreases systematically to the northwest, ranging from Late Cretaceous (Campanian) at Morro Bay, California, to early Tertiary (Eocene) in northern California. Within this geographic span, however, parts of the complex formed prior to Campanian time and were unaffected by more recent episodes of penetrative deformation may represent discrete terranes.

#### CAUSE OF ALLOCHTHONOUS DEFORMATION THAT CREATED THE FRANCISCAN COMPLEX

The structural fabric of the Franciscan Complex may have been produced through gravity thrusting and sliding away from one or more triple junctions that migrated northwestward along the interface between the North American plate and the oceanic plates to the west. The chief bases for this hypothesis, as originally proposed (Fox, 1976), were (1) the existence of triple junctions of the required dynamic type is implicit in the plate-tectonic theory; and (2) the structural fabric of the Franciscan Complex is more compatible with shearing at low confining pressure inherent in this process than the high confining pressures seemingly required by the

subduction theory; and (3) this process provides a means of recovering and stirring exotic clasts of eclogite and blueschist into the melange. To these reasons a fourth may now be added, namely, that the deformation that produced the Franciscan Complex was apparently episodic and, where best dated, was diachronous.

If the premise of episodic deformation is accepted, the age data schematically projected in figure 11 provide a means of identifying and tracking the causal triple junctions. The Late Cretaceous and early Eocene deformational event is the track of a Humboldt-type triple junction that migrated northwestward along the plate margin at a rate of roughly 4 cm/yr. At any given time, the margin of the North American plate was bordered by a transform fault to the northwest and by a subduction zone southeast of this triple junction. Hence the northwest transit of the triple junction marks the end of a strike-slip-dominated tectonic regime and the beginning of a subduction-dominated tectonic regime.

Both the middle Early Cretaceous and middle Late Cretaceous events are presumed to represent northwestward transits of Humboldt-type triple junctions (fig. 11), as yet too obscure to justify any firm conclusion as to their precise age or rate of northwestward migration. Tentatively, they appear to have moved somewhat faster than the Late Cretaceous (Campanian) and early Tertiary event of central and northern California (fig. 11).

The Campanian and early Tertiary event marks a transition from what was previously strike-slip-dominated to subduction-dominated tectonism along the continental plate margin. Presumably, each of the preceding episodes of allochthonous deformation do also. Intervening episodes in which the subduction zone was converted to a strike-slip transform fault could be episodes during which a Mendocino-type triple junction (Fox, 1976) transited the margin of the continental plate, or episodes during which a change in plate motion was coupled with a ridge jump.

Cooper and others (1976) showed that the lithosphere underlying the eastern Bering Sea basin is a fragment of oceanic plate that broke away and was trapped as the subduction zone at the northern edge of the Kula plate jumped south to its present location at the Aleutian trench. They estimated the date of this event to be approximately 70 Ma (Cooper and others, 1976, p. 1125). Presumably this event was part of a general reorganization of the boundaries of the Kula plate that roughly coincided with the middle Late Cretaceous (approximately 75 Ma) transition along the California coast from subduction to strike-slip faulting. If so, that transition was probably precipitated by a ridge jump (fig. 11), rather than by transit of a Mendocino-type triple junction.

On the basis of the spreading history of the Pacific plate, Larson and Chase (1972) postulated a 2,000-km southeastward jump of the Kula-Farallon ridge about 100 Ma. This jump probably entailed a jump of the Kula-Farallon-North American triple junction, hence coincides with a transition from subduction to strike-slip faulting along a segment of the western edge of the North American plate (fig. 11).

The following model (fig. 12) is proposed: Beginning in latest Jurassic or Early Cretaceous time, the spreading ridge between two oceanic plates first intersected the margin of the North American plate, forming a triple junction with the transform fault to the northwest and the subduction zone to the southeast. Subsequently, this triple junction migrated northwest along the margin of the continental plate at a rate comparable to that suggested in figure 11, that is, about 5½ cm/yr (or more, if, as is likely, pre-Late Cretaceous elements of the Franciscan Complex have been telescoped by faulting an amount greater than the 315 km restored in fig. 11).

The space problem at the triple junction caused by the encroachment of the subducting oceanic slab on the transform-bounded edge of the continental plate was relieved by the plowing up of the lip of the continental plate and the consequent detachment of slabs and sheets of the Late Jurassic and Early Cretaceous turbidite deposits underlying the continental slope. These slabs cascaded or were rammed inland, stacking melanges, broken formations, and allochthonous imbricated masses of rocks on the floor of the forearc basin to the east, which was locally underlain by Late Jurassic (Knoxville Formation) and Early Cretaceous rocks deposited over oceanic basement. Rip-ups from this autochthonous floor were locally incorporated in the melanges. The subjacent autochthon was depressed beneath the weight of the melange and, being under compression from the west, broke along the crustal flexure that formed near the eastern extremity of the allochthonous mass, and was then partially overridden by the Knoxville Formation and the Great Valley sequence of the craton on a zone of thrust and high-angle reverse faults (the first phase of thrusting on the Coast Range thrust of Bailey and others, 1970). This scenario was apparently repeated with varying degrees of severity during middle Late Cretaceous and again in Late Cretaceous (Campanian) and early Tertiary time. In these later episodes, strata laid down on the melange were themselves disrupted and imbricated.

COMPARISON OF CRETACEOUS THROUGH EARLY  
EOCENE TECTONIC REGIMES AS PREDICTED  
BY THE TRIPLE-JUNCTION HYPOTHESIS  
WITH CONCEPTS SUGGESTED BY OTHER EVIDENCE

The plate configuration from which the Early Cretaceous Humboldt-type triple junction evolved is un-

known. Ernst (1965, p. 905) suggested that the Late Jurassic elements of the Franciscan "Group" represent trench deposits, a suggestion adopted as a working hypothesis by Hamilton (1969). This implies that in Late Jurassic and Early Cretaceous time, central western North America was bounded by a subduction zone or zones. Plutonic rocks (fig. 11) that could be related to this subduction zone include both Late Jurassic and Early Cretaceous plutonic rocks with representatives in northern California (Lanphere and others, 1968) and central California (Evernden and Kistler, 1970, p. 623). Further definition of the Jurassic setting is required before the nature of the transition, which could involve as yet undefined plates, from Late Jurassic subduction to the Cretaceous melange-forming transit of the Kula-Farallon spreading ridge can be specified.

The timing and geographic extent of the Late Cretaceous subduction zone required by the scenario given in figure 11 correlates roughly with the plutonic episode Evernden and Kistler named the Cathedral Range intrusive epoch (1970, p. 623). The Early Cretaceous subduction zone correlates less satisfactorily with the Huntington Lake intrusive epoch. The Yosemite intrusive epoch and the age of plutonic rocks of the Trinity Mountains (Lanphere and others, 1968) do not correlate with any subduction episode represented in the boundary regimes (fig. 11). This may imply that marginal parts of the North American plate have been dislocated by

strike-slip faulting from the Early Cretaceous volcanic arcs of the craton and subsequently rejoined elsewhere to the craton as tectonostratigraphic terranes.

The relations depicted in the schematic chart (fig. 11) imply that a strike-slip regime prevailed along the western margin of the North American plate for about 20 m.y. in Late Cretaceous and early Tertiary time. This conclusion is vital to the interpretation of plate geometry developed in later sections, hence corroboration independent of the triple-junction hypothesis is particularly desirable. Snyder and others (1976) postulated development of a strike-slip regime in latest Cretaceous and early Tertiary time, on the basis of timing of offset on the proto-San Andreas fault, which seemingly requires a period of strike-slip faulting roughly 50–70 Ma (1976, p. 103). Development of the transform through a rise-trench encounter was followed by a cessation of arc magmatism to the east. Their compilation of ages of igneous rocks indicates that there was a null period in magmatism about 65–40 Ma. They attributed the apparent 5- to 10-m.y. timelag in cessation and renewal of magmatism to the time required for the trailing edge of the subducted slab to pass and the leading edge of the succeeding slab to reach appropriate depth for melting to begin (Snyder and others, 1976, p. 92, 103).

The Late Cretaceous to early Eocene transit of a Humboldt-type triple junction inferred from the ages of melanges is roughly synchronous with the transit of the

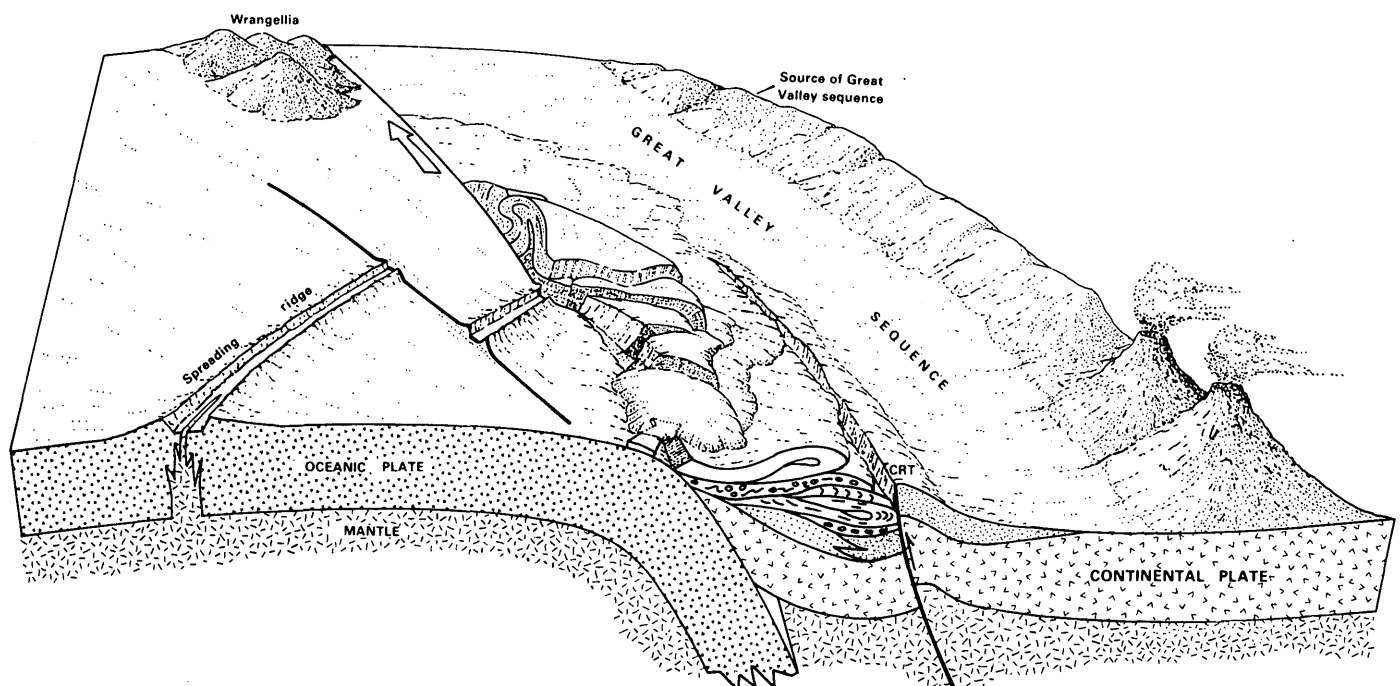


FIGURE 12.—View to northwest showing transit of Early Cretaceous Humboldt-type triple junction with accompanying formation of melange and a proto-Coast Range thrust (CRT) to east. Western source of detritus in the Franciscan Complex is a tectonostratigraphic terrane (Beck and others, 1980), such as Wrangellia (Jones and others, 1977), locked in an oceanic plate and drifting with it to northwest relative to craton and source area of the Great Valley sequence.

Kula-Farallon-North American triple junction originally proposed by Atwater (1970, p. 3531) through extrapolation of present rates of plate movement back to that time. The rate of right-lateral offset between the Pacific and North American plates of 6 cm/yr adopted by Atwater (1970) in her constant-motion model was based principally on Larson and others' (1968) estimate of the average spreading rate for the past 2 m.y. across the extension of the East Pacific Rise into the Gulf of California. The slip rate was amended slightly by Minster and others (1974) to 5½ cm/yr on the basis of simultaneous solution of rotation vectors between 11 major plates.

Atwater and Molnar (1973) deduced greatly different slip rates between the North American and Pacific plates throughout most of Tertiary time by chaining spreading rates between the North American, African, Indian, East and West Antarctic, and Pacific plates. On this basis, they suggested that the rate of motion between the Pacific and North American plates averaged about 5 cm/yr between 29 and 21 Ma, 1.3 cm/yr between 21 and 10 Ma, 4 cm/yr between 10 and 4.5 Ma, and 5.5 cm/yr since 4.5 Ma. While cautioning that the details should not be taken literally, in particular noting weaknesses in the 21-m.y. and 29-m.y. reconstructions, they concluded that "an average relative rate of about 2 cm/yr between 38 and 10 Ma is almost certainly realistic" (Atwater and Molnar, 1973, p. 142).

If the rates postulated by Atwater and Molnar (1973) are approximately correct, the transition from strike-slip faulting to subduction at any given place along the plate margin would be expected to have occurred much more recently than is implied by the latest Cretaceous through middle Eocene age of the younger melanges of the Franciscan Complex. If the triple-junction hypothesis for the origin of the melanges is correct, then the deformational record of those melanges suggests that the average rate of movement from Cretaceous to the present approaches the present rates of plate movement and in general validates Atwater's (1970) direct extrapolation of those rates back to the Cretaceous ("constant-motion model"). Conversely, if the rates of offset proposed by Atwater and Molnar (1973) are approximately correct, the triple-junction hypothesis must be wrong.

#### EVIDENCE FROM THE FRANCISCAN COMPLEX CONTRADICTORY TO THE TRIPLE-JUNCTION HYPOTHESIS

Resistance to the hypothesis that melanges of the Franciscan Complex originated through tectonism at migrating triple junctions as advanced by the author (Fox, 1976) commonly focuses on two questions: (1) Do any of the ophiolite-Knoxville Formation-Cretaceous sequences found as numerous discrete terranes structur-

ally enclosed by Franciscan Complex actually represent exposed elements of the autochthonous pre-melange basement, or are they all part of an allochthonous upper plate? (2) Does the triple-junction hypothesis provide a structural setting in which the exotic blocks of high-grade blueschist and the more extensive terranes of low-grade blueschist could form?

The contact relations between internally deformed rocks of the Franciscan Complex and the stratally intact ophiolite-Knoxville-Cretaceous sequences that are commonly referred to the Great Valley sequence have been and remain a vexing problem. In part because of inherent stratigraphic and structural complexity and in part because of poor exposure, geologic opinion on this problem has been dominated by successive reigns of various ruling theories which may or may not have a sound observational basis. Three such theories can be readily distinguished: (1) the Knoxville Formation is younger than, and grades downward into, the Franciscan "Formation" of former usage (Taliaferro, 1943); (2) the Great Valley sequence is broadly coeval with the Franciscan assemblage, and the two groups of rocks have been juxtaposed by faulting (Bailey and others, 1964; Irwin, 1957); (3) the various isolated remnants of the Great Valley sequence are parts of a formerly continuous sheet underthrust by the Franciscan assemblage (Bailey and others, 1970).

Contributing to the credibility of the third hypothesis is the fact that in broad areas of central California, Upper Cretaceous rocks contiguous with, and commonly correlated with, the Great Valley sequence do indeed structurally overlie Franciscan rocks. This relation is perhaps best illustrated in the area of the Diablo antiform (fig. 10) (Bailey and others, 1964, p. 154). Detailed maps (Dibblee, 1973, 1975) show that a conformable sequence of stratally intact Upper Cretaceous to Eocene rocks wrap around Franciscan rocks exposed in the core of the southeast-plunging nose of this fold. And as previously noted, north of the Diablo antiform, both Lower and Upper Cretaceous rocks of the Great Valley sequence, *sensu stricto* (that is, as exposed along the western flank of the Great Valley), have structurally overridden the Franciscan Complex along a reverse fault or thrust fault.

Proponents of the subduction-complex theory, extrapolating from these relations, argue not unreasonably that all the isolated patches of Great Valley-like rocks to the west structurally overlie the Franciscan Complex; if the local contact is in fact a high-angle fault or if it can be demonstrated that the Franciscan structurally overlies the Great Valley-like rocks, then the contact is interpreted as a folded or overturned thrust fault with Franciscan in the lower plate. In some recent compilations, all patches of Great Valley-like rocks are

shown as klippen, regardless of the present attitude of the contact and of whether the original mapper believed the contact to be depositional or structural.

This dogma is contradicted by both the conception of the Franciscan Complex as being part mesoallochthonous and partly allochthonous (Hsu, 1969) and by the implication of the triple-junction hypothesis that the Franciscan could overlie a basement composed in part of Great Valley-like rocks. What is in question, then, is the structural and depositional relations of the isolated areas of Great Valley-like rocks to the surrounding Franciscan Complex. Field evidence is commonly ambiguous because the contacts between these rocks are typically poorly exposed and either are, or have been modified by, high-angle faults. The presence of Franciscan structurally overlying Great Valley rocks locally has been reported, as at the St. John Mountains thrust fault, on which Franciscan rocks have been thrust over the Knoxville Formation a distance of at least 8 km (5 mi) (Weaver, 1949, p. 137; Bailey and others, 1964, p. 157).

Stratigraphic differences between the rocks in these "outliers" and the Great Valley sequence, *sensu stricto*, have been noted, leading some workers to postulate that the outliers were deposited in local basins of deposition separate from the main body of the Great Valley sequence (Maxwell, 1974). Moore and Karig (1976) postulated that the outliers might represent sediments accumulated in local basins on the trench slope adjacent to, or within the surface trace of, the subduction zone. In their view, these sediments may have been deposited on a part of the accretionary wedge previously converted to melange, and subsequently or concurrently deformed by distributed thrusting as subduction continued. This concept, which was echoed by Howell and others (1977) and by Underwood (1977), has merit in that it does recognize and, to a degree, accounts for the contact and structural relations peculiar to the mesoallochthonous deposits.

In summary, observational and theoretical basis is now sufficient to reopen the question of the relations, both structural and stratigraphic, of the outliers of Great Valley-like rocks to the Franciscan Complex. These outliers could include: (1) klippen of the Coast Ranges thrust, (2) an autochthonous basement that is structurally overlain by the Franciscan Complex, (3) mesoallochthonous slabs that depositionally overlie older melange, and are structurally overlain by younger melange; and (4) neoautochthonous strata that depositionally overlie the Franciscan Complex.

The origins of (1) the regionally metamorphosed generally low grade blueschist formations, such as the South Fork Mountain Schist (Blake and others, 1967) and the Colebrooke Schist (Coleman, 1972), and (2) the

high-grade blueschist and eclogitic exotic blocks are two of the very puzzling riddles of the Franciscan Complex. It may be significant that the potassium-argon ages of the exotic blocks reported by Coleman and Lanphere (1971) are older at any given place than the admittedly speculative middle Early Cretaceous event (fig. 11). This could imply that these blocks formed during a period of strike-slip-dominated tectonism preceding that event. Possibly they originated as blocks of material that were scraped off the wall of the oceanic plate at its transform boundary, metamorphosed at local sites of high contact pressure, and left as horses in the fault zone, then elevated and incorporated in melange during the ensuing passage of the Humboldt-type triple junction.

The rubidium-strontium isochron age of  $125 \pm 18$  m.y. for the Colebrooke Schist (reported as  $128 \pm 18$  m.y. by Coleman, 1972, p. 54, and recalculated by Lanphere and others, 1978, using refined decay constants) compares with the probable metamorphic age of 115–120 m.y. of the South Fork Mountain Schist (Lanphere and others, 1978). These ages straddle the time of passage of the middle Early Cretaceous triple junction as conjectured in figure 11, suggesting that metamorphism of these rocks was related to this episode of allochthonous deformation.

The questions raised here bear directly on the validity of the triple-junction concept. Even assuming that this concept is correct in principle, the tectonic scenario given in figure 11 for the Early and early Late Cretaceous must be regarded as tentative because of the extreme fuzziness of the dating of the melanges of those ages, and because of the possibility of undetected lateral translation of the data points in part, perhaps, as discrete tectonostratigraphic terranes.

The speculative nature of that scenario can perhaps be accentuated by framing some of the more troublesome questions that occur to the author: (1) Were there in fact two diachronous episodes of allochthonous deformation in Cretaceous time prior to the Campanian, or only one, possibly with a more complex path? (2) What is the significance of the fact that exotic clasts of blueschist and eclogite were mainly introduced into the melange during the deformational events prior to the Campanian?

#### OREGON-WASHINGTON BORDERLAND

##### AGE, DISTRIBUTION, AND PLATE-TECTONIC SETTING OF THE BORDERLAND

The early and middle Eocene age of the allochthonous oceanic crust represented by basalts of the Metcho-sin, Crescent, and Siletz River Volcanics, the basement of the Oregon-Washington borderland, roughly equates



with the expected time of transit past northwestern California and western Oregon of the Kula-Farallon spreading ridge (fig. 11). Presuming that the basalts are indeed oceanic crust, their restricted age indicates that they represent a block sliced away from the near-flank and perhaps the axial zone of a spreading ridge. That the spreading ridge was near the continental plate is confirmed by the 3-m-diameter quartz diorite boulders incorporated in sedimentary beds interlayered with Crescent Formation as reported by Cady (1975).

Paleomagnetic data from the western Cordillera of North America suggest that the region consists of large crustal blocks which were rotated clockwise and translated northwestward relative to the North American craton, as if caught and rotated like ball bearings in a wide zone of right-lateral shear (Beck, 1976). In this context, rocks of the Oregon-Washington borderland are remarkable and to a degree atypical, in that some, though relatively youthful, show very substantial rotations (Cox, 1957; Simpson and Cox, 1977) but no detectable northward translation (Plumely and Beck, 1977; Beck and Burr, 1979, p. 178).

Paleomagnetic data reported by Simpson and Cox (1977) indicate that after deposition the Siletz River Volcanics was rotated clockwise en bloc about  $68^\circ \pm 12^\circ$ , the overlying middle Eocene Tyee Formation and related rocks about  $64^\circ \pm 16^\circ$ , the late Eocene Yachats Basalt about  $51^\circ \pm 33^\circ$ , an Oligocene sill about  $28^\circ$ , and nearby Miocene basalt  $0 \pm 44^\circ$ . Simpson and Cox propose two alternative tectonic models: (1) a 225-km segment of coastal Oregon originated as a small plate related to northward migration of the Kula-Farallon-North American triple junction, then rotated clockwise about a pivot near its southern end; (2) a much longer block encompassing what is now the entire Oregon-California borderland rotated clockwise about a pivot near its northern end.

A variation of the first model better accords with the plate geometry required if the Campanian and early Tertiary episode of allochthonous deformation also represents the transit of this triple junction. To document this opinion requires a slight digression from the main thread of this discussion but one necessary to put the melange-forming processes that occurred before and after formation of the borderland into better perspective.

The angular and, in places, even jagged outline of basement as inferred in figure 9 suggests that the borderland is an aggregation of numerous crustal fragments wedged into a reentrant in the continental plate, rather than a single coherent crustal block. If it is, the blocks must have been individually rotated clockwise after their formation, some as much as about  $70^\circ$ , to account for the paleomagnetic data. The north-trending fissures

that were the source of part of the Siletz River Volcanics (Snively and others, 1968, p. 480) therefore must have trended about N.  $70^\circ$  W. when formed. These fissures thus reflect a tensional axis oriented parallel to that of the Kula-Pacific spreading ridge rather than the supposedly nearby but northeast-trending Kula-Farallon ridge.

On the basis of Duncan's (1977) potassium-argon ages, which show that the Siletz River Volcanics ranges in age from 49.3 to 54.7 Ma, it appears that anomaly 22 (53 Ma) and possibly anomaly 23 (55 Ma) are represented within the rotated blocks of oceanic crust making up the basement of the borderland. But study of the paleomagnetic map of the northeastern Pacific (fig. 13) shows that at the time of anomaly 24 (56 Ma), the easternmost part of the Kula-Pacific spreading ridge terminated at a ridge-ridge-ridge triple junction some 1,300 km west of the North American plate.

Yet it also appears from this map (fig. 13) that the Kula-Pacific spreading ridge either vanished (Byrne, 1978; Geotimes, 1978, p. 24) or jumped some undefined but considerable distance northward shortly after formation of the Y-shaped anomaly labeled "24?" located at about  $54^\circ$  N.,  $158^\circ$  W. The ridge jump is the preferred hypothesis because it better rationalizes the presence of the Kula-Pacific spreading orientation with the Siletz River Volcanics and, as will be discussed later, extensional faulting and rift-related volcanism in British Columbia and northern Washington. If there was such a jump, the Y-shaped anomaly 24? could be the fossilized triple junction between the Kula, Pacific, and Farallon plates formed immediately before the jump.

#### ORIGIN OF THE BORDERLAND THROUGH PLATE COLLISION

The fragmentation and differential rotation of the allochthonous blocks forming the borderland indicates that their emplacement was forcible. Could the borderland have formed through a collision of oceanic and continental plates? Atwater (1970, p. 3531), in her constant-motion model (fig. 1), assumed that in the Late Cretaceous and early Cenozoic, the motion of the Pacific plate was parallel to the edge of the North American plate and that the motion of the Kula and North American plates had a significant component of strike slip. Indeed, the Kula-North American motion may have been essentially strike-slip, as judged by the evidence summarized of a time-transgressive change in tectonism associated with northwestward advance of the subducting Farallon plate. But the paths of the Pacific and North American plates, not then in mutual contact, could have been slightly or even markedly convergent.

If the paths of the North American and Pacific plates were convergent, a collision would inevitably follow, and the borderland could be a product of that collision. This concept accommodates the paleomagnetic evidence of a ridge jump, the evidence of tectonic fragmentation and rotation of the borderland, and the deformational features east of the borderland. The following scenario is suggested (fig. 14). As the Pacific plate approached the North American plate through plate growth and path convergence, the shrinking Kula plate broke apart, causing the Kula-Pacific spreading ridge to jump northward (fig. 14C) and intersect the continental margin. Enlarged by the addition of part of the Kula plate, the Pacific plate sideswiped the North American plate, driving a widening wedge of recently formed oceanic crust inland (fig. 14D) and crunching adjacent rocks of the craton in northern California, Oregon, and Washington. The Pacific and North American plates were deflected by the impact of this collision, ultimately adopting paths parallel to their bounding transform

faults. As they did, the allochthonous wedge was sheared off and fragmented. Caught between two major plates moving right laterally past each other, the fragments rotated clockwise and lodged against the North American plate.

The change in spreading directions between the Pacific and Farallon plates recorded by the difference in trend of anomalies 22 and 21 (53–50 Ma) (fig. 13) may represent adaptation of the movement of the Farallon plate to the changing paths of Pacific and North American plates. As a consequence of this change in spreading direction, several right laterally stepping fracture zones, including the Aja, formed along the new segment of Pacific-Farallon spreading ridge (the northeast-trending segment that had been the Kula-Farallon spreading ridge).

Relative movement between the Pacific and North American plates has assuredly been parallel to the transform between them since contact of the two plates in the area between the Pioneer and Murray fracture

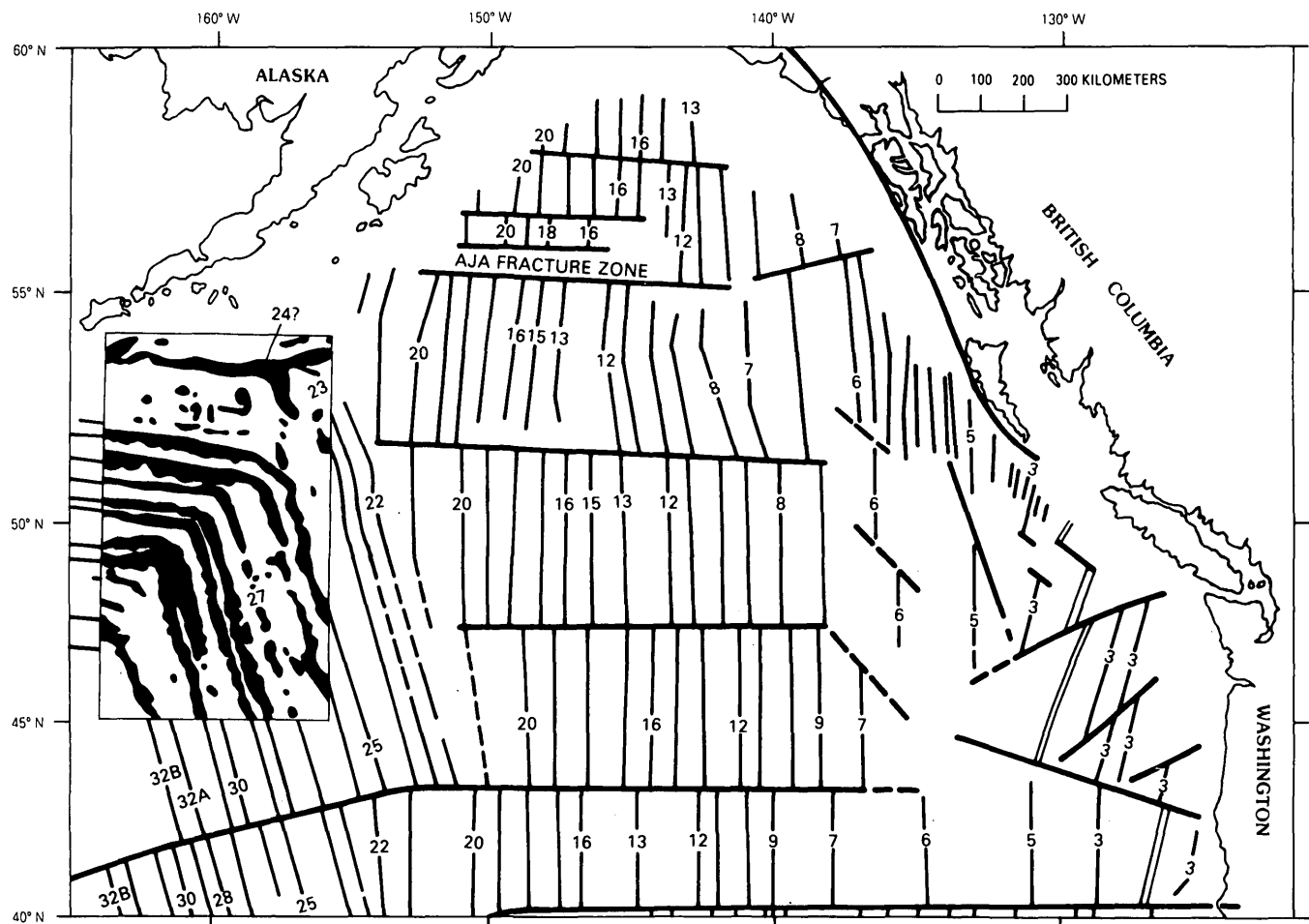
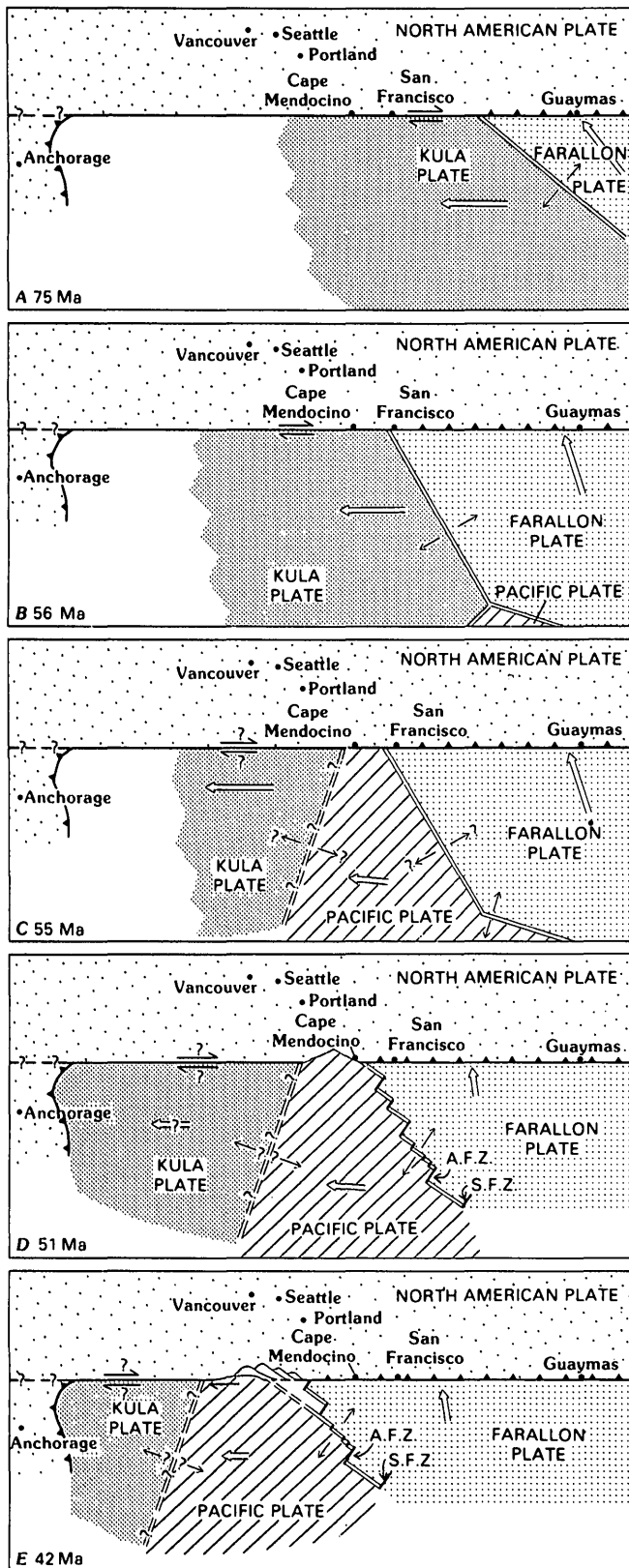


FIGURE 13.—Paleomagnetic map of floor of northeastern Pacific Ocean (after Hilde and others, 1976, p. 223, except detailed inset, which is after Atwater and Menard, 1970, p. 448). Heavy lines indicate fracture zones, dashed where uncertain; light numbered lines indicate magnetic anomalies, dashed where uncertain.

zones after about 30 Ma. The adjustment of the mechanism which drives the plates that was required to bring the direction of their relative movement into con-

formity with the bounding transforms by about 30 Ma probably began contemporaneously with the jump of the Kula-Pacific ridge about 55 Ma, continued through the change in spreading directions between the Pacific and Farallon plates at 53 to 50 Ma (anomalies 22 and 21), and was essentially complete before 30 Ma.

The Earth's hot spots appear to constitute a fixed frame of reference by which absolute motion of the lithospheric plates may be defined (Minster and others, 1974). The only significant shift in direction of movement of the Pacific plate relative to the Hawaiian hot spot during early and middle Tertiary time occurred about 42 Ma, when the Pacific plate veered from a northward to a northwestward path (Dalrymple and Clague, 1976). During the earlier part of the Tertiary, the Pacific plate was apparently holding steady on course. The initial contact between Pacific and North American plates, if, as suspected, it occurred simultaneously with the jump of the Kula-Pacific ridge about 55 Ma, is detectable in the magnetic record of the ocean floor some 13 m.y. before the Pacific plate finally veered away to the northwest. The path change at 42 Ma proba-



EXPLANATION

—▲▲▲ Subduction zone—Sawteeth on upper plate; dashed where approximately located

⇌ Transform fault—Queried where uncertain. Arrows show relative movement

==?== Spreading ridge—Queried where approximately located

FIGURE 14.—Late Cretaceous and early Tertiary plate geometry west of North American plate. Spreading directions shown by thin arrows, plate movements relative to a fixed North American plate by broad arrows. Projection is oblique Mercator as in figure 3. A, About 75 Ma, Kula plate was moving right laterally past North American plate, Farallon plate was being slowly subducted, and Pacific plate was drifting toward North American plate. B, By 56 Ma, with movement continuing as in A, triple junction between Kula, Farallon, and North American plates had moved northwestward past "San Francisco." C, About 55 Ma, ridge between Kula and Pacific plates jumped northward, adding a large block of Kula plate to Pacific plate. D, About 51 Ma, spreading directions between Pacific and Farallon plates changed, causing reorientation of ridge system. Aja (A.F.Z.) and Sila (S.F.Z.) Fracture Zones originated as ridge-ridge transform faults at this time. Motion of Pacific and North American plates was convergent, causing a salient of more rigid oceanic crust to impinge on North American plate. E, As direction of movement between North American and Pacific plates shifted to right-lateral strike-slip about 42 Ma, wedge of Pacific plate that had impaled North American plate sheared off, and Pacific-Farallon ridge jumped northwestward to position shown by dashed lines.

bly marks the end of the period of convergence and collision between the North American and Pacific plates.

RECONCILIATION OF THE COLLISION HYPOTHESIS  
WITH OTHER TECTONIC FEATURES  
OF THE PACIFIC NORTHWEST

The collision hypothesized here provides an explanation for several otherwise enigmatic structural features of probable Eocene age in Washington and adjacent areas. The Devils Mountain fault (fig. 9), for which Whetten (1978) has postulated 60 km of left-lateral displacement, may represent a tear fault formed during the early phase of the collision when plate paths were most convergent. The Straight Creek fault (fig. 9) and its probable continuation in Canada, the Hope fault, appear to be right-lateral strike-slip faults with displacement estimated at 200 km (120 mi) by Misch (1977). The trace of the fault is interrupted by younger plutonic rocks but appears to truncate the Devils Mountain fault zone and to truncate or merge with the Olympic-Wallowa lineament. The Straight Creek fault may have been an active strike-slip fault during the later phases of the collision as the paths of the North American and Pacific plates approached parallelism and the salient of oceanic crust forming the borderland was torn away from the Pacific plate.

The eastern continuation of the Devils Mountain fault could be marked by the southeastern part of the Olympic-Wallowa lineament of Raisz (1945) (fig. 9), a zone of structural weakness marked chiefly by an echelon anticlines and associated reverse faults. According to Bentley (1977), these features formed by draping of Miocene and younger rocks over rotated basement blocks. Alternatively, the lineament may represent a pre-Miocene fault zone separating basement rocks of somewhat contrasting rheomorphic properties. By focusing regional stresses along this discontinuity, the fault has printed up through the cover of Miocene and younger rocks that are present along most of its extent.

In British Columbia, the long period of volcanic quiescence that had begun in the Late Jurassic ended abruptly in the early Tertiary with widespread explosive eruption of lavas, mainly acidic to intermediate (Souther, 1970, p. 559). According to Souther, their eruption was accompanied by block foundering, north-south block faulting, formation of large cauldron subsidence features, and emplacement of north-south dike swarms. Correlative volcanic rocks were erupted in northern Washington, particularly thick sequences accumulating in north-northeast-trending volcanotectonic depressions such as the Republic graben (Muessig, 1967, p. 95-96) and, Toroda Creek graben (Pearson and Ob-

radovich, 1977, pl. 1). Potassium-argon ages show that this episode of volcanism began about 53 Ma, climaxed about 51-50 Ma, and continued with interruptions through 45 Ma (Mathews, 1964; Pearson and Ob-  
radovich, 1977). These volcanic rocks and the tensional features associated with them formed contemporaneously with the collision of the Pacific and North American plates postulated above. Because the formation of north-south tensional features is incompatible with east-west compression, the impact area was probably entirely south of this area of volcanism. If it was, the oceanic plate immediately west of the volcanic field was probably decoupled from the Pacific plate during the collision. This suggests that rather than vanishing, the Kula-Pacific ridge jumped northward 56-55 Ma, reestablishing itself southwest of the area of volcanism. Tensional features and the related volcanic rocks probably formed in response to the tearing effect of the right-lateral component of motion of the impinging Pacific plate.

In Washington, the grabens and allied tensional features along with the associated volcanic and hypabyssal intrusive rocks have a north to north-northeast trend. The en echelon alinement of these volcanic features defines a diffuse, east-trending volcanic field that forms the western section of the so-called "Challis arc." The association of these volcanic rocks, at least those in the segment of the arc in Washington, with extensional features suggests that the arc originated through rifting, not through melting of a subducted slab. This suggestion is supported by the fact that in southern British Columbia and northeastern Washington, lavas and associated intrusive rocks near the base of the middle Eocene sequences are alkalic, including analcitic lava, extrusive rhomb porphyry, trachyte, phonolite, and trachyandesite (Daly, 1912, p. 98; Monger, 1968; Church, 1971; Fox, 1973). Though overlain by andesite, rhyodacite, and rhyolite, the alkalic rocks at the base give the sequence a compositional flavor more commonly associated with tension or rift-related volcanism than with the calc-alkaline andesitic volcanism of conventional island arcs.

In southern Oregon, the early Eocene deformation of the Roseburg Formation associated with, or perhaps culminating in, the emplacement of an allochthon of the Colebrooke Schist cannot be readily explained by deformation related to the postulated transit in Campanian to Eocene time of the Humboldt-triple junction along the continental margin to the south. But the age of thrusting and related deformation (fig. 11) does roughly coincide with the change in spreading direction of the Pacific-Farallon ridge (53-50 Ma), and the rift-related volcanism to the north (53-45 Ma), may thus date extreme compression that occurred at the initial site of Pacific-North American plate contact and convergence.

## MELANGES OF THE OLYMPIC PENINSULA

## THE AJA FRACTURE ZONE AND THE FORMATION OF A HUMBOLDT-TYPE TRIPLE JUNCTION

The magnetic lineations in the northeastern Pacific, as mapped by Naugler and Wageman (1973) and incorporated in figure 13, appear to step right laterally across the Aja fracture zone. The fracture zone and nearshore anomalies trend eastward into a disturbed zone within which the magnetic anomalies have apparently been obliterated by later heating (Naugler and Wageman, 1973). Judged by the mapping, it is likely that north of the Aja fracture zone, the spreading ridge system and coexisting subduction zone shrank, then vanished about 21½ Ma (fig. 13).

A right-lateral transform, the ancestor of the Queen Charlotte fault, would at that time have intersected the Aja fracture zone and the still-active subduction zone along the continental shelf southeast of the Aja, forming a transform-transform-subduction zone triple junction. With northwest movement of the Pacific plate relative to the North American plate, this triple junction would necessarily be of the Humboldt-type. That triple junction would then persist through part of early Miocene time, finally dying as the ridge system south of the Aja fracture zone stepped eastward, intersecting the subduction zone.

Judged by spreading rates and amount of right-lateral offset of the spreading ridge at the Aja fracture zone indicated by offset of the magnetic lineations, the Humboldt type triple junction would have persisted through about 5½ m.y. (until about 16 Ma) before being succeeded by the stationary to slow-moving (Riddihough, 1977, p. 392-393) transform-spreading ridge-subduction zone triple junction that now forms the northern terminus of the Juan de Fuca ridge. The allochthonous deformation related to transit of the triple junction might then diminish gradually as the position of the leading edge of the subducted plate stabilized (fig. 7C).

## ORIGIN OF MELANGES AND BROKEN FORMATIONS

Melanges and other deformational features of the Olympic Peninsula were formed during at least two, and possibly three, episodes of deformation, the earliest in middle or late Eocene time (Snively and Pearl, 1975) and the most recent in latest early and middle Miocene time. Potassium-argon ages from the rocks of the eastern core may record a third event at about 29 Ma (Tabor, 1972), somewhat later if those ages represent older material incompletely retrograded during metamorphism.

The middle or late Eocene event evidently coincided with the initial impact of the Pacific and North American plates, which, as postulated in the preceding section, culminated in suturing of the block of oceanic crust now forming the basement of the Oregon-Washington borderland to the North American plate. As allochthonous deformation and formation of melanges or broken formation within and near the suture zone, particularly at the leading edge of the block, might be expected, no further explanation of the middle or late Eocene melanges seems required.

The timing of the Humboldt-type triple junction formed by the intersection of the Aja transform with the Queen Charlotte fault and the subduction zone to the south coincides at least approximately with the time of formation of the latest early and middle Miocene melanges. In order to account for the structural fabric and geographic extent of these melanges through tectonism associated with this Humboldt-type triple junction, that triple junction at its inception about 21½ Ma would probably have been near the southern part of the Olympic melanges (fig. 15) and would have existed until it reached the approximate latitude of the northern part about 16 Ma.

If this spatial relation is valid, the Olympic melanges and broken formations of Miocene age probably originated as follows. At about 21½ Ma, the Aja fracture zone intersected the edge of the continental plate, forming a northwestward-migrating Humboldt-type triple junction (figs. 15, 16). At this time the underthrusting part of the Juan de Fuca plate began incrementally extending itself northwestward along the continental plate margin at a rate commensurate with the northwestward slip of the Pacific plate. As it did, the underthrusting slab rammed, then plowed aside, the Queen Charlotte transform-fault-bounded lip of the continental plate, sending the contents of one or more deep marginal basins cascading toward the east in a catastrophic series of gravity slides and thrusts. These displaced masses bent the Crescent Volcanics and superjacent beds into the Olympic horseshoe, where, arrested by the restraining bulk of this barrier, they piled up at the present site of the Olympic Mountains. At about 16 Ma, the spreading Juan de Fuca ridge again intersected the subduction zone (figs. 15, 16), and shortly thereafter the creation of melanges and broken formations of the Olympic Peninsula ceased.

In examining the map of the northeastern Pacific (fig. 13), one observes other right-stepping fracture zones north of Aja; the northernmost of these persisted at least through the time of anomaly 10(?). Other such zones may once have existed farther north, but if they did, they have now been subducted beneath Alaska. As each of the active ridge-ridge transform faults whose

existence the fracture zones record in turn intersected the Queen Charlotte fault, a Humboldt-type triple junction would form. The Olympic Peninsula or other areas immediately to the south could have been affected by tectonism associated with these triple junctions. As reconstructed by me, a Humboldt-type triple junction formed at the eastern end of the northernmost fracture zone shown on the map (fig. 13) about 29 Ma and was in existence for about 2 m.y. (fig. 11).

Correlation of the Miocene allochthonous deformation of the Olympic Peninsula with transit of the Aja fracture zone, as postulated above, requires an average slip rate of about 6 cm/yr for the past 20 m.y. or so, comparable to that measured by Larson and others (1968) for the past 2 m.y. Were the average rate substantially

less, as postulated for example by Atwater and Molnar (1973), tectonism associated with transit of the Aja fracture zone between 21½ Ma and 16 Ma would be focused off the coast of British Columbia rather than the Olympic Peninsula.

#### SAN ONOFRE BRECCIA

The San Onofre Breccia of southern California may have originated through tectonism associated with the transit of an identifiable feature of the Pacific plate. Magnetic anomalies of the northeastern Pacific floor appear to be offset left laterally about 275 km on the Pioneer fracture zone (fig. 3). This relation implies that the segment of spreading ridge north of the Pioneer

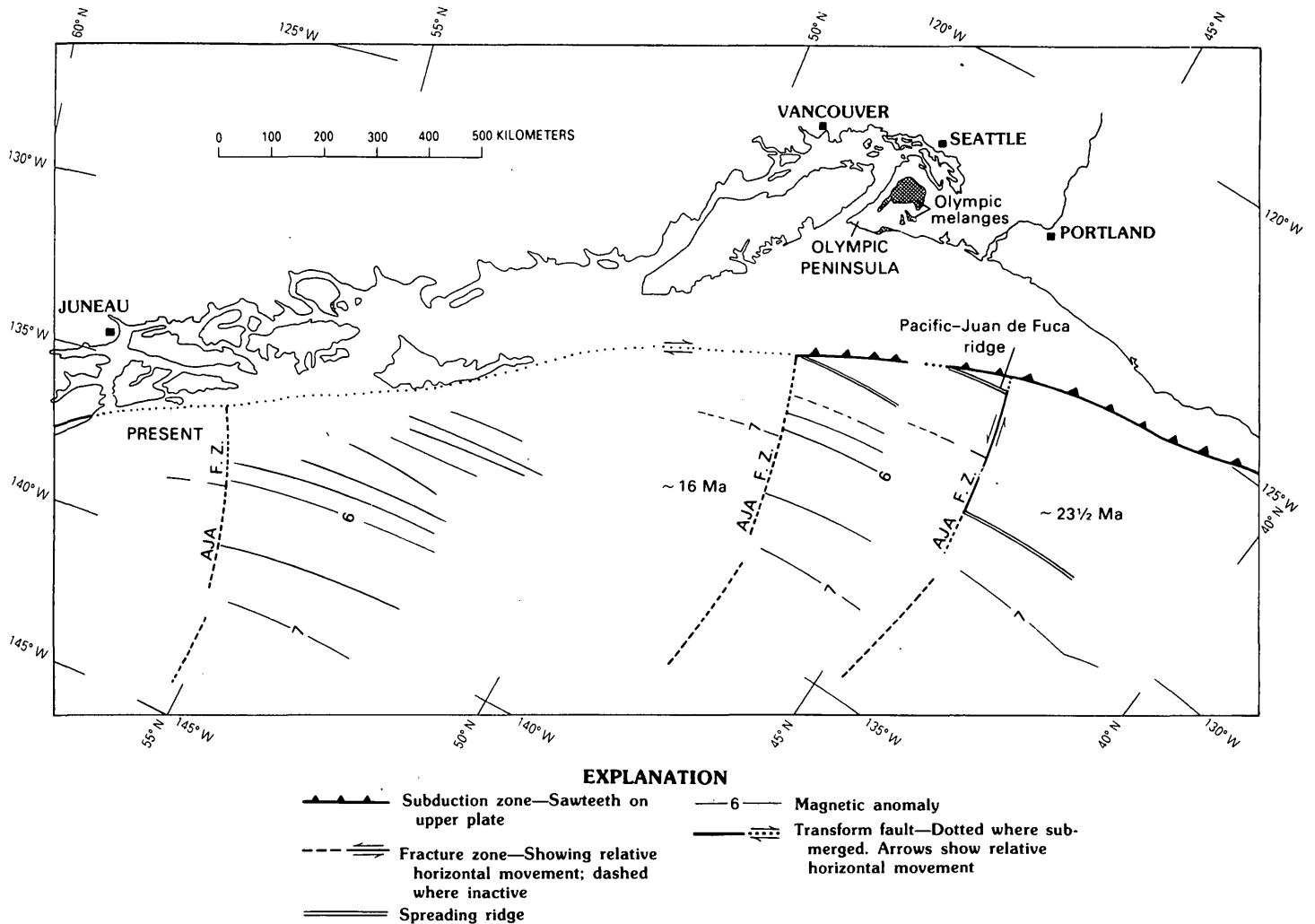


FIGURE 15.—Successive positions of Aja fracture zone relative to North American plate (arbitrarily considered fixed). About 23½ Ma, a short segment of Pacific—Juan de Fuca ridge is still present north of Aja Fracture Zone but will vanish about 21½ Ma through continued spreading. About 16 Ma, ridge south of the Aja Fracture Zone first intersects plate margin. Humboldt-type triple junction that existed between 21½ and 16 Ma probably created the Olympic melanges of early and middle Miocene age. Assuming that to be true, spatial relations between oceanic and continental features at 23½ and 16 Ma shown above were adjusted to associate melanges with Humboldt-type triple junction.

fracture zone intersected the North American plate significantly later than did the segment of ridge to the south.

Assuming that the half-spreading rate of about  $4\frac{1}{2}$  cm/yr measured between anomalies 13 and 8 was maintained, the northern end of the spreading ridge between the Mendocino and Pioneer fracture zones probably intersected the North American plate after 27 Ma and was active at its southern end until after 25 Ma, some 5 to 6 m.y. after initial contact of the Pacific and North American plates to the south. The spatial and temporal association of the San Onofre Breccia with the jump of the triple junction from the Pioneer to the Mendocino fracture zone (fig. 11) suggests that this jump might have initiated the catastrophic uplift and erosion of the source

area of the San Onofre Breccia. That spatial and temporal association is admittedly less perfect than expected, however. In figure 11, the position of the San Onofre has been adjusted to compensate for the 315-km offset on the San Andreas fault, and the northwestern part of the deposit has been moved 160 km southeast to restore movement postulated by Stuart (1976) on the East Santa Cruz Basin fault system. With these adjustments, and given a rate of offset between the Pacific and North American plates of 6 cm/yr (as in fig. 11), the San Onofre appears to be displaced about 200 km farther northwest than expected. Were the rate only  $5\frac{1}{2}$  cm/yr as calculated by Minster and others (1974), the discrepancy would be about 100 km. This amount can probably be accounted for by the displacement between the

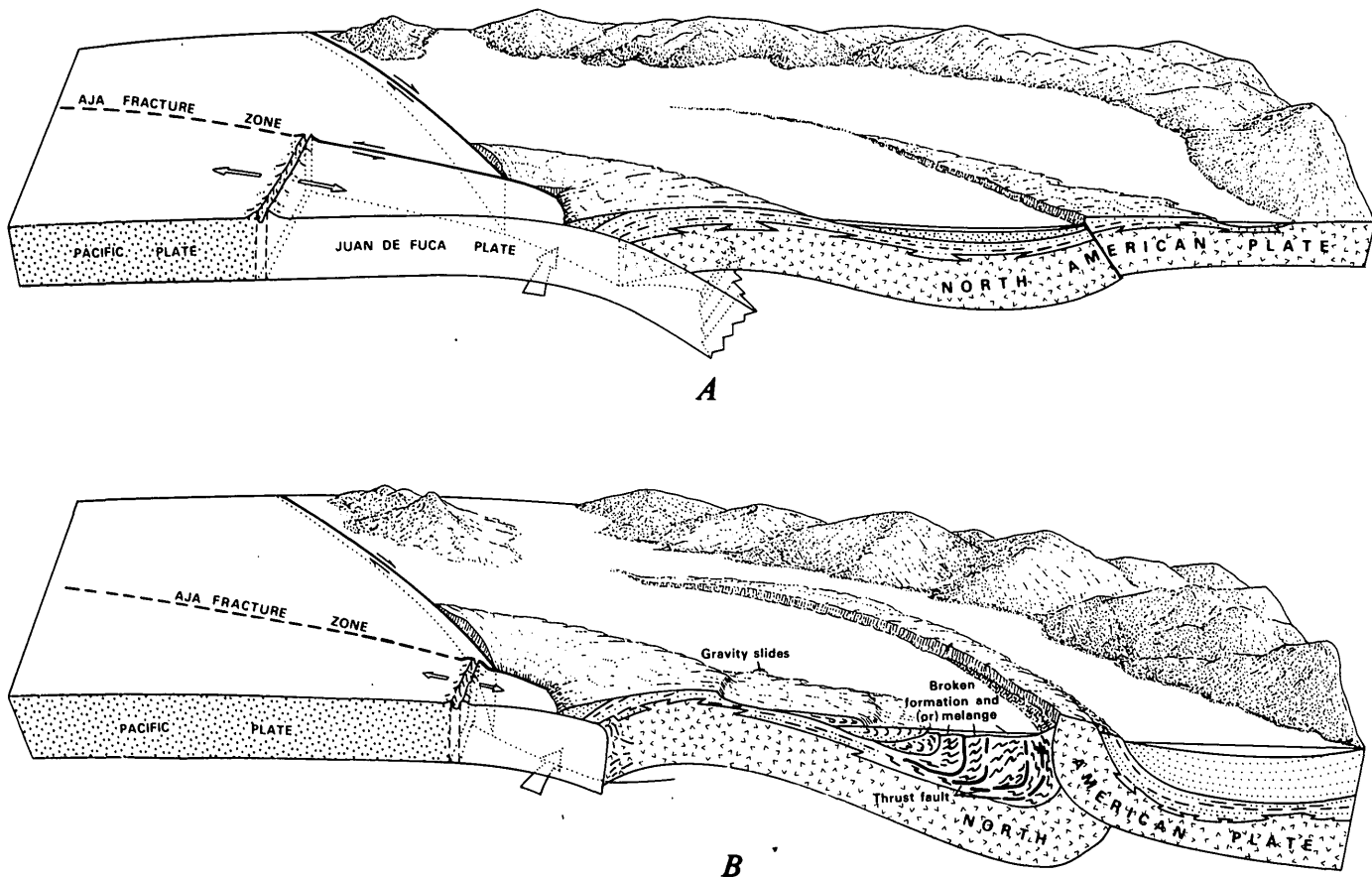


FIGURE 16.—Views to north showing deformation and generation of melanges and broken formations at present site of Olympic Peninsula in early and middle Miocene time. *A*, In early Miocene, Aja transform fault has intersected margin of North American plate, forming a Humboldt-type triple junction. North side of the Juan de Fuca plate, defined by Aja transform at surface and by its subducted extension in subsurface, follows northwestward movement of Pacific plate, causing north side of subducted part of Juan de Fuca plate to impinge on North American plate at their interface in subsurface (toward direction indicated by broad arrow). North American plate is compressed and buckles upward near triple junction and downward along a curving axis to north and east. Speculatively, a curving reverse fault forms at inflection in North American plate north and east of this curving downfold. *B*, In latest early Miocene, continuing impingement of Juan de Fuca plate drives a segment of North American plate landward and beneath main part of this plate. At triple junction, lip of North American plate buckles upward, and upper part of this uplifted mass sloughs away to north and east in a series of catastrophic gravity slides and thrust plates, forming melange and broken formation. These sheets of displaced material pile up within curving downfold where they are further deformed through compression against overriding and upfaulted edge of North American plate to north and east (Olympic "horseshoe" of Cady, 1975). Lower parts of this pile are sufficiently heated through reestablishment of normal geothermal gradient to be weakly metamorphosed.

Pacific and North American plates that was distributed across faults outside the San Andreas fault system. For example, Thompson and Burke (1973) estimated that N. 55° W. extension across the entire Basin and Range province is about 100 km. Hence it is likely that the total displacement between the San Onofre Breccia and the North American plate east of the Basin and Range province substantially exceeds the 315 km allowed for offset on the San Andreas fault, and that the outcrop of the San Onofre correlates more perfectly with the Pioneer-Mendocino triple-junction jump than is shown on figure 11.

### CONCLUSIONS

Latest Cretaceous and Tertiary melanges of the North American plate apparently can be correlated in both time and location with triple junctions that migrated along the western edge of this plate. The existence of triple junctions of the required dynamic type, the Humboldt-type triple junctions of Fox (1976), is implied by the magnetic record of crustal formation preserved in the ocean floor. The temporal and also the spatial correlation is required if the rate of movement of the North American plate with respect to the Pacific plate has averaged roughly 6 cm/yr for the past 21½ m.y. and approached that figure for the entire Tertiary.

Atwater and Molnar (1973) have calculated that this rate averaged only 2 cm/yr between 38 Ma and 10 Ma. The discrepancy between this rate and the 6-cm/yr rate invoked to correlate the Miocene melanges of the Olympic Peninsula with the transit of the causal triple junction must be resolved before a genetic link between melanges and triple junctions can be accepted with complete confidence. Direct correlation of the melanges of the Olympic Peninsula with what are presumed to be the causal plate-tectonic features suggests that plate movements have been continuous and the rate of rotation roughly constant from at least earliest Miocene time to the present.

If the melanges of the Franciscan Complex and Olympic Peninsula did form at migrating triple junctions, the ages of these melanges, together with the paleomagnetic record preserved in the ocean floor, suggest the following scenario:

(1) In latest Cretaceous to early Eocene time, a triple junction between the Kula, Farallon, and North American plates migrated northwestward along the edge of the North American plate at about 4 cm/yr.

(2) In early Eocene time, the southern part of the Kula plate broke away and was added to the Pacific plate through a northward jump of the Kula-Pacific spreading ridge.

(3) During middle through late Eocene time, the convergent motion of the obliquely colliding Pacific and

North American plates was arrested as fragments of the Pacific plate were sheared off, rotated clockwise, and sutured to the North American plate, forming the allochthonous Oregon-Washington borderland.

(4) In latest Oligocene to middle Miocene time, right-stepping ridge-ridge transform faults, including the Aja, intersected the Queen Charlotte fault, forming Humboldt-type triple junctions west of the present site of the Olympic Peninsula. At these triple junctions, the convergence of the subducted part of the oceanic plate on the south and the transform-bounded part of the North American plate on the north culminated in the formation of the melanges and broken formations of the Olympic Peninsula.

Latest Cretaceous to early Tertiary transit of the Kula-Farallon-North American triple junction apparently introduced a subduction-dominated tectonic regime that was to persist for at least 30 m.y. along the coast of California and to the present time along the coast of Oregon and Washington. Were melanges produced as part of the subduction process, melanges representing that age and age span should be widespread. Their general absence, except for the Olympic Peninsula, and the prevalence instead of melanges dating from the time of the postulated transition from strike-slip to subduction-dominated tectonism suggest that these melanges originated near the migrating Kula-Farallon-North American triple junction. Corroboration or refutation of this hypothesis should be sought through refinement of the age(s) of the melanges of the Franciscan Complex, through reevaluation of the contact relations of the Franciscan to the patches of Great Valley-like rocks, and through further consideration of the origin of blueschist.

The allochthonous Oregon-Washington borderland with its varyingly rotated blocks of oceanic crust seems to have originated through a glancing collision of the Pacific and North American plates. Many otherwise obscure tectonic features of the Pacific Northwest, including the allochthon of Colebrooke Schist, the Olympic-Wallowa lineament, the extensional volcanogenic grabens and related features of northern Washington, and, lastly, the allochthoneity of the borderland itself can be rationalized by this hypothesis. Such a collision, however, implies that the paths of the North American and Pacific plates were at least slightly convergent prior to late Eocene. Confirmation of this corollary should be sought through mapping of the tracks of hotspots and through determination of paleomagnetic poles for the Paleocene, Eocene, and Oligocene.

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