PLATE TECTONIC EVOLUTION OF NORTH PACIFIC RIM

William R. DICKINSON

Geology Department, Stanford University, Stanford, California, U.S.A.

(Received May 22, 1978)

The North Pacific Rim is a segment of the circum-Pacific orogenic belt lying along the great circle between Mesoamerica and Indochina. Paleotectonic reconstructions rely upon integration of information about rocks exposed on land, crustal thicknesses, paleolatitudes of crustal blocks, sediment layers cored at sea, and geomagnetic anomalies. Continental margins have been modified by accretion of oceanic materials during subduction, suturing of continental blocks by collision, and opening or trapping of marginal seas. Prior to the breakup of Pangaea, a vast Paleopacific seafloor was built by spreading coeval with the subduction that elsewhere assembled Pangaea. After the breakup of Pangaea, circum-Pacific subduction accreted deformed increments of the Paleopacific seafloor to the edges of continental blocks now along the North Pacific Rim. Cretaceous crustal collisions closed the North Pacific Rim and isolated the Arctic Ocean. Paleogene accretion of the continental Okhotsk block caused subduction to shift from the Bering shelf edge to the Aleutian chain. The elbow in the Emperor-Hawaii hotspot track records a change in Pacific plate motion at about the same time. Current circum-Pacific arcs include east-facing island arcs and west-facing continental arcs in a consistent pattern that implies net westward drift of continental lithosphere with respect to underlying asthenosphere.

1. Introduction

The northern margin of the Pacific Ocean extends from Central America on the east to the Philippine Sea on the west, and has the Bering Sea at its northern extremity. This North Pacific Rim lies along a global great circle upon which Japan and California are spaced about 90° apart. A continuation of the same great circle down the western side of the Americas leads to Chile, which lies about the same angular distance from California as does Japan. In the study of circum-Pacific tectonics, we must thus apply to the geology of the North Pacific Rim the same kind of integrated view that we should apply also to the western Cordilleras of the Americas. For example, British Columbia, Alaska, and Kamchatka form a single continuous segment of the circum-Pacific belt as surely as do the Latin American countries from Mexico through Columbia to Ecuador and Peru.

The purpose of this paper is to review the general status of our understanding about the plate tectonic history of the North Pacific Rim. Many details of present knowledge are omitted to allow a focus on broad relationships. My interest in the questions discussed was stimulated especially by my trip to Japan in 1976 as a visitor at the Earthquake Research Institute of the University of Tokyo, where I was a participant in the scientist exchange program sponsored by the American Geophysical Union and supported by the U.S. National Science Foundation under the U.S.-Japan Cooperative Science Program in liaison with the Japan Society for the Promotion of Science. My subsequent work was supported by the U.S. National Science Foundation with Grants EAR75-14568 and EAR77-27542.

2. Overview

The present configuration of the Pacific borders of North America and Eurasia, and the present geologic relationships of rock assemblages within the continental margins, is the result of long-continued processes of tectonic evolution within the circum-Pacific orogenic belt. Valid paleogeographic and paleogeologic reconstructions of these lands that are now part of the North Pacific Rim must be based on the integration of several kinds of data:

- a) distribution and age of diagnostic rock assemblages mapped on land,
- b) varying crustal thicknesses on land and at sea,
- c) paleomagnetic data on paleolatitudes for different continental blocks,
- d) patterns of geomagnetic anomalies on the deep-sea floor,
- e) information on sediment thicknesses and facies from deep-sea drilling.

Data from the deep sea applies directly only to times since the mid-Mesozoic, for no pre-Jurassic seafloor is known in the Pacific Ocean. In common with those in the Atlantic and Indian oceans, Pacific seafloor anomalies thus provide some record of events since the breakup of Pangaea, but not before.

The major types of tectonic events that have affected the Pacific Rim since the Mesozoic breakup of Pangaea include:

- a) the subduction and accretion of oceanic materials during plate consumption at various bounding trenches,
- b) the collision and suturing of microcontinental blocks against the surrounding continental margins,
- c) the opening of interarc basins to form or expand marginal seas lying mainly on the western side of the open ocean,
- d) the cancellation of spreading centers (or belts) by rise-trench encounters occurring mainly on the eastern side of the ocean,
- e) the development of marginal and intracontinental transforms causing strike slip either longitudinal or transverse to associated continental margins.

Prior to the breakup of Pangaea, the world ocean Panthalassa was mainly a paleo-Pacific realm (DICKINSON, 1977a, b), and the Tethys Sea can be regarded as a gulf of the Paleopacific Ocean (Fig. 1) during Permo-Triassic time. In Permo-Carboniferous time, the earlier assembly of Pangaea (IRVING, 1977) presumably required subduction of ocean floor to allow Laurasia and Gondwana to be sutured together west of the Tethyan gulf. Late Paleozoic subduction can be inferred along both the Hercynian-Variscan (and Appalachian-Ouachita) orogenic belts of Laurasia and the Gondwanide-Tasmanide orogenic trend of Gondwana (see Fig. 1). Coeval spreading within the Paleopacific Ocean was presumably required to maintain a global mass balance. Subduction at continental margins facing the Paleopacific Ocean was apparently not required prior to the later breakup of Pangaea.

The oldest granitic components in batholiths of the circum-Pacific orogenic belt do not date much beyond about 200 my, which was near the Triassic-Jurassic boundary. This fact suggests that the present regime of subduction beneath continental margins now facing the Pacific Ocean was not established before about mid-Triassic time. Since then, circum-Pacific and Alpine-Himalayan subduction have been paired in time with opening of the Atlantic and Indian oceans. Widespread mid-Carboniferous to mid-Triassic

Fig. 1. Inferred Triassic world map (Mercator projection) showing Pangaea and the large Paleopacific Ocean. Japan is restored against Eurasia but remnant oceans within Eurasia are not shown (Indonesian islands depicted in present configuration for orientation only). From DICKINSON (1977b).

oceanic facies exposed now within the circum-Pacific orogenic belt of the North Pacific Rim apparently represent deformed increments of the old Paleopacific seafloor now incorporated into the margins of continental blocks. They were accreted tectonically to the edges of North America and Eurasia by Mesozoic subduction as seafloor spreading generated younger Pacific seafloor farther offshore. No vestige of the once vast Paleopacific seafloor remains within the confines of the present Pacific Ocean.

The enclosed outline of the North Pacific Rim did not attain its present overall shape until the closure of late Mesozoic suture belts welded the Eurasian and American continental blocks together across the Alaska-Bering-Yakutia region (CHURKIN, 1972). Full details of this complex process will not be known until the plate tectonic evolution of the Arctic Ocean is better documented.

3. Current Tectonics

Figure 2 is a sketch map showing key tectonic features of the North Pacific Rim and the adjacent Pacific Ocean. Volcanic chains that mark active magmatic arcs stand parallel to active subduction zones at trenches, but are absent elsewhere around the periphery of the ocean. Young seafloor marks the crests of active midoceanic rises and forms the floor of active interarc basins. The Emperor Seamounts chain and the Hawaiian Ridge form linked segments of a hotspot track generated by the hotspot now beneath Hawaii (MORGAN, 1972). The Emperor-Hawaii elbow evidently records a marked change in the motion of the Pacific plate with respect to the hotspot about 40 mybp (DALRYMPLE and CLAGUE, 1976).

On Fig. 2, Japan and California appear to lie on opposite sides of an intervening ocean, but this erroneous impression reflects distortion that is inherent in the customary Mercator projection used as a base map. In reality, the North Pacific Rim is a belt that approximates a great circle (see Fig. 2, inset). Figure 3 is a tectonic sketch map showing much the same information as Fig. 2, but drawn using a projection upon which that great circle plots as a straight line. Japan and California are thus shown correctly as lying on the

Fig. 2. Current tectonic elements of the North Pacific Rim and the northern Pacific Ocean shown on a standard Mercator projection. Seafloor ages modified after PITMAN *et al.* (1974) and HILDE *et al.* (1977). American-Eurasian plate boundary after CHAPMAN and SOLOMON (1976).

Fig. 3. Current tectonic framework of the North Pacific Rim plotted on a projection showing that segment of the circum-Pacific great circle as a linear belt bordering the northern Pacific Ocean. Double line denotes Atlantic spreading center; subduction zones shown as on Fig. 2.

same continuous margin of the Pacific Ocean. The ocean in reality has no "sides" because its whole periphery approximates the great circle that delimits the watery hemisphere of the earth.

Nevertheless, Figs. 2 and 3 both reflect a distinct east-west asymmetry in Pacific

tectonics (NELSON and TEMPLE, 1972). In the open ocean, spreading centers lie well to the east of the central meridian within the oceanic region. The continental margins with subduction zones also have different characters. On the western "side" of the ocean, east-facing island arcs are associated with marginal seas formed by interarc spreading. On the eastern "side" of the ocean, west-facing magmatic arcs stand on the edges of intact continental blocks. These differences imply some fundamental distinction between subduction systems where seafloor is being subducted either eastward or westward beneath continental margins that have generally meridional orientations.

4. *Backarc Behavior*

Although the rates of tectonic and sedimentary accretion vary in the forearc region between the trench and the volcanic chain, evolutionary trends are similar in all arc-trench systems (DICKINSON, 1973a). In the backarc region, however, two opposite extremes of behavior are noted (DICKINSON, 1972, 1973b, 1974a, b):

a) Behind some intra-oceanic arcs, seafloor spreading within an interarc basin widens the marginal sea that separates the island arc from the nearby continental margin; this process involves separation of lithosphere and upwelling of asthenosphere to form new oceanic lithosphere in the backarc region.

b) Behind some continental-margin arcs, fold-thrust belts form a subsidiary mountain chain that rises between the volcanic chain and the adjacent continental interior; this process involves contraction of lithosphere, crustal thickening within the mountain belt, and the development of a retroarc foreland basin on a depressed part of the continental block in the backarc region.

For a third and intermediate style of backarc behavior, neither process occurs.

Several workers have discussed the probable plate motions associated with backarc spreading and backarc thrusting (HAVEMANN, 1972; HYNDMAN, 1972; MOBERLY, 1972; WILSON and BURKE, 1972). In general, advective heat flow associated with arc magmatic activity apparently softens the lithosphere along the trend of the arc, and thus allows lithosphere in the backarc region to move independently of the narrow sliver of lithosphere occupying the band between arc and trench. The arc structure itself remains in place above the descending slab of lithosphere being subducted. The sliver plate in the arc-trench gap is thus constrained to maintain its position relative to the flexure where lithosphere bends at the subduction zone to descend into the mantle. Meanwhile, backarc lithosphere is able to shift position with respect to that flexure.

Two fundamental causes of relative motion between the backarc lithosphere and the flexure in the subducted slab of lithosphere have been suggested (e.g., MOLNAR and ATWATER, 1978; UYEDA and KANAMORI, 1979):

a) One mechanism considers the tendency of the descending slab to sink into the asthenosphere. Where the sinking slab is old and thick, with a high bulk density, the rate of sinking is fast in relation to the rate of plate convergence across the arc-trench system; the flexure in the descending slab thus tends to migrate oceanward, and backarc spreading accommodates the resulting extension as the arc-trench system pulls away from backarc lithosphere. Where the sinking slab is young and thin, with a low bulk density, the rate of sinking is slow in relation to the rate of plate convergence across the arc-trench system; the flexure in the descending slab thus tends to migrate landward, and backarc

Fig. 4. Plot showing relationship between Cenozoic backarc tectonics and geographic orientation of associated arc-trench systems. "Facing" azimuth is given by a line drawn normal to the subduction zone and leading away from the trench side of the system. See text for discussion.

thrusting accommodates the resulting contraction as the arc-trench system presses against the backarc lithosphere.

b) The other mechanism considers potentially independent motions of the backarc lithosphere with respect to underlying asthenosphere. The descending slab is held to anchor the arc-trench system with respect to the part of the asthenosphere into which the slab is being inserted. Backarc spreading then occurs where backarc lithosphere is skidding away from the flexure in the descending slab, and backarc thrusting occurs where backarc lithosphere is skidding toward the flexure in the descending slab.

The two mechanisms are not mutually exclusive, and each may serve to reinforce or counteract the effect of the other in a particular case.

A census of modern arc-trench systems (Fig. 4) shows that backarc spreading is characteristic of those that face eastward (subduction downward to the west), whereas backarc thrusting is most widespread in those that face westward (subduction downward to the east). Although "neutral" systems that lack either backarc spreading or backarc thrusting are known to face both eastward and westward, they are most typically southward-facing (northward-facing arcs are absent on the modern earth). Consequently, backarc spreading is typical for arcs along the western periphery of the Pacific and backarc thrusting is common for arcs along the eastern periphery of the Pacific. Figure 5 is a schematic diagram of standard relations across the modern Pacific.

The east-west dichotomy of current arc behavior and the east-west asymmetry of the modern Pacific Ocean may be wholly fortuitous products of plate motions that are currently suitable for that pattern but are directionally random over the long term. How-

Fig. 5. Diagram showing characteristic east-west asymmetry of placement of midoceanic rise and east-west dichotomy of backarc behavior. See text for discussion.

ever, several workers have suggested that the present relationships are the systematic result of net shear between lithosphere and asthenosphere (BOSTROM, 1971; KNOPOFF and LEEDS, 1972; MOORE, 1973). Such shear may be inherent between these two loosely coupled layers of the outer earth as the rotation of the earth decelerates. Westward lag of the lithosphere layer above asthenosphere that rotates faster could account for both the dichotomy of arc behavior and the asymmetry of the ocean (see Fig. 5):

a) For east-facing subduction zones (subduction downward to the west), backarc lithosphere would move away from the arc-trench system, which would be anchored by a steepened slab.

b) For west-facing subduction zones (subduction downward to the east), backarc lithosphere would move toward the arc-trench system, which would be anchored by a slab being entrained beneath overriding lithosphere.

c) Gradual eastward migration of midocean rises relative to bounding continental margins might occur in response to the interaction between asthenosphere and the portions of plates of lithosphere that are inserted into the asthenosphere as descending slabs. West-facing continental margins would tend to override and entrain eastward-subducting plates, and thus to encroach upon the eastern flanks of midocean rises. Slabs of differing age, thickness, and consequent negative buoyancy would thus come to descend on eastern and western borders of the ocean. The contrast would be such as to reinforce the behavioral tendencies established for east-facing and west-facing arc-trench systems (see Fig. 5). Moreover, interaction between lithosphere and asthenosphere would help to steepen the angle of descent of westward-subducting plates and to press the zone of plate flexure away from associated east-facing continental margins, whereas the angle of descent of eastward-subducting plates could be reduced and their zones of flexure pressed toward associated west-facing continental margins.

The relationships depicted by Fig. 4 seem too clearcut to be wholly coincidental, and hence suggest that the rotational effects are real.

5. Late Cenozoic Tectonics

For tectonic reconstructions during the Cenozoic, the key feature in the northern Pacific Ocean is the Emperor-Hawaii hotspot track (Figs. 2, 3). During the past 40 my, the Hawaiian Ridge has been generated by movement of the Pacific plate over the Hawaii hotspot at an essentially constant rate (DALRYMPLE *et al.*, 1977). Figure 6 shows inferred

relationships in the northern Pacific Ocean during that time span. Prior to 40 mybp, back to about 70 mybp, movement of the Pacific plate over the Hawaii hotspot at a similar rate, but in a more northerly direction, generated the Emperor Seamounts. Both paleomagnetic and paleoecologic data confirm the requisite northward motion of the seamounts during the Cenozoic (MARSHALL, 1978; GREENE *et al.*, 1978).

Figure 6 indicates that the existence of the Meiji sediment tongue of Neogene terrigenous clay (SCHOLL *et al.*, 1977) cannot be used as a valid argument against such motion of the Pacific seafloor. The area near Meiji seamount has occupied positions close to

Fig. 6. Sketch maps showing key tectonic elements in the northern Pacific Ocean at present (above) and 40 mybp (below). Approximate position of Emperor Seamount chain is shown also at 22.5 mybp (Oligocene-Miocene boundary) on each plot. Rates of generation of Hawaiian and Pratt-Welker hotspot tracks modified after DUNCAN and McDOUGALL (1976), JARRARD and CLAGUE (1977), and DALRYMPLE *et al.* (1977). Plate boundaries and continental configurations at 40 mybp modified after COOPER *et al.* (1976), STONE and PACKER (1977), and PITMAN and TALWANI (1972).

Fig. 7. Configurations of western North Pacific plate boundaries and island arcs at present (left) and 40 mybp (right). See text for discussion.

sediment sources along the Aleutian Ridge since the sediment tongue first began to form. However, the restored position of the Aleutian abyssal plain is problematical (MARLOW *et al.*, 1973; SCHOLL *et al.*, 1975, 1977), because the source terrane for its mid-Cenozoic turbidites lay somewhere along the continental margin between Vancouver Island and Kodiak Island (STEWART, 1976). The reconstruction of Fig. 6 implies that unsuspected complexities in the configuration of plate boundaries may have existed in the northeastern corner of the mid-Cenozoic Pacific. BYRNE (1978) has recently argued that the Kula-Pacific spreading center ceased operating about 57.5 mybp. If this idea is confirmed, the Kula plate is incorrectly included in Fig. 6 (below) for 40 mybp, and no plate boundary would have been present to block the delivery of mid-Tertiary turbidites from sources along the northeastern margin of the Pacific to the Aleutian abyssal plain on the Pacific plate.

In the western Pacific, interarc seafloor spreading (KARIG, 1970) behind east-facing island arcs has opened the Sea of Japan (MATSUDA and UYEDA, 1971; SILLITOE, 1977) and broadened the Philippine Sea (TOMODA *et al.*, 1975; WATTS *et al.*, 1977) since the early Cenozoic. Figure 7 shows the changing configuration of island arcs within this region during the time span represented by Fig. 6. At 40 mybp, the Marianas frontal arc and the Palau-Kyushu remnant arc were united as a single ancestral island arc (KARIG, 1971). Past plate configurations in the area of the Philippine Islands are problematical (KARIG, 1973). In Taiwan and the Ryukyus along the western side of the Philippine Sea, no subduction was underway in the middle parts of the Cenozoic (MURPHY, 1973). Complex strike slip is implied for the Sakhalin region during formation of the Sea of Japan, but the restoration depicted in Fig. 7 is schematic only.

Along the American border of the North Pacific (Fig. 8), the major events during the late Cenozoic were (a) ridge or rise subductions that occurred as the asymmetry of the ocean basin was accentuated by consumption of the Kula plate and most of the Farallon plate, (b) generation of the San Andreas and Queen Charlotte transform systems as the Pacific plate came into contact finally with the American plate, and (c) development of the extensional Basin and Range province by incipient disruption of the American plate in the region adjacent to the San Andreas transform.

Fig. 8. Configurations of eastern North Pacific plate boundaries and subduction zones at present (above) and 40 mybp (below). See text for discussion.

6. Rise-Trench Encounter

So-called ridge or rise subduction is better described as rise-trench encounter. Generation of new lithosphere is the dominant process at a rise or ridge crest, but can occur only near the surface of the earth. Only there does plate separation involve the kind of pressure release required to trigger partial melting of the asthenosphere on a large scale, and only there can heat loss be rapid enough to chill upwelling material sufficiently to form new lithosphere. When a rise and a trench meet after the intervening plate has been consumed, the zone of plate separation that is marked by a discrete ridge crest at the surface will no longer form such a discrete belt where it becomes subterranean. The overall plate kinematics do require that the wholly consumed plate descend into the mantle faster than the plate on the other side of the rise or ridge crest (else no plate separation occurs!). As the zone of separation between the two is drawn into a subterranean position, however, it is marked by a broad and expanding region of sublithospheric mantle upwelling, and not by a belt of steady-state width where new lithosphere is created, as would occur at the surface.

Rise-trench encounter can cause two different but related results depending upon whether the plate beyond the rise or ridge crest is subducted or not following the encounter:

a) Where it is subducted, as happened along the Aleutian trench following a mid-Cenozoic encounter with the Kula-Pacific ridge (DeLong *et al.*, 1978), several distinct but simultaneous events punctuate the geologic history of the arc-trench system. These serve to record the rise-trench encounter as a discontinuity in the evolution of the Aleutian Ridge. The genetically related effects stem either from the temporary absence of a descending slab beneath the arc-trench system, or from the high heat flow and thermal expansion imposed across the arc-trench system while the cold subterranean slab was absent (DeLong and Fox, 1977). The changing thermal regime was reflected by an episode of broad uplift affecting the whole arc-trench system, and by a pulse of metamorphism at

crustal levels. A temporary cessation of arc magmatism extinguished the volcanic chain while no subducted slab was present.

b) Where it is not subducted, the trench is converted to a transform like the modern San Andreas, which lengthens as the triple junctions at either end migrate away from one another. In this case, a gradually expanding region that lacks a subducted slab develops in a triangular form adjacent to the transform (DICKINSON and SNYDER, 1979b). This no-slab region occupies the space above a gradually enlarging window or hole in the descending slab. Arc magmatism is extinguished where a descending slab is absent, and upwelling of asthenosphere to occupy the slab-window can contribute also to uplift and extensional tectonics within a region of triangular shape adjacent to the transform. Figure 9 depicts these relationships for the San Andreas transform system and the Basin-and-Range province adjacent to it. Note the following geometric relationships shown: (a) the gradual shortening of the Cascades volcanic arc as the expansion of the no-slab region above the slab-window in the descending Farallon plate expanded to extinguish the southern extension of the arc in progressive fashion through the Neogene, (b) the overall coincidence between the inferred extent of the modern no-slab region and the known extent

Fig. 9. Sketch maps showing evolution of the San Andreas coastal transform system and an adjacent subcontinental region of triangular shape lacking a subducted slab. After DICKINSON and SNYDER (1979a, b). See text for discussion. Points *M* and *R* are Mendocino and Rivera triple junctions, respectively.

of uplifted and block-faulted continental crust underlying the Basin-and-Range province and Colorado Plateau where mantle upwelling through the slab-window is to be expected, and (c) the manner in which the site of the San Andreas transform boundary between Pacific and American plates has shifted gradually inland from an original position near the continental slope to its present location along the San Andreas fault proper.

In either scenario for events that follow rise-trench encounter, thermal effects near triple junctions that terminate rise crests at the trench may promote anatectic melting of otherwise cold subduction complexes (MARSHAK and KARIG, 1977). This effect can give rise to magmatism at sites anomalously close to the trench. Small plutons and volcanic fields of Cenozoic age in the coastal regions of California, Alaska, and Japan may all stem from this potential effect of rise-trench encounter.

7. *Early Cenozoic Tectonics*

Latest Cretaceous and earliest Cenozoic tectonics in the western Cordillera of North America were dominated by the Laramide Orogeny. In the central part of the Cordillera where the deformation was most characteristic, fault-bounded uplifts and intervening sediment-filled depressions developed across a broad arc massif that was essentially dormant magmatically. This style of diastrophism occurred during the period from 70 to 40 mybp, and was most intense at about 55 mybp in the Wyoming and Colorado Rockies. The classic Laramide orogenic style, essentially amagmatic with basement involvement in contractional structures, can be attributed to underthrusting of a subducted plate at a low angle beneath the continental plate (CONEY, 1976, 1978). This inference is based on the areal distribution of subduction-related igneous suites having varied alkalinity and potassicity (LIPMAN *et al.*, 1971). This shallow mode of plate consumption contrasts with the more normal steep mode that generates arc magmatism (see Fig. 10). Where the descending plate dives steeply into the asthenosphere, magmas are generated (BARAZANGI and ISACKS, 1976), and a standard type of arc orogen develops. Where the descending plate scrapes along beneath the overriding plate, magmatism is suppressed and buckling of the overriding plate causes the basement-cored uplifts of a Laramide-style orogen (DICKINSON and SNYDER, 1978).

Pacific asymmetry that dictates the presence of spreading centers in comparative proximity to the American coasts means that relatively young lithosphere is subducted beneath the Americas (see Fig. 8). Plate buoyancy may thus commonly promote Laramide-type phases of evolution for west-facing American arc massifs, whereas similar deformation may never or seldom affect east-facing Eurasian island arcs. In this sense, Laramide-style deformation is akin genetically to backarc thrusting and is incompatible with backarc spreading (CONEY, 1972).

The prominent elbow in the Emperor-Hawaii hotspot track (Figs. 2, 3, and 6) reflects an abrupt change in the direction of Pacific plate motion across the Hawaii hotspot at about 40 mybp. The movement of a subducting plate is governed mainly by the descending slabs attached to it at subduction zones (FORSYTH and UYEDA, 1975; CHAPPLE and TULLIS, 1977). In effect, the pull of the slab as it falls into the mantle causes the plate to skid over the asthenosphere. Consequently, the most direct way to affect the overall motion of the Pacific plate is to change the configuration of the subduction zones at its boundaries.

Tectonic relations across northeastern Eurasia between the Bering Sea and the Hok-

Fig. 10. Diagrams illustrating amagmatic Laramide-style shallow subduction (above) and more ordinary steeper subduction (below) that generates arc magmatism. After DICKINSON and SNYDER (1978).

kaido-Sakhalin region suggest a major change in plate boundaries during the early Cenozoic. Most of the Sea of Okhotsk is underlain by continental crust at least twice as thick as standard oceanic crust (BURK and GNIBIDENKO, 1977). Despite this, a calc-alkalic volcano-plutonic belt lay west and north of the present Sea of Okhotsk during the Late Cretaceous and early Cenozoic (ZONENSHAIN *et al.*, 1974). These relations suggest that a microcontinental Okhotsk block of unknown origin lodged against the margin of Eurasia during the early Cenozoic (DEN and HOTTA, 1973). Previously, an unknown width of ocean intervened between Eurasia and the Okhotsk block.

Figure 11 shows the key relationships of the Okhotsk block in map view. Prior to the accretion of the Okhotsk block to Eurasia, the subduction system forming the North Pacific Rim lay farther west and north than it does now. The subduction zone lay through Taiwan, the Shimanto belt of outer Japan, central Hokkaido, Sakhalin, the Magadan coast, and the Koryak Mountains at the root of Kamchatka; thence along the continental slope of the Bering Sea and the Shumagin-Kodiak-Chugach trend in southern Alaska. The parallel magmatic arc lay in coastal China, peninsula Korea, parts of inner Japan, Sikhote-Alin in coastal Primorye, the Okhotsk belt, and northeasternmost USSR; thence along the Bering shelf and coastal Alaska. After accretion of the Okhotsk block, subduction shifted eastward and southward to the Izu-Mariana arc east of the Philippine Sea, the Kuril-Kamchatka arc along the edge of the accreted Okhotsk block, and the Aleutian arc south of the Bering Sea.

The Bering Sea contains north-south geomagnetic anomalies formed at the Kula-Farallon plate boundary during the Early Cretaceous (COOPER *et al.*, 1976). This Mesozoic seafloor was trapped behind the Aleutian Ridge when subduction and arc magmatism jumped from the Bering shelf edge to the Aleutian trend (SCHOLL *et al.*, 1975). Accretion of the Okhotsk block directly choked the segment of the pre-accretion subduction zone that lay along the Magadan coast parallel to the Okhotsk volcano-plutonic belt, and southward through Sakhalin to Hokkaido. Abandonment of the subduction system

Fig. 11. Sketch map showing inferred evolution of subduction systems before and after accretion of the Okhotsk block by crustal collision followed by a subduction jump.

through the Koryak Mountains and along the Bering shelf edge was evidently an indirect effect of Okhotsk accretion. Attachment of the Okhotsk block to Eurasia left the Koryak-Bering segment of the pre-accretion subduction zone adjacent to a deep re-entrant in the continental margin. Rather than mold itself in a tight flexure following the outline of the re-entrant, the Pacific plate apparently broke across the re-entrant to connect post-accretion subduction along the southeast edge of the Okhotsk block with continuing subduction in southern Alaska by way of the newly established Aleutian trend. The oldest well dated rocks exposed on the Aleutian Ridge are Eocene (MARLOW *et al.*, 1973), and the oldest arc volcanics on Kamchatka are of similar age (AVDEIKO, 1971). The completion of Okhotsk accretion was thus timed closely with the change in Pacific plate motion at about 40 mybp. The reasons for the initiation of subduction along the Izu-Mariana trend to create the Philippine Sea plate are still uncertain (UYEDA and BEN-AVRAHAM, 1972; UYEDA and MIYASHIRO, 1974), but the oldest arc volcanics in the Marianas are also Eocene. Termination of Laramide deformation in the North American Cordillera and of subduction in the Greater Antilles is even more difficult to relate to either the accretion of the Okhotsk block or the formation of the Emperor-Hawaii elbow, but these other events also took place at about 40 mybp (CONEY, 1971). Some linkage of plate interactions throughout the North Pacific region is seemingly implied by the widespread significance of that date (cf. CONEY, 1971).

8. Crustal Collision-Accretion

Accretion of exotic crustal blocks to the continental margins that now form the North Pacific Rim has occurred repeatedly throughout the Mesozoic and the Cenozoic. Both equant microcontinental blocks and elongate island arcs or aseismic oceanic ridges have been involved. In both cases, accretion occurs by crustal collision when the buoyancy of lithosphere capped by a thick crustal profile resists subduction. The accretion of discrete

crustal masses by such crustal collision is a process apart from the incremental accumulation of a growing subduction complex formed of offscrapings from the seafloor.

Two main kinds of crustal collision provide accretionary additions to continental margins (Fig. 12). In one case, an active island arc collides with a passive continental margin, which it partially subducts. The arc structure is thus attached to the continental margin. Such an event occurred in Taiwan in the late Cenozoic (CHAI, 1972). If the overall pattern of plate kinematics induces subduction to resume following such arc-continent collision, then subduction beneath the opposite side of the accreted arc structure may generate an active continental margin following accretion.

Such a sequence of events was involved in the onset of circum-Pacific subduction in California (Fig. 13). An east-facing island arc of late Paleozoic age collided with the Cordilleran margin to produce an episode of Permo-Triassic deformation called the Sonoma Orogeny, during which the Havallah-Pumpernickel subduction complex was

Fig. 12. Diagrams depicting main variants of accretionary events involving crustal collision at continental margins.

Fig. 13. Regional geologic relations of the Sierran-Klamath arc terrane at the onset of Mesozoic subduction, which was initiated by polarity reversal following accretion of the terrane to the continental margin by crustal collision during the Sonoma Orogeny near the close of the Paleozoic.

emplaced across the continental margin as an allochthonous mass atop the Golconda thrust (DICKINSON, 1977a). Following accretion of the island arc by crustal collision in the mid-Triassic, reversal of arc polarity allowed Jura-Triassic subduction to continue along the western side of the accreted arc terrane in the Sierra Nevada foothills (SCHWEICKERT and COWAN, 1975). This was the earliest inception of the continental-margin Cordilleran arc-trench system.

In the kind of accretion represented by the attachment of the Okhotsk block to Eurasia, the continental margin is active and draws a passive block against its bounding subduction zone from a position at sea. Following crustal collision, subduction jumps to the opposite side of the accreted block. Not only may microcontinental blocks be accreted in this way, but also dormant island arcs, oceanic seamount chains, and aseismic oceanic ridges (DICKINSON, 1976). Extensive terranes in the Cordillera of North America have been accreted in this general fashion.

Figure 14 depicts inferred crustal relations along a generally east-west profile across the Hidaka collision orogen in Hokkaido. During the early Cenozoic, a southern extremity of the Okhotsk block was sutured against a western terrane then attached to Eurasia prior to the opening of the Sea of Japan. Prior to collision, the Cretaceous and early Cenozoic orogen was an east-facing arc-trench system on the Eurasian mainland (OKADA, 1974). Clastics shed eastward from the igneous terrane to the west fill an old forearc basin where they rest on ophiolitic rocks. This ophiolitic substratum is tilted up and faulted against strongly deformed but weakly metamorphosed oceanic facies representing the subduction complex. Along a fault contact interpreted here as the main suture belt, these strata are in contact with a belt of amphibolites, gabbros, migmatites, and gneisses (HASHIMOTO, 1975). These strongly metamorphosed rocks are taken here to be part of the basement of the Okhotsk block that lodged against the old subduction zone. Subduction then jumped eastward to the new subduction zone along the Kuril trend. During the late Cenozoic, sediments were shed westward from the collision orogen to mask parts of the old forearc basin.

Late Mesozoic crustal collisions across the Alaska-Bering-Yakutia region welded together for the first time the crustal blocks that form the North Pacific Rim (Fig. 15). The positions and ages of the various suture belts involved is not yet well known. Large tracts are accretionary collages of oceanic rock assemblages. Closure of the most signifi-

Fig. 14. Inferred structural relations in Hokkaido where Paleogene accretion of the Okhotsk block along the Hidaka suture belt triggered a subduction jump that initiated the Kuril trench.

Fig. 15. Sketch map showing main crustal sutures joining North America and Eurasia across the Alaska-Bering-Yakutia region to form the North Pacific Rim.

cant oceanic regions probably occurred between mid-Jurassic and mid-Cretaceous time (CHURKIN, 1972), but some contraction across the region was still underway in the Cenozoic (PITMAN and TALWANI, 1972).

9. Review

The major points made are these:

- 1) The North Pacific Rim is a continuous great-circle belt on the globe.
- 2) Prominent east-west asymmetry of the Pacific Ocean and systematic east-west dichotomy of arc behavior both probably stem from rotational influences on plate tectonics.
- 3) Late Cenozoic tectonics around the North Pacific Rim involved mainly the opening of interarc basins behind east-facing Eurasian arcs and rise-trench encounters at west-facing American subduction zones.
- 4) The formation of the Emperor-Hawaii elbow at about 40 mybp was roughly coeval with accretion of the Okhotsk block to Eurasia by crustal collision and with termination of the classic Laramide deformation, which was caused by plate descent at an abnormally shallow angle beneath America.
- 5) The North Pacific Rim lacked geographic continuity prior to the late Mesozoic closure of remnant ocean basins along suture belts within the land bridge between America and Eurasia, and even circum-Pacific subduction itself was probably not underway prior to the early Mesozoic.

REFERENCES

- AVDEIKO, G.P., Evolution of geosynclines on Kamchatka, *Pac. Geol.*, **3**, 1-15, 1971.
- BARAZANGI, Muawia and B.L. ISACKS, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America, *Geology*, **4**, 686-692, 1976.
- BOSTROM, R.C., Westward displacement of lithosphere, *Nature*, **234**, 536-538, 1971.
- BURK, C.A. and H.S. GNIBIDENKO, The structure and age of acoustic basement in the Okhotsk Sea, in *Island Arcs, Deep Sea Trenches, and Back-Arc Basins*, edited by Manik Talwani and W.C. Pitman, III, pp. 451-462, Am. Geophys. Union Maurice Ewing Ser. 1, 1977.
- BYRNE, Tim, Early Tertiary demise of the Kula-Pacific spreading center, *Geol. Soc. Am. Abstr. with Programs*, **10**, 98, 1978.
- CHAI, B.H.T., Structure and tectonic evolution of Taiwan, *Am. J. Sci.*, **262**, 389-422, 1972.
- CHAPMAN, M.C. and S.C. SOLOMON, North American-Eurasian plate boundary in northeast Asia, *J. Geophys. Res.*, **81**, 921-930, 1976.

- CHAPPLE, W.M. and T.E. TULLIS, Evaluation of the forces that drive the plates, *J. Geophys. Res.*, **82**, 1967-1984, 1977.
- CHURKIN, Michael, Jr., Western boundary of the North American continental plate in Asia, *Geol. Soc. Am. Bull.*, **83**, 1027-1036, 1972.
- CONEY, P.J., Cordilleran tectonic transitions and motion of the North America plate, *Nature*, **233**, 462-465, 1971.
- CONEY, P.J., Cordilleran tectonics and North America plate motion, *Am. J. Sci.*, **262**, 603-628, 1972.
- CONEY, P.J., Plate tectonics and the Laramide orogeny, in *Tectonics and Mineral Resources of Southwestern North America*, edited by L.A. Woodward and S.A. Northrop, New Mex. Geol. Soc. Spec. Publ. No. 6, pp. 5-10, 1976.
- CONEY, P.J., Mesozoic-Cenozoic Cordilleran plate tectonics, *Geol. Soc. Am. Mem.*, **152**, 33-50, 1978.
- COOPER, A.K., D.W. SCHOLL, and M.S. MARLOW, Plate tectonic model for the evolution of the eastern Bering Sea basin, *Geol. Soc. Am. Bull.*, **87**, 1119-1126, 1976.
- DALRYMPLE, G.B. and D.A. CLAGUE, Age of the Emperor-Hawaii bend, *Earth Planet. Sci. Lett.*, **31**, 313-329, 1976.
- DALRYMPLE, G.B., D.A. CLAGUE, and M.A. LANPHERE, Revised age for Midway volcano, Hawaiian volcanic chain, *Earth Planet. Sci. Lett.*, **37**, 107-116, 1977.
- DELONG, S.E. and P.J. FOX, Geological consequences of ridge subduction, in *Island Arcs, Deep Sea Trenches, and Back-Arc Basins*, edited by Manik Talwani and W.D. Pitman, III, Am. Geophys. Union Maurice Ewing Ser. 1, pp. 221-228, 1977.
- DELONG, S.E., P.J. FOX, and F.W. McDOWELL, Subduction of the Kula ridge at the Aleutian trench, *Geol. Soc. Am. Bull.*, **89**, 83-95, 1978.
- DEN, N. and H. HOTTA, Seismic refraction and reflection evidence supporting plate tectonics in Hokkaido, *Pap. Meteorol. Geophys.*, **24**, 31-54, 1973.
- DICKINSON, W.R., Evidence for plate-tectonic regimes in the rock record, *Am. J. Sci.*, **272**, 551-576, 1972.
- DICKINSON, W.R., Widths of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs, *J. Geophys. Res.*, **78**, 3376-3389, 1973a.
- DICKINSON, W.R., Reconstruction of past arc-trench systems from petro-tectonic assemblages in the island arcs of the western Pacific, in *The Western Pacific; Island Arcs, Marginal Seas, Geochemistry*, edited by P.J. Coleman, pp. 569-601, Univ. Western Australia Press, Perth, 1973b.
- DICKINSON, W.R., Sedimentation within and beside ancient and modern magmatic arcs, in *Modern and Ancient Geosynclinal Sedimentation*, edited by R.H. Dott, Jr. and R.H. Shaver, Soc. Econ. Paleontol. Mineral. Spec. Publ. No. 19, pp. 230-239, 1974a.
- DICKINSON, W.R., Plate tectonics and sedimentation, in *Tectonics and Sedimentation*, edited by W.R. Dickinson, Soc. Econ. Paleontol. Mineral. Spec. Publ. No. 22, pp. 1-27, 1974b.
- DICKINSON, W.R., Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America, *Can. J. Earth Sci.*, **13**, 1268-1287, 1976.
- DICKINSON, W.R., Paleozoic plate tectonics and the evolution of the Cordilleran continental margin, in *Paleozoic Paleogeography of the Western United States*, edited by J.H. Stewart, C.H. Stevens, and A.E. Frietsche, Pac. Sec. Soc. Econ. Paleontol. Mineral. Pac. Coast Paleogeogr. Symp. 1, pp. 137-156, 1977a.
- DICKINSON, W.R., Subduction tectonics in Japan, *EOS, Trans. Am. Geophys. Union*, **58**, 948-952, 1977b.
- DICKINSON, W.R. and W.S. SNYDER, Plate tectonics of Laramide Orogeny, *Geol. Soc. Am. Mem.*, **151**, 355-366, 1978.
- DICKINSON, W.R. and W.S. SNYDER, Geometry of triple junctions related to San Andreas transform, *J. Geophys. Res.*, **84**, 1979a (in press).
- DICKINSON, W.R. and W.S. SNYDER, Geometry of subducted slabs related to San Andreas transform, *J. Geol.*, **87**, 1979b (in press).
- DUNCAN, R.A. and Ian McDUGALL, Linear volcanism in French Polynesia, *J. Volcanol. Geotherm. Res.*, **1**, 197-227, 1976.
- FORSYTH, Donald and S. UYEDA, On the relative importance of the driving forces of plate motion, *Geophys. J. R. Astr. Soc.*, **43**, 163-200, 1975.
- GREENE, H.G., G.B. DALRYMPLE, and D.A. CLAGUE, Evidence for northward movement of the Emperor Seamounts, *Geology*, **6**, 70-74, 1978.
- HASHIMOTO, S., The basic plutonic rocks of the Hidaka metamorphic belt, *J. Fac. Sci. Hokkaido Univ.*, Ser. IV, **16**, 367-420, 1975.
- HAVEMANN, H., Displacement of dipping slabs of lithosphere, *Earth Planet. Sci. Lett.*, **17**, 129-134, 1972.
- HILDE, T.W.C., S. UYEDA, and L. KROENKE, Evolution of the western Pacific and its margin, *Tectonophysics*, **145-165**, 1977.
- HYNDMAN, R.D., Plate motions relative to the deep mantle and the development of subduction zones, *Nature*, **238**, 263-265, 1972.

- IRVING, E., Drift of the major continental blocks since the Devonian, *Nature*, **270**, 304–309, 1977.
- JARRARD, R.D. and D.A. CLAGUE, Implications of Pacific island and seamount ages for the origin of volcanic chains, *Rev. Geophys. Space Phys.*, **15**, 57–76, 1977.
- KARIG, D.E., Ridges and basins of the Tonga-Kermadec island arc system, *J. Geophys. Res.*, **75**, 239–255, 1970.
- KARIG, D.E., Structural history of the Mariana island arc system, *Geol. Soc. Am. Bull.*, **82**, 323–344, 1971.
- KARIG, D.E., Plate convergence between the Philippines and the Ryukyu Islands, *Mar. Geol.*, **14**, 153–168, 1973.
- KNOPOFF, Leon and A. LEEDS, Lithospheric momenta and the deceleration of the earth, *Nature*, **237**, 93–95, 1972.
- LIPMAN, P.W., H.J. PROSTKA, and R.L. CHRISTIANSEN, Evolving subduction zones in the western United States, as interpreted from igneous rocks, *Science*, **174**, 821–825, 1971.
- MARLOW, M.S., D.W. SCHOLL, E.C. BUFFINGTON, and T.R. ALPHA, Tectonic history of the central Aleutian arc, *Geol. Soc. Am. Bull.*, **84**, 1555–1574, 1973.
- MARSHAK, R.S. and D.E. KARIG, Triple junctions as a cause for anomalously near-trench igneous activity between the trench and volcanic arc, *Geology*, **5**, 233–236, 1977.
- MARSHALL, Monte, The magnetic properties of some DSDP basalts from the North Pacific and inferences for Pacific plate tectonics, *J. Geophys. Res.*, **83**, 289–308, 1978.
- MATSUDA, T. and S. UYEDA, On the Pacific-type orogeny and its model—Extension of the paired belts concept and possible origin of marginal seas, *Tectonophysics*, **11**, 5–27, 1971.
- MOBERLY, R., Origin of lithosphere behind island arcs, with reference to the western Pacific, *Geol. Soc. Am. Mem.*, **132**, 35–55, 1972.
- MOLNAR, Peter and Tanya ATWATER, Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere, *Earth Planet. Sci. Lett.*, **41**, 330–340, 1978.
- MOORE, G.W., Westward tidal lag as the driving force of plate tectonics, *Geology*, **1**, 99–100, 1973.
- MORGAN, W.J., Plate motions and deep mantle convection, *Geol. Soc. Am. Mem.*, **132**, 7–21, 1972.
- MURPHY, R.W., The Manila Trench-West Taiwan foldbelt, a flipped subduction zone, *Geol. Soc. Malaysia Bull.*, No. 6, 27–42, 1973.
- NELSON, T.H. and P.G. TEMPLE, Mainstream mantle convection; a geologic analysis of plate motion, *Am. Assoc. Pet. Geol. Bull.*, **56**, 226–246, 1972.
- OKADA, H., Migration of ancient arc-trench systems, in *Modern and Ancient Geosynclinal Sedimentation*, edited by R.H. Dott, Jr. and R.H. Shaver, Soc. Econ. Paleontol. Mineral. Spec. Publ. No. 19, pp. 311–320, 1974.
- PITMAN, W.C., III, R.L. LARSON, and E.M. HERRON, The age of the ocean basins, *Geol. Soc. Am. Map*, 1974.
- PITMAN, W.C., III and Manik TALWANI, Sea-floor spreading in the North Atlantic, *Geol. Soc. Am. Bull.*, **83**, 619–646, 1972.
- SCHOLL, D.W., E.C. BUFFINGTON, and M.S. MARLOW, Plate tectonics and the structural evolution of the Aleutian-Bering Sea region, *Geol. Soc. Am. Spec. Pap.*, **151**, 1–31, 1975.
- SCHOLL, D.W., J.R. HEIN, M.S. MARLOW, and E.C. BUFFINGTON, Meiji sediment tongue; North Pacific evidence for limited movement between the Pacific and North American plates, *Geol. Soc. Am. Bull.*, **88**, 1567–1576, 1977.
- SCHWEICKERT, R.A. and D.S. COWAN, Early Mesozoic tectonic evolution of the western Sierra Nevada, California, *Geol. Soc. Am. Bull.*, **86**, 1329–1336, 1975.
- SILLITOE, R.H., Metallogeny of an Andean-type continental margin in South Korea; implications for opening of the Japan Sea, in *Island Arcs, Deep Sea Trenches, and Back-Arc Basins*, edited by Manik Talwani and W.C. Pitman, III, Am. Geophys. Union Maurice Ewing Ser. 1, pp. 303–310, 1977.
- STEWART, R.J., Turbidites of the Aleutian abyssal plain: Mineralogy, provenance, and constraints for Cenozoic motion of the Pacific plate, *Geol. Soc. Am. Bull.*, **87**, 793–808, 1976.
- STONE, D.B. and D.R. PACKER, Tectonic implications of Alaska Peninsula paleomagnetic data, *Tectonophysics*, **37**, 183–201, 1977.
- TOMODA, Y., J. KOBAYASHI, M. SEGAWA, M. NOMURA, K. KIMURA, and T. SAKI, Linear magnetic anomalies in the Shikoku basin, northern Philippine Sea, *J. Geomag. Geoelectr.*, **28**, 47–56, 1975.
- UYEDA, S. and Zvi BEN-AVRAHAM, Origin and development of the Philippine Sea, *Nature*, **240**, 176–178, 1972.
- UYEDA, S. and H. KANAMORI, Back-arc opening and the mode of subduction, 1979 (in press).
- UYEDA, S. and A. MIYASHIRO, Plate tectonics and the Japanese Islands, *Geol. Soc. Am. Bull.*, **85**, 1159–1170, 1974.
- WATTS, A.B., J.K. WEISSEL, and R.L. LARSON, Sea-floor spreading in marginal basins of the western Pacific, *Tectonophysics*, **37**, 167–181, 1977.
- WILSON, J.T. and Kevin BURKE, Two types of mountain building, *Nature*, **239**, 448–449, 1972.
- ZONENSHAIN, L.P., M.I. KUZMIN, V.I. KOVALENKO, and A.J. SALTYKOVSKY, Mesozoic structural-magmatic pattern and metallogeny of the western part of the Pacific belt, *Earth Planet. Sci. Lett.*, **22**, 96–109, 1974.