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Plate tectonics and island arcs

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ABSTRACT

The plate-tectonic concepts that developed rapidly in the late 1960s made possible the understanding of island arcs. Before that time, mobilistic concepts evolved slowly, hindered, particularly in the United States, by an obstructionist geoscience establishment.

The volcanic belts of island arcs form about 100 km above subducting plates. Convergent-plate boundaries evolve complexly with time and, at any one time, vary greatly along their lengths. Seismicity defines positions, but not trajectories, of descending slabs, which sink more steeply than they dip and are overridden by advancing upper plates. Subduction occurs beneath only one side at a time of an internally rigid plate, and the common regime in an overriding plate, behind a surficial accretionary wedge, is extensional, except where a collision is underway. Back-arc–basin lithosphere is built behind, or by, migrating island arcs, which lengthen and increase their curvatures. A collision can involve two active arcs, in which case, intervening lithosphere sinks beneath both of them, or an active margin and a passive one. Either type of collision generally is followed by the breaking through of new subduction, beneath the composite mass of light crust, from a new trench on the outside of the aggregate; conversely, a new subduction system commonly is a by-product of collision. A strip of back-arc–basin crust is in many cases left attached to the aggregate, in front of the new trench, and becomes the basement for a fore-arc basin, the leading edge of which is raised as mélange is stuffed under it.

Sedimentation in trenches is predominantly longitudinal and can be from distant sources. Accretionary wedges are dynamic, being thickened at both toes and bottoms by tectonic accretion and thinned by gravitational forward flow; mélange is largely a product of tectonic imbrication and flowage driven by these conflicting processes, not of submarine sliding. High-pressure metamorphic rocks form beneath overriding plates, not within wedges in front of them.

Arc magmas incorporate much material from the lithosphere through which they rise and vary correspondingly with the evolving composition of that lithosphere. Arc crust is inflated into geanticlines by intrusive rocks and thermal expansion. Submarine island-arc volcanic rocks are widely spilitized, with Na enrichment and Ca depletion, by hydrothermal reaction with sea water. The lower crust of mature island arcs consists of granulite-facies rocks of mafic, intermediate, and felsic-intermediate compositions. The Mohorovičić discontinuity may be primarily a constructional boundary, representing the shallow limit of crystallization of voluminous rocks of ultramafic composition or plagioclase-free mineralogy.

INTRODUCTION

Arc systems develop where oceanic plates sink beneath overriding plates that can be continental, transitional, or oceanic. Many individual arcs are continuous across the diverse crustal types; continental and oceanic arcs belong to a continuum and should be considered together. Arcs are not steady-state tectonic systems but instead evolve and change complexly and rapidly, and different parts of a single, continuous arc can have grossly different histories and characteristics. Arcs commonly are inaugurated by subduction reversals consequent on collisions between other arcs and light crustal masses, and collision histories vary greatly along trend. Oceanic sectors of arcs migrate and lengthen with time, and one sector of a continuous arc can have been inaugurated tens of millions of years later than another sector. Petrologic and crustal features evolve as activity continues in a given sector.

Such characteristics can be illustrated from many modern arc systems. I use the arcs of the Indonesian–southern Philippine–western Melanesian region for my major examples in the following discussion. This is both the region I know best and the region of the greatest modern variety and complexity, and hence of the most informative examples.

In the first section of this report, I review the development of the mobilist concepts that made preliminary comprehension of island arcs possible by 1970. The remainder of the essay is a summary of the characteristics and behavior of island arcs, both as oceanic features and as assemblages accreted to continents.

DEVELOPMENT OF CONCEPTS

Progress that finally permitted our present modest comprehension of island arcs was slow and erratic before the late 1960s and was encumbered by the rejection by most of the geoscience community, particularly in the United States, of large-scale lateral mobilism. My review here of this slow progress emphasizes, where appropriate, publications of the Geological Society of America (GSA) and also emphasizes my own viewpoint and experiences as a pro-drift continental geologist. Menard (1986) presented a superb insider's review of the development of concepts of sea-floor spreading, and then of plate tectonics, from marine-geophysical data in the 1960s. Glen (1982) detailed the development of the paleomagnetic time scale which provided the key component in that evolution.

Mobilists and Stabilists

The first broadly important proposal of a continental-drift theory was Frank Taylor's (1910) paper in the GSA *Bulletin*. Taylor proposed that

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the Tethyan and circum-Pacific orogenic belts are being crumpled in front of drifting Atlantic and northern continents, which are sliding away from the Mid-Atlantic Ridge and Arctic Ocean. Trenches are depressed by the weight of arcs thrust over them. The 90° inflection in tectonic trends in southern Alaska is an orocline (in Carey's later terminology). Nares Strait is a strike-slip fault, and the geometry of the Canadian Arctic region requires that Greenland, Baffin, the Arctic Islands, and mainland Canada moved as separate plates. Taylor (1860–1938) published many papers on the Pleistocene geology of the Great Lakes region, and analogy with spreading ice sheets provided the impetus for his insightful foray into continental drift.

Occasional major works on the road to plate tectonics appeared outside the United States before 1960. Meteorologist Alfred Wegener (1915, and subsequent revisions) recognized that many paleoclimatic and paleontologic features of the Gondwana continents required prior juxtaposition of those continents, and he deduced that the oceans were underlain by dense material, the continents by light. Emile Argand (1924) saw that orogenic belts within continents were products of continental collisions. He dimly perceived sea-floor spreading and subduction and regarded island arcs as migrating overfolds. Argand recognized that the North Atlantic Ocean had closed during Paleozoic time, producing the Appalachians and Caledonides by collision, then reopened later, and he coined the term "Proto-Atlantic Ocean" for the early ocean. (Wilson, 1966, mistakenly claimed credit for this concept four decades later.) Arthur Holmes (1931 and other papers) added other geologic evidence for drift, which he explained as due to mantle convection currents rising and diverging beneath spreading ocean basins and converging and sinking at migrating trenches—30 years ahead of the next clear statements of this model. A. L. Du Toit (1937) systematized and added great detail to the analysis of geologic ties between the Gondwana continents. S. W. Carey (1958) published a global analysis of mobilistic continental tectonics that has proved correct in many aspects, although he was by then mired in an expanding-Earth concept.

Clegg, Almond, and Stubbs (Clegg and others, 1954) proposed that the magnetization directions they measured in Triassic strata were evidence for post-Triassic rotation and latitudinal shift of Britain. Soon other British (as, Creer and others, 1957; Runcorn, 1959) and other groups were generating continental paleomagnetic data which provided, as they emphasized, strong evidence for drift. Much such evidence had been amassed when Cox and Doell (1960) reviewed global paleomagnetic data for the GSA *Bulletin*; although they then sought stabilist explanations, they were tentatively advocating drift within a few years. A contemporary broad pro-drift synthesis of paleomagnetic data (Deutsch, 1963; written in 1960) was published in a rare symposium, convened by Arthur Munyan, that included pro-drift participants. Although only a few were then writing and lecturing about it, paleomagnetic latitudes were compatible with those deduced from paleoclimatic and paleobiogeographic data, and the complementary data sets required not only continental drift but also the aggregation of continents with orogenic belts between collided lesser continents. (A limited modern review of such relationships was given by Van der Voo, 1988.) Opdyke and Runcorn (1960) argued that late Paleozoic paleowind directions in the western United States fit trade-wind orientations as predicted from paleomagnetic latitudes.

Mobilism, however, came slowly to GSA publications, which before 1969 were filled primarily with papers describing, in stabilist terms, the geology of bits of North America. Gutenberg (1936) proposed that the Atlantic Ocean had opened by gravitational flattening and spreading of the flanking continents, which overrode the Pacific basin; he misinterpreted teleseismic data to indicate the Atlantic Ocean to have a thin continental crust, whereas Wegener had deduced that it does not. Gutenberg (1954) summarized his evidence for a low-velocity asthenosphere, which we now recognize as the zone of decoupling of lithosphere plates from the deeper mantle. Benioff (1949, 1954) defined the inclined seismic zones that dip arcward from trenches (and that had been recognized earlier by K. Wadati in Japan and by H. H. Turner in South America) and the thrust character of shallow coseismic slip in those zones.

The infrequent broad syntheses of orogenesis in GSA reports mostly were variants of themes of collapsing geosynclines, contraction, thermal uplift and subsidence, and gravitational sliding. The GSA Presidential Addresses on megatectonics by geologist Billings (1960) and geophysicist Birch (1965), both then exceedingly influential, dismissed mobilism; the earlier megatectonic address by petrologist Knopf (1948) ignored it. Gilluly (1949) also neglected drift in his address, but he became a tentative advocate for it in the 1950s and an explicit one in the 1960s.

My own acceptance of a mobilistic view of the Earth had come with my reading in graduate school, about 1949, of Du Toit's (1937) "Our wandering continents." Although the reality of continental drift was demonstrated by evidence such as Du Toit, Holmes, and others had by then assembled, most American geologists and geophysicists dismissed the subject. I began writing and lecturing on pro-drift topics (as, Hamilton, 1963c, 1963d; papers written in 1960 and 1961, respectively) after my 1958 field season in Antarctica, when I realized that the geology predicted by Du Toit's reconstructions was indeed present there. It was generally difficult in those years to get pro-drift materials published outside of the rare mobilistic symposia, whereas it was both easy and commendable to publish anti-drift papers. A 1962 manuscript by L. W. Morley, correctly interpreting the magnetic lineations of oceanic crust as due to sea-floor spreading during alternating periods of normal and reversed geomagnetic fields, was rejected by both *Nature* and the *Journal of Geophysical Research* (*JGR*; Glen, 1982). On the other hand, G.J.F. MacDonald as a young man received widespread acclaim for his repeatedly published calculations (for example, MacDonald, 1964), based on invalid assumptions regarding the Earth's rigidity and heat loss, that continental drift was impossible. (The trend continues in that much published geophysical modeling incorporates bad assumptions, but nowadays the assumptions are mobilistic.) F. G. Stehli published in major journals many anti-drift presentations of his misconceptions of the distribution of Permian fossils indicative of water temperatures (as, Stehli, 1957, 1970, and many between). The *JGR* published an anti-drift rationalization of paleofloras by Axelrod (1963; he has since published important biogeographic evidence for drift). I wrote a detailed pro-drift refutation, but the editor would accept only an undocumented note (Hamilton, 1964). A long review of global late Paleozoic and younger paleontologic, paleoclimatic, and paleomagnetic evidence for continental drift and aggregation that I wrote in the early 1960s for U.S. Geological Survey monographic publication was basically correct in its content but was cycled in series to hostile reviewers who collectively delayed it for 2 years before I gave up on it; only small parts of it were published, within short papers (as, Hamilton, 1964 and 1968, the latter written in 1965).

Very large strike-slip offset on the San Andreas fault was demonstrated in a GSA paper by Hill and Dibblee (1953). My first mobilistic GSA paper (Hamilton, 1961) built on this to link the San Andreas fault to oblique opening of the Gulf of California. (My manuscript had previously been rejected, as foolish speculation, by the *Bulletin of the American Association of Petroleum Geologists*; indeed, my proposed mechanism was foolish.) The distribution of upper Paleozoic tillites in the Gondwana continents had long been recognized by geologists in those continents as powerful evidence for continental drift, although American geologists tended to assume that the deposits at issue were not glacial; Hamilton and Krinsley (1967) reiterated field evidence for glacial origin, added petrographic and electron-micrographic evidence, and argued for drift. J. C. Crowell and associates, beginning with Frakes and Crowell (1967), applied modern sedimentological methods to Gondwana glacial strata and soon thereafter (Frakes and Crowell, 1969, in a GSA paper; papers published elsewhere in 1968) argued that continental drift was required to explain the distribution of the glacial materials.

Spreaders and Subducters

The early evidence for continental drift came from the continents, and it was unclear how the ocean floors fit into the picture. Some advocates of continental drift, from Wegener on, had visualized continental rafts floating across dense oceanic material, whereas others, from Taylor on, had visualized sea-floor spreading. Direct evidence for spreading came with the oceanographic data accumulated during the 1950s (Glen, 1982). Bruce Heezen and Marie Tharp (as, Heezen and others, 1959) presented GSA bathymetric maps of the oceans, from which Heezen argued in other papers for the globe-girdling character of ridges that spread because the Earth is expanding, whereas Maurice Ewing (as, Ewing and others, 1964) for a while argued that the ridges were not spreading. Raff and Mason (1961) presented a map of sea-floor magnetic lineations west of the northwest United States, for which Vacquier, Raff, and Warren (Vacquier and others, 1961) recognized strike-slip, but not spreading, significance.

Holmes (1931) visualized what we would now term sea-floor spreading, subduction, and migrating plate boundaries, all of which were ignored by most of the earth-science community. The suggestion by Griggs (1939) that ocean floors underthrust continents from trenches also met general indifference. U.S. Navy bathymetry of the trenches, island arcs, and marginal basins of the west-central Pacific was presented by Hess (1948), who then regarded trenches as formed by local downbuckling. Dietz (1954) published a Japanese Navy map of about the same region and proposed, correctly, that the Japan and Okhotsk Seas had opened as island arcs and continental fragments migrated away from Asia. Coats (1962) had perhaps the first clear visualization of subduction and postulated that magmatic arcs formed by melting of sedimentary rocks thrust beneath arcs along Benioff seismic zones.

The lasting recognition that sea floor produced by spreading might disappear beneath arcs and continents by subduction probably came first to Hess (1962; Glen, 1982), but Dietz (1961) had it in more sophisticated form. Their initial views were essentially two-dimensional and were in that sense more primitive than those of Holmes, whereas Wilson (1961) saw that spreading ridges must themselves migrate and change shapes and lengths. Wilson was a major contributor to mobilist concepts in the early 1960s, although he had been a militant stabilist in the 1950s.

Plate Tectonicists

The short period from 1963 to 1968 saw the demonstrations from geophysical data that the Earth's lithosphere is fragmented into plates, all moving relative to all others—pulling apart at ridges, sinking beneath one another at trenches, sliding past one another on transform faults. This drama played in journals, especially *JGR*, *Nature*, and *Science*, which previously had been bastions of stabilism. The history of this development has been discussed in detail by Glen (1982), Menard (1986), and others.

Vine and Matthews (1963), unlike Morley, were able to publish their proposal that the magnetic anomalies parallel to oceanic ridges recorded conveyor-belt crystallization during spreading in alternating periods of normal and reversed magnetic polarity. Their suggestion generated mostly a mixture of disinterest and hostile responses for 3 years but then was proved correct by various groups, notably by the well-organized Lamont group (for example, Heirtzler and others, 1968), which demonstrated the magnetic symmetry of ridges and integrated the dating of oceanic crust by deep-sea drilling with an extrapolated geomagnetic time scale. Coode (1965) and Wilson (1965) proposed simultaneously that the fracture zones known to mark offsets of the ridges did not postdate the ridges but rather were "transform faults" (Wilson's term) formed by stepping of spreading between ridge segments that were perpendicular to the spreading direction; Sykes (1967) demonstrated that the slip sense of fracture-zone earthquakes accorded with this concept. Other geophysicists added more confirming data for the evolving mobilistic concepts. So many independent lines of evidence required the same conclusions that the general validity of those conclusions was quickly established.

Euler-plate geometry was used implicitly by Carey (1958), who made reconstructions on a transparent hemisphere moved about a globe and drew reconstructions incorporating spherical geometry. Bullard and others (1965) used a computer to fit Atlantic continents together and specified the Euler pole required. First to formalize the global Euler-plate behavior required by the spherical geometry of spreading ridges and transform faults probably was Morgan (1968). Only a few months behind were McKenzie and Parker (1967; their paper was written after Morgan's), and behind them Le Pichon (1968), who had been publishing stabilist papers several years before. McKenzie and Morgan (1969) analyzed the geometric behavior of evolving triple junctions between plates.

Plate tectonics (at that time, "the new global tectonics") was a demonstrated reality. Most geophysicists who were paying attention were quickly convinced, whereas most geologists lagged behind. (My own conversion, from a previously muddled view that had incorporated little awareness of marine geophysics, came in 1968, a year or two behind the involved geophysicists.) It remained to apply the concepts to global geology.

Continental and Island-Arc Geologists

Geologists at last had a framework within which to place the empirically related features of island arcs and continents. Davis (1969) discussed the Klamath Mountains in terms of Mesozoic subduction imbrication, which he had in part perceived earlier (Davis, 1968). Interpretations of island arcs in plate-tectonic terms first appeared in the GSA *Bulletin* in 1969 (Isacks and others, 1969; Molnar and Sykes, 1969; Rodolfo, 1969), although rearguards Von Huene and Shor (1969) argued that the Aleutian Trench recorded downwarping, not subduction. The same year came my analysis (Hamilton, 1969a) of California as a product of Jurassic tectonic accretion and Cretaceous Andean-style tectonics; this paper was the first clear statement of the assembly of a broad orogenic tract from island arcs and other bits conveyor-belted in from far away. (The manuscript was held up for half a year by U.S. Geological Survey reviewers and a supervisor who considered it too radical for public display, and an abstract based on it was one of the few volunteered papers rejected for presentation at a 1970 regional GSA meeting.) Dickinson (1969, 1970c) and Hamilton (1969a, 1969b) argued that batholiths such as the Sierra Nevada were the roots of continental volcanic arcs and were not products of anatexis in "geosynclines." This expanded on the analysis by Hamilton and Myers (1967) that batholiths in general are overlain by silicic volcanic complexes and underlain by migmatites; our concept was widely rejected at the time. The relationship of belts of high-pressure, low-temperature metamorphic rocks such as blueschists to likely trenches was recognized by Miyashiro (1961), who, like Ernst (1965), invoked depression by "downbuckling," whereas Blake and others (1969) and Coleman (1967) appealed to "tectonic overpressures." Blueschists were put in the context of subduction by Ernst (1970) and Hamilton (1969a). Hsü (1968, and other papers) began to make sense of the Franciscan mélanges, which he at that time attributed to gravity sliding, of coastal California; Hamilton (1969a) put them in an accretionary-wedge context.

In 1969, only a dozen papers on mobilist topics were presented at all seven GSA meetings—and half of those papers took stabilist positions. Late 1969, however, saw the important GSA Penrose Conference on "The meaning of the new global tectonics for magmatism, sedimentation, and metamorphism in orogenic belts," convened by William R. Dickinson at

Asilomar, California (Dickinson, 1970a, 1970b). The 90 attendees included not only most of the few geologists who were already active in the new field but also most of those who would make important plate-tectonic geologic contributions during the 1970s. Dickinson's conference produced an abrupt dissemination of awareness that convergent-plate tectonics controls much of the evolution of continents.

The year 1970 brought a large increase in mobilist publication by the GSA. Bracey and Vogt (1970), Grow and Atwater (1970), and Luyendyk (1970) presented important papers on the tectonics of island arcs. Atwater (1970) put the Cenozoic geology of western North America into the essential framework of evolving triple junctions. Bird and Dewey (1970) explained the Appalachians, and I (Hamilton, 1970) the Uralides, as products of continental collisions as intervening oceans were subducted beneath flanking continents and beneath intervening arcs that were accreted to the continents. Coney (1970) summarized what the synthesizers were learning. There were other plate-tectonic and pro-drift papers—and also rearguard papers arguing that subduction had nothing to do with trenches or continental tectonics. Among particularly important 1970 papers on plate tectonics and continental geology in other journals was that by Dewey and Bird (1970), on broad aspects of orogenic systems, and that by Dickinson (1970c), integrating volcanism, plutonism, and sedimentation into a plate framework.

Papers dealing with plate tectonics, subduction, and island arcs have been numerous in GSA publications since 1970. I mention here a few of the papers from the early 1970s that advanced understanding of continental and arc geology. Island-arc migration and back-arc spreading were documented by Karig (1971, 1972) and Sclater and others (1972). Grow (1973) presented the best geophysical analysis to that time of an accretionary wedge and fore-arc basin, those of the Aleutian Islands. Silver (1971a, 1971b) applied marine geophysics to analysis of the Mendocino triple junction, critical for comprehension of California tectonics. Barbat (1971) and Page (1972) much advanced understanding of the nature of the contact along which Cretaceous California had overridden oceanic materials. Broad syntheses were attempted in plate-tectonic terms by Dewey and others (1973) and Ernst (1973) for the Alpine system, James (1971) for the Andes, Hatcher (1972) for the southern Appalachians, and Malfait and Dinkelman (1972) for the Caribbean region.

Although plate tectonics provided the framework within which the behavior of island arcs could potentially be understood, the requisite geologic data had long been accumulating. Hess (1948) and Dietz (1954), among others, focused attention on the tectonic bathymetry of arc systems. Kay (1951) recognized that island arcs are important components of continental orogenic belts—a major advance, although he explained their presence with stabilist geosynclinal theory. Hess (1955) recognized the continuity of belts of mantle peridotites—mostly accreted ophiolites, in modern parlance—in orogenic belts but also sought an explanation in geosynclinal theory and vertical tectonics. Dietz (1963, 1966) made early attempts to relate continental drift to conveyor-belting atop convecting mantle and continental-margin tectonics to convergence and subduction. I showed (Hamilton, 1963a, 1963b) that the metavolcanic rocks of western Idaho were of oceanic island-arc petrology and had been overthrust from the east by continental-crustal rocks. In Hamilton (1963d; written in 1961), I proposed that the north and south flanks of the Caribbean and Scotia arc systems had been plated out on the sides as the arcs migrated eastward, and in Hamilton (1966), I suggested that western Pacific arcs were migrating eastward faster than were the continents behind them. In my 1966 paper, I argued on petrologic grounds that both oceanic island arcs and the floors of marginal seas were incorporated in continental "eugeosynclines." Krause (1965, 1966) presented moderately mobilistic explanations for Indonesian and Melanesian arcs and marginal seas. Burk (1965) sought vertical-tectonics explanations for the transition he described from offshore Aleutian arc to onshore Alaskan one. Dickinson and Hatherton (1967) and Kuno (1966 and earlier papers) showed how cross-strike variations in island-arc volcanoes correlate with depth to the inclined seismic zone beneath, although not until later (Dickinson, 1969, 1970c; Hatherton and Dickinson, 1969) did they perceive the relationships in terms of subduction.

Vening Meinesz (1954) summarized for GSA his pioneer gravity work with Indonesian arcs. The "isostatic" anomalies he calculated were very strongly negative along the fore-arc ridges, and he proposed that trenches are held down dynamically, far out of gravitational equilibrium, as "tectogenes." His gravity anomalies were calculated with the invalid assumption that all material beneath the sea floor has the same density. In their analogous report on the gravity anomalies of the West Indies, Ewing and Worzel (1954) recognized that thick low-density material, not dynamic imbalance, produced the negative anomalies; they did not attempt an explanation for the trenches in that paper, although in other papers of the period, they argued for extensional origins. We now know that (as anticipated by Ewing and Worzel) the maximum thickness of accretionary wedges lies along the fore-arc ridges and that Vening Meinesz's anomalies were dominated by the thicknesses of those wedges. Free-air anomalies of the ridges are positive and broadly correlative with bathymetry (Watts and others, 1978), and so the accretionary-wedge load is in part supported by beam strength of the subducting plate. Karig and others (1976) evaluated quantitatively the depression of subducting plates by accretionary-wedge loading.

Current Status

Plate tectonics has given us the framework within which to begin to comprehend the geology of continents and island arcs. Relationships between the tectonic and magmatic components of modern convergent-plate systems are so systematic that derived generalizations now allow predictions, the testing of which refines our understanding. The obvious success of the plate-tectonic paradigm has, however, produced a complacency that has cluttered the geological and geophysical literature with invalid convergent-plate models that reflect naive assumptions rather than understanding of actual plate systems. The problems are being passed on to the next generation; I have just examined eight current physical-geology textbooks, all of which incorporate gross misconceptions regarding plate convergence, and most of which are little better regarding plate divergence.

PLATE TECTONICS

Seven very large lithospheric plates, and numerous mid- and small-sized ones (the concept of coherent plates breaks down at the small-scale end), are now all moving relative to all others. All plate boundaries—divergent, convergent, strike-slip, and oblique—are also moving, at widely varying rates, and most boundaries change greatly in length and shape with time. Although plates tend to be internally rigid and to interact mostly at their boundaries, parts of many plates undergo severe internal deformation. Relative velocities between adjacent plates presently range up to about 13 cm/yr.

Mechanism

"Absolute" velocities of present large plates—their relative velocities in an approximate zero-sum frame, with or without qualifications regarding true polar wander (Davis and Solomon, 1985) or rationalizations regarding semifixed hot spots—correlate positively with the lengths of ridges and of trenches along their perimeters and negatively with the proportion of continental lithosphere within them (Carlson, 1981). It appears from the quantitative correlations between these parameters that plates are propelled primarily by gravitational forces and that on average, pull by the descending slab is about 2.5 times as important in moving plates as is slide of plates away from ridges, whereas thick continental lithosphere retards motion by drag (Carlson, 1981). The 80 or 100 km of relief of the base of an oceanic-lithosphere plate, between lithosphere and less-dense asthenosphere, is much more important in producing ridge slide than is the 3 or 4 km of bathymetric relief of the top of the plate. Major plate motions thus apparently are controlled by large lateral variations in lithosphere density and thickness that result primarily from cooling (Carlson, 1981; Hager and O'Connell, 1981), although much of the negative buoyancy, mechanical behavior, and seismicity of subducting slabs is due to density-phase changes (Pennington, 1983; Rubie, 1984). Many complications are discussed by Jarrard (1986). Velocity of lithosphere is in general greater at low latitudes than at high latitudes, and so the Earth's rotation likely is an additional factor in driving forces (Solomon and others, 1975), perhaps by a gyroscopic feedback mechanism. Motions of small plates are primarily by-products of motions of adjacent large plates.

Convection in the upper mantle is largely a complex product, not a major cause, of plate motion (Alvarez, 1982). Spreading ridges form where plates move apart and hot mantle wells into the gap, and ridges migrate and change shape and length at widely varying rates. The return flow that compensates for lithosphere motions probably occurs mostly in the asthenosphere, where it likely is pervasive beneath oceanic plates (Chase, 1979) but may be concentrated in channels beneath thin lithosphere, as in the Scotia and Caribbean gaps, where continents are involved (Alvarez, 1982; as he emphasized, this process was anticipated by Hamilton, 1963d).

Hot spots—sites of long-continuing asthenospheric upwelling beneath moving plates, shown at the surface as migrating zones of volcanism—figure in many analyses and explanations of plate kinematics and commonly are assumed to represent sources of heat fixed in the mantle. An alternative explanation is that hot spots are products of propagating rifts in the lithosphere and hence are primarily responses to cooling at the top rather than to heating at the bottom. Hot-spot volcanism is controlled by upper-lithosphere fractures which can be explained as related to interacting regional-plate and volcano-loading stresses. (For discussions and citations of some of the relevant references, see Clague and Dalrymple, 1987, and ten Brink and Brocher, 1987.) Even the best behaved of the oceanic hot spots are moving relative to one another with velocities of 1–2 cm/yr (Molnar and Stock, 1987), perhaps more. Many linear volcanic chains proposed as hot-spot tracks in fact lack systematic age progressions (as, Turner and Jarrard, 1982), and the best examples display much irregularity. The apparent requirement of the hot-spot concept that lava productivity not be a function of plate velocity is not met (McNutt, 1988).

Heat and Variations with Time

Plate motions are responsible for most of the Earth's heat loss. Of the total heat lost by the Earth, about 60% is lost by magmatism at spreading ridges and by the subsequent cooling of new oceanic lithosphere as it moves away from ridges (Sclater and others, 1981). Because the rate of heat loss by the Earth has probably decreased with time and because ancient crustal nonmagmatic thermal gradients demonstrable by petrologic thermobarometry were little if any steeper than modern ones, it seems likely that plate motions have become slower on average with time. There may have been fluctuations within this progression, representing variations of 10% or 20% in the rates of plate generation and consumption (compare Parsons, 1982), and there certainly have been major unidirectional changes in the petrologic evolution of crust and mantle. Nevertheless, plate tectonics appears to have operated, broadly as it does now, at least during Proterozoic and Phanerozoic time. Archean crust displays the effects of much more voluminous, and in part higher temperature, magmatism than that of younger time and of expulsion of light, continent-forming elements directly from a little-differentiated mantle, and specific processes that then operated are much debated. Many of us see Archean geology as likely recording the more-rapid motions of more and smaller plates than those of later time.

Subduction

Much published tectonic speculation and geophysical modeling have been built on the false assumption that a subducting plate rolls over a hinge and slides down a slot that is fixed in the mantle, and that overriding plates commonly are shortened compressively across their magmatic arcs and belts of foreland deformation. These assumptions are disproved both by the characteristics of modern convergent-plate systems in which the subducting plate is of normal oceanic lithosphere and the Benioff seismic zone has a moderate to steep inclination, and by analyses of "absolute" plate motions. Hinges commonly retreat—roll back—into incoming oceanic plates as overriding plates advance, even though at least most subducting plates are also advancing in "absolute" motion. Subducting slabs sink more steeply than the inclinations of Benioff seismic zones, which mark positions, not trajectories, of slabs. Perhaps the most obvious evidence for rollback comes from the fact that the Pacific Ocean is becoming smaller with time as flanking continents and marginal-sea plates advance trenchward over ocean-floor plates, but many other types of evidence for the phenomenon have been presented by, among others, Carlson and Melia (1984), Chase (1978), Dewey (1980), Garfunkel and others (1986), Hamilton (1979), Hawkins and others (1984), Kincaid and Olson (1987), Malinverno and Ryan (1986), Molnar and Atwater (1978), and Uyeda and Kanamori (1979). As most of these authors emphasized, the typical regime in an overriding plate above a sinking slab is one of extension, not shortening.

A corollary, often overlooked by geologists producing palinspastic cartoons, is that subduction can occur beneath only one side at a time of an internally rigid plate. Retrograde motion could occur only if a dense slab could push light mantle forward and upward out of its way—an impossibility in a gravity-dominated system.

Exceptions that can be argued to counter these interpretations are of doubtful validity. Plate-motion analyses which deduce retrograde motion for the Mariana arc and trench are no stronger than their poorly constrained estimates of internal motions within eastern Asia and its marginal seas. Subduction now occurs inward beneath both sides of the Caribbean region—Antilles on the east, Central America on the west—but poorly understood plate boundaries intervene. Subduction now occurs at both east and west sides of southern Mindanao, but the trajectories, and in part even boundaries, of the many small plates in that region are so poorly constrained that this cannot yet be evaluated properly.

Arc Migration and Back-Arc Spreading

Karig (as, 1972, 1975) demonstrated that the Mariana island arc has migrated Pacificward as new back-arc–basin oceanic crust formed behind it. Karig and many others since (as, Taylor and Karner, 1983) have found that island arcs generally migrate in such fashion. Some migration is accomplished by the splitting of the magmatic arc and the migration of the forward half away from the rear half, and some, by irregular sea-floor spreading behind the entire arc. The magmatic welt can move forward with the advancing part of the overriding plate, can be abandoned as a remnant arc on the relatively retreating part, or can be split longitudinally between them. Oceanic island arcs do not bound rigid plates of old lithosphere but, instead, mark the fronts of plates of young lithosphere that are widening in the extensional regimes above sinking slabs. Oceanic arcs commonly are not inaugurated by the breaking of subduction through old oceanic crust but, rather, break through near boundaries between thin and thick crust and migrate over the plates of thin crust (Hamilton, 1979; Karig, 1982). In any one system, periods of back-arc spreading may alternate irregularly with periods of magmatism along a volcanic-arc welt (Crawford and others, 1981; some authorities disagree).

An island arc should be viewed as a product of a subducting slab rather than as a fixture of an overriding plate. A belt of arc-magmatic rocks forms above that part of a subducting slab, the top of which is 100 km or so deep—and migrates to track that contour as the slab falls away. Mechanisms of back-arc spreading are still debated, but it appears to me, as to some others (perhaps including Hawkins and others, 1984, and Shervais and Kimbrough, 1985), that although some oceanic back-arc–basin lithosphere forms by regular or irregular spreading behind an arc, much forms instead by the rapid migration of a magmatic arc which plates out a variable-thickness sheet of arc crust rather than forming a full island-arc welt of thick crust.

Arc Festoons

Arcs increase in curvature as they migrate. A migrating arc becomes pinned where it encounters thick crust in the subducting plate that either is nonsubductible or that forms a stiffening girder, and festoons and sharply curving arcs result where migration continues away from such obstructions (McCabe, 1984). Pinning against the Caroline Ridge may explain the Yap-Mariana syntaxis, and pinning against the Emperor Seamount Ridge may explain the Kamchatka-Aleutian one.

Ophiolites

On-land ophiolites are sections of upper oceanic lithosphere that were long assumed to be samples of spreading mid-ocean–ridge materials. Many researchers now believe that instead, most, perhaps all, large sheets of ophiolite incorporated tectonically into the continents are products of arc magmatism, back-arc spreading, or both together (Bloomer and Hawkins, 1983; Coleman, 1984; Hawkins and others, 1984; Pearce and others, 1984; Shervais and Kimbrough, 1985). Much has yet to be learned about the pre-collision evolution of these complexes, but the mechanisms of irregular spreading and fast-migrating arcs appear capable of explaining many relationships.

The Eocene Acoje ophiolite of western Luzon was described, as a "nascent island arc," by Hawkins and Evans (1983). The moderately dipping Acoje section exposes the entire crust, about 9 km thick, and about 10 km of the underlying mantle. All but the top 1 km of the mantle section consists of serpentinized and tectonized residual harzburgite and subordinate dunite and chromite; clinopyroxene-rich pods that increase in abundance downsection crystallized from late melts that may have been either introduced or segregated nearby. The upper 1 km or so of the geophysical mantle, but the basal 1 km of the arc-magmatic section, consists of undeformed cumulates of olivine and clinopyroxene. These are intercalated, over a thickness of several hundred meters, with the basal part of the gabbroic rocks that make up the lower 7 km or so of the overlying crust, which has a total thickness of about 9 km. Most of this gabbroic section consists of layered-cumulate two-pyroxene gabbro. The cumulates grade upward into massive gabbro and norite, about 1 km thick, in the upper part of which are abundant small plutons and dikes of plagiogranites (hornblende tonalite and leucotonalite). The top 1 or 2 km of the crustal section consists of dikes, sills, and pillow flows of basalt compositionally like that of modern primitive island arcs rather than like spreading-ridge lava. The crustal section is much thicker than that formed at mid-ocean ridges. Formation in a steady-state magma chamber nevertheless seems likely, and rapid migration of a belt of arc magmatism in a spreading-marginal-basin setting can be inferred.

Little in the description just given of the Acoje ophiolite, except for irregular variations in thickness, would have to be changed to apply to many sections of ophiolites in continental accreted terranes around the world. The Cretaceous Oman ophiolite of the Arabian Peninsula (Lippard and others, 1986) and the Jurassic Coast Range ophiolite of California (Hopson and others, 1981) are well-studied examples that are dimensionally and petrologically similar to the Acoje complex, although Lippard, Hopson, and their associates favored explanations in terms of spreading-ridge magmatism. Fragments of ophiolites of these types have been dredged from the arcward slopes of trenches—the leading edges of overriding plates—in open-ocean settings in which there is little development of masking accretionary wedges (Bloomer and Hawkins, 1983).

There appear to me to be two major processes of emplacement of ophiolites within orogenic belts, and neither of them represents capture of random bits of spreading-ridge lithosphere. One mode is in the collision of an advancing arc with a continent or other island arc, the thin ophiolitic leading edge of the overriding plate ramping onto thick-crustal parts of subducting plates. Such thrusting is in the sense of subduction. (The hypothetical process of "obduction," whereby a great sheet of oceanic lithosphere is split from a subducting slab and shoved, in the opposite sense of thrusting, atop the thick crust of an overriding island-arc or continental plate, is invoked by many writers—but the process defies mechanical analysis and has yet to be proved to have operated anywhere. Confusion is introduced by those writers who misuse the term "obduction" to imply onramping in the sense of subduction, which is opposite to the original definition of the term.)

The second major process of ophiolite emplacement is a subset of the first and is a common by-product of an arc collision. A new subduction system of opposite dip breaks through behind the collided arc and leaves attached to it a strip of back-arc–basin crust that becomes raised as accretionary-wedge materials are stuffed beneath it. Such an ophiolitic strip may remain at the leading edge of a plate, or may become part of a suture system after other crustal masses collide with it. Examples are noted in subsequent sections.

TECTONICS: ARCS OF INDONESIA AND VICINITY

Introduction

The complex characteristics and histories of island arcs are exemplified by the arcs of Indonesia and surrounding regions. The active tectonism and magmatism there record the complex interactions of the Asian, Pacific, and Indian-Australian lithosphere megaplates and of dozens of lesser plates. In various reports and maps, culminating in a monograph (Hamilton, 1979) and an accompanying tectonic map (also published separately: Hamilton, 1978a), I integrated onshore and offshore geological and geophysical data for Indonesia, southeast Asia, the southern Philippines, western Melanesia, and the adjacent seas into a synthesis of modern plate behavior and of the evolution of plate-tectonic features. My concepts have evolved since I completed the book, but interpretations not otherwise credited herein come primarily from that monograph, which contains the relevant documentation both as voluminous data newly reported there and as synthesis of the findings of others. Some reports published since the completion of the book are cited herein and also in a more detailed update (Hamilton, 1988b); the new data require modification of details of my synthesis but have in general substantiated it. Figures 1 and 2 show locations of features discussed, and Figures 3 and 4 illustrate some of the concepts. The bathymetric map by Mammerickx and others (1976) is more detailed than the map used as the base for my maps. Map summaries of offshore geophysical data, in part incorporating data and interpretations from Hamilton (1974a, 1974b), were presented by Anderson and others (1978, thermal properties), Hayes and Taylor (1978, earthquakes), Hayes and others (1978, crustal structure), Mrozowski and Hayes (1978, sediment isopachs), Watts and others (1978, free-air gravity), and Weissel and Hayes (1978, magnetic anomalies).

The diverse subduction systems of the Indonesian region record the interactions between three megaplates and many smaller plates. Relative to internally stable northwestern Eurasia, the India–Indian Ocean–Australia megaplate is moving approximately northward in this region, whereas the Pacific megaplate is moving west-northwestward. The Asian continental megaplate is fragmented into dozens of internally deformed subplates. Many small oceanic and continental plates intervene between parts of the megaplates, and many of these small plates also have been much deformed internally. Southeast Asia was crowded eastward out of the way of the indenting Indian subcontinent and has since been rotating clockwise over the oceanic Bay of Bengal (Hamilton, 1979; Tapponnier and others, 1986). Convergence between Indian and Asian megaplates is now being taken up primarily by the continuous Burma-Andaman-Sunda-Banda subduction system, whereas that between Pacific and Asian megaplates is taken up on many subduction systems that trend mostly northerly into the Philippines and along boundaries farther east. Complex subduction and strike-slip systems separate the plates in the zone of interaction between Indian and Pacific megaplates, along and north of New Guinea and in the tectonic knot in northeastern Indonesia and surrounding regions.

If present gross plate motions continue for another 50 m.y. or so, the continental scraps, composite island arcs, and accretionary wedges of much of the Indonesian–Philippine–northern Melanesian region likely will be squashed between Australia and Asia. The result will be another broad orogenic terrane akin to those we elsewhere term Tethyan, Hercynian, Caledonian, Pan-African, and so on.

Sunda Subduction System

A great subduction system is continuous from Burma around the Banda Arc. In this section, I discuss the central 3,000-km Sunda sector, along Sumatra, Java, Bali, and Sumbawa, of this plate boundary. This sector consists of concentric, arcuate tectonic features that typify those along other active margins of continents, mature island arcs, and the transitions between them. In the south is the trench, and northward from it rises the surface of the accretionary wedge, at the front of the overriding plate, to a culmination at a fore-arc ridge.[1] Islands stand on the ridge along Sumatra, but the ridge is wholly submarine south of Java, Bali, and Lombok. Between the ridge and the magmatic arc is the submarine fore-arc basin. Along the Sunda sector, Indian Ocean lithosphere is being subducted, at high to moderate convergence angles, beneath an arc system that changes along strike from continental in Sumatra through transitional in Java to oceanic in Bali and Sumbawa. This sector of the subduction system has been active only since middle Tertiary time.

Trench. The Sunda Trench, like trenches that mark traces of subduction systems along continental margins and mature island arcs elsewhere, has inner and outer "walls" that slope only 7° or so. The trench does not mark either an abrupt hinge in the subducting Indian Ocean lithosphere or the contact between lithosphere plates, but rather is the dihedral angle between a surficial accretionary wedge, in front of the overriding plate, and oceanic lithosphere depressed by that wedge. An outer rise on the oceanward side of the trench is an elastic response to that depression. The tectonic hinge, where the subducting plate tips downward into the mantle, lies 100–200 km arcward from the bathymetric trench. Trenches of oceanic island-arc systems commonly are illustrated with reflection profiles with vertical exaggerations of 25× or so, giving the visual impression of very steep slopes, but actual slopes of these also commonly are gentle.

Clastic sedimentation in trenches is primarily in the form of longitudinal turbidites, and the long profiles of trench-floor fills slope gently away from the sources. Sunda Trench sediments as far southeast as Java came largely from the Ganges and Brahmaputra Rivers, 3,000 km away (see also Ingersoll and Suczek, 1979, and Moore and others, 1982); the supply has recently been cut off by collision of the Ninetyeast Ridge with the trench in the Andaman sector. Aleutian Trench turbidites sluice a similar distance from Alaskan rivers. Source terranes thus need bear little similarity to nearby parts of the overriding plate against which trench turbidites are plated in an accretionary wedge. Dickinson (1982) demonstrated this to be true for various fossil accretionary wedges around the Pacific Ocean. Continental detritus sluiced along trenches, or abyssal-fan materials from continents, can be accreted to, and subducted beneath, oceanic sectors of arc systems.

Accretionary Wedge. Sediments and other materials scraped from subducting Indian Ocean lithosphere accumulate, snowplow fashion, in the accretionary wedge at the front of the overriding Sunda plate. The surface of the wedge is furrowed by longitudinal ridges and basins defined by imbricate thrust faults (Karig and others, 1980b). Trench fill can be seen on reflection profiles to be scraped off at the front of a wedge, the shallowest materials being accreted against the toe, the deeper being accreted beneath the wedge farther back. Quaternary coral reefs are raised high above sea level on islands along the fore-arc ridge—the crest of the accretionary wedge—and the rapid uplift presumably is a result of thickening of the wedge by underplating. The base of the Sunda wedge—the top of the subducting plate—dips very gently at least as far arcward as the crest of the fore-arc ridge; the wedge is a thin, dynamic debris pile only 15 km or so thick 75–150 km from the trench. Reflection profiles showing internal structure of this and analogous wedges elsewhere generally display semiconstant imbrication angles, dipping 30° or so arcward, independent of position in the wedge, discordant to the gently dipping décollement atop the subducting plate. (Steeper planes may also be present, for they would not be imaged in reflection profiles.) Surface slopes of most accretionary wedges define broadly similar convex-upward curves regardless of the widths and thicknesses of the wedges and hence presumably are profiles of dynamic equilibrium.

Such features indicate to me that an accretionary wedge is simultaneously thickened, by underplating and by dragging back of its base, and thinned, by flowing forward by gravitational spreading. The result is internal imbrication of the wedge and maintenance of a dynamic profile, akin to that of an ice sheet, as the wedge grows both laterally and vertically. Some other observers see wedges as more static features, broadened by imbrication and offscraping at their toes but relatively stable in their arcward portions.

Reflection profiles across the accretionary wedge indicate that ratios of imbricated, disrupted, and coherently folded materials vary widely but relate systematically to the convergence rates and directions and to the thickness and character of sedimentary sections being accreted (Moore and others, 1980b). No wells have yet been drilled into the Sunda wedge. Drillholes in other similar sediment-rich modern wedges show them to be typified near their toes by broken formations with scaly-clay matrices and by highly variable proportions of broken formations and coherently imbricated strata farther back in the wedges. Island exposures of the top of the Sunda wedge have been studied primarily on Nias (Moore and Karig, 1980; Moore and others, 1980a), where coherent, unmetamorphosed lower Miocene to lower Pliocene strata structurally overlie on the northeast, and elsewhere are imbricated with, polymict mélange composed of undated materials. The mélange is slightly metamorphosed, is extremely

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[1] I have previously (as, 1979) used the term "outer-arc ridge" for this feature because of the conflict of the more widely used term "fore-arc ridge" with the classical term "foreland." I here yield to the more common usage. Similarly, the "fore-arc basin" of most recent literature and this essay is the "outer-arc basin" of my previous reports. Note that a "foreland basin" is on the same side of an arc as is a "back-arc basin" and on the side opposite to a "fore-arc basin."

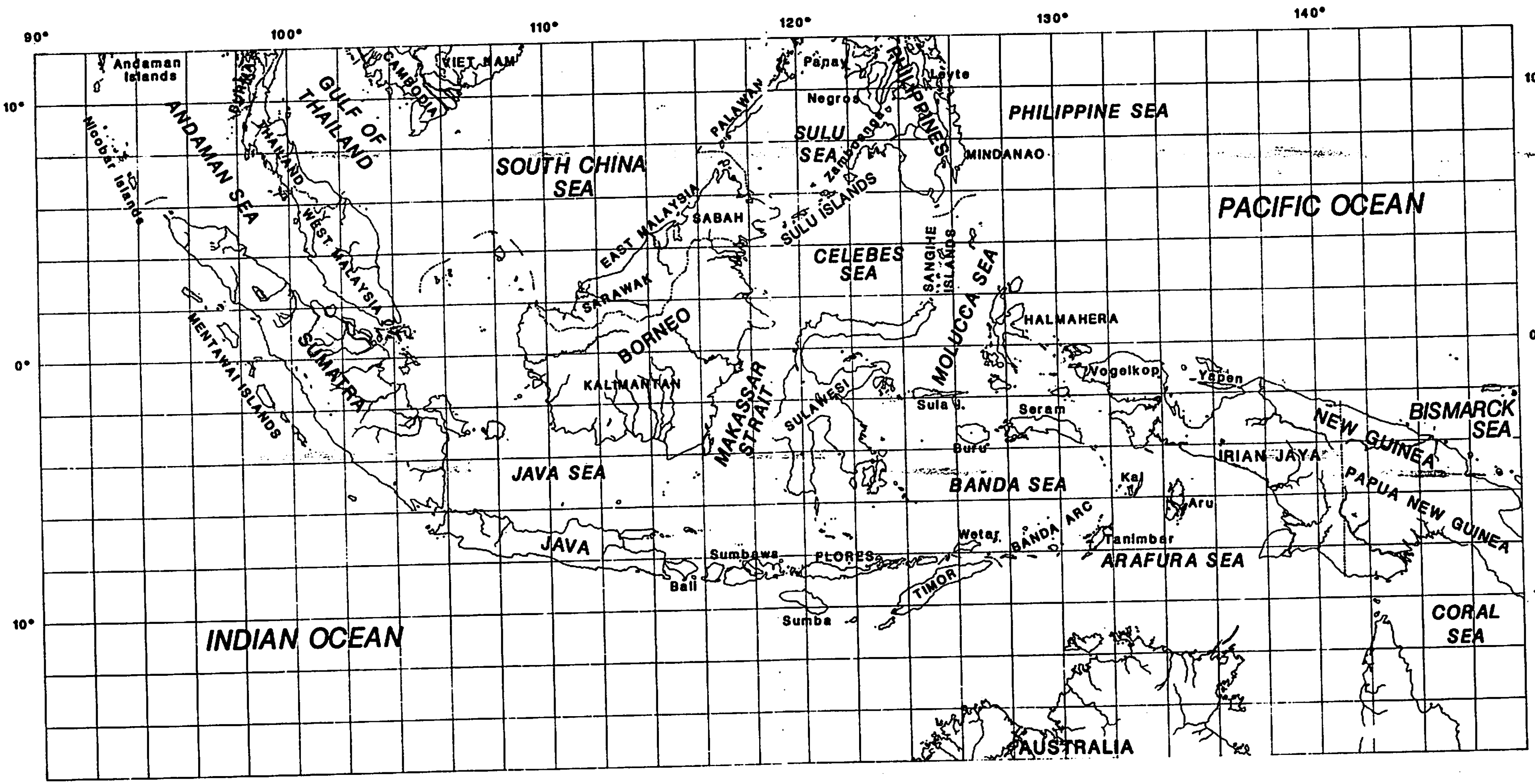

Figure 1. Index map of the Indonesian region. For bathymetry and more detail, see Hamilton (1978a or 1979, Plate 1) or Mammerickx and others (1976).

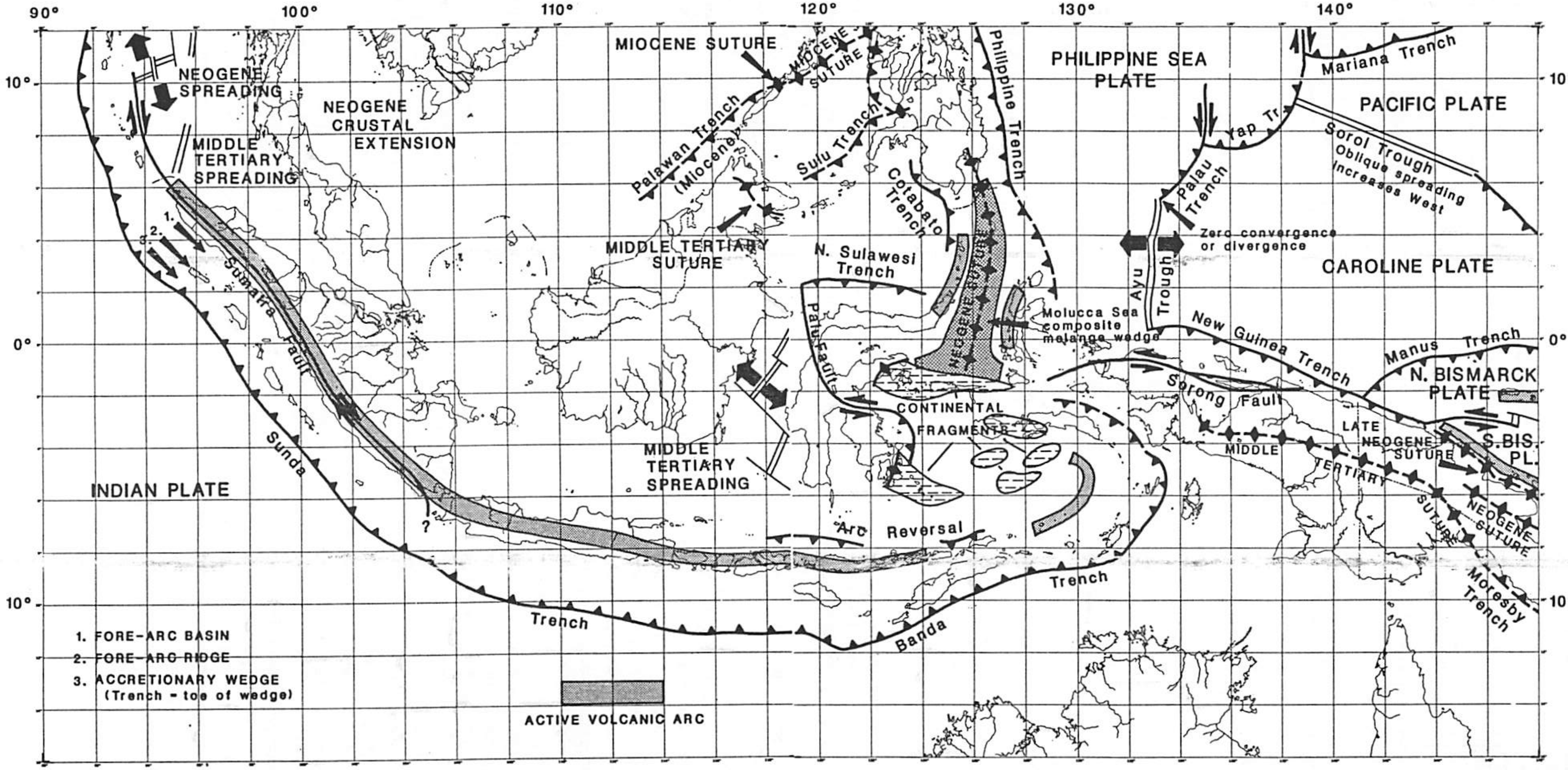

Figure 2. Late Cenozoic tectonic elements of the Indonesian region. Adapted from 1981 edition of Hamilton (1978a) and other sources. Plate boundaries are not complete in the poorly understood region between Sulawesi and New Guinea. The composite mélange wedge of the collided Sangihe and Halmahera arcs is darkly shaded.

sheared and disrupted, and is dominated by terrigenous clastic sediments of deep-water origin but contains abundant fragments of chert and basalt from the upper oceanic crust, and sparse fragments of mafic and ultramafic deeper-seated oceanic rocks. Fossils indicate the coherent strata to have been deposited in water depths that decreased with time. Although no depositional contacts of strata on mélange were found, Moore and his associates inferred that the Neogene strata were deposited atop the wedge and imbricated into it. Alternative possibilities are that at least the older Neogene materials were scraped off the subducting plate and imbricated into the wedge with little internal deformation or that they were deposited on the crystalline oceanic basement of what was then the outer part of the fore-arc basin, that basement having been since removed by tectonic erosion by the subducting plate and itself subducted. In the latter terms, the fore-arc ridge would have migrated arcward with time, not seaward as Moore and associates, and Karig (1982), inferred, and the formation of the undated polymict mélange might largely overlap in time the deposition of the older Neogene strata. Similar inferences seem to me to be plausible for the analogous Cretaceous systems of coastal California, where geometric relationships are much better known but where also interpretations are disputed.

Some investigators (for example, Silver and Reed, 1988) interpret ambiguous reflection profiles to indicate that the overriding-plate backstops for accretionary wedges commonly slope trenchward under the wedges rather than arcward. The apparent lack of on-land exposures of such phenomena is one of many lines of evidence I see against the general validity of such interpretations.

Many students of fossil accretionary wedges assume most broken formation and mélange in them to have formed as thick olistostromes (submarine slumps). Minor slumps may be abundant on the surfaces of wedges, but only one major slump (Moore and others, 1976) has yet been documented on reflection profiles across the floors of the Sunda or other modern trenches, and so I regard sedimentary-mélange interpretations of accretionary wedges as in general unlikely. Any sedimentary mélanges that are formed in trench settings must be imbricated into wedges and tectonized in the process. Broken formation in wedges is produced primarily by shear related to subduction, not by downslope sliding. The ratios within exposed accretionary wedges of polymict mélange, broken formation, and strata coherent at outcrop scale vary greatly, as does the proportion of soft-sediment to brittle deformation. These variables reflect differences in convergence rates, in amount and character of sedimentary strata being added to the wedges, and in positions within wedges. Consolidated sediments and shreds of the subducting lithosphere plate are scraped off against the bottom of the wedge or are carried beneath the overriding plate.

Oceanic lithosphere disappears beneath overriding plates at rates typically near 50 or 100 km/m.y., and most light material on subducting plates is destined for tectonic accretion against overriding plates. Something like 3,000 km of Indian Ocean lithosphere have disappeared beneath Sumatra and Java in the 30 m.y. that the Sunda subduction system has been operating, and so much far-traveled material must be incorporated in the accretionary wedge. Far more subduction is recorded in complexes, as along western North America and many other parts of the world, that incorporate the products of series of such subduction systems.

Arcward slopes of active intraoceanic island arcs, in settings in which little sediment is present on the subducting plate so that little accretionary wedge is present, have been sampled in the Mariana and Tonga Trenches. The Mariana slope consists mostly of igneous rocks of arc origin—calc-alkalic, tholeiitic, and high-magnesium basalts, andesites and dacites, cumulate and massive two-pyroxene gabbros, and serpentinized ultramafic rocks including both cumulate and residual types (Bloomer, 1983;

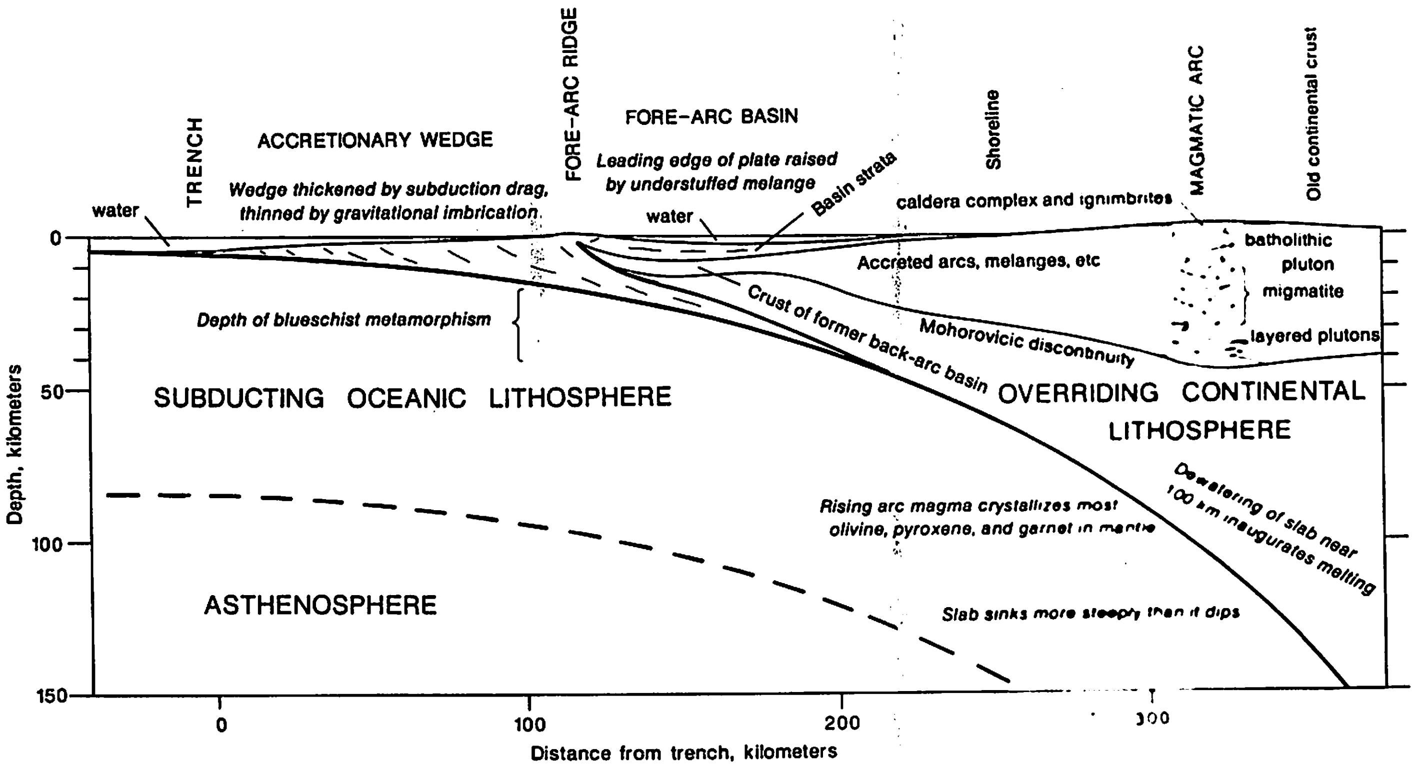

Figure 3. Section across a continental-margin subduction system. The diagram is scaled to modern Sumatra (Indian Ocean to left, southwest; Sumatra on the right, northeast), following constraints of surface dimensions and geology and of seismicity and refraction seismology (mostly from Hamilton, 1979). The dimensions and geology greatly resemble those of middle Cretaceous California also (compare with Hamilton, 1978b, 1988a). The deep erosion of parts of the California analogues exposes variations with depth which are integrated.

Bloomer and Hawkins, 1983; Natland and Tarney, 1981). The Tonga slope yielded what appears to be a nearly complete crustal and upper-mantle section of primitive arc rocks (Bloomer and Fisher, 1987). Tectonic erosion of the bases of the overriding Mariana and Tonga plates is inferred. Analogous complexes would be termed "ophiolitic" if they were encountered in ancient accreted terranes, but they clearly are of arc origins (Bloomer and Fisher, 1987; Bloomer and Hawkins, 1983).

Fore-Arc Basin. Between the fore-arc ridge and the shoreline of the Sunda system is the bathymetric and structural fore-arc basin, which is 150–200 km wide and contains at least 5 km of strata in the Sumatra sector (Beaudry and Moore, 1981; Hamilton, 1979; Karig and others, 1980a). On the arcward side of the basin, undeformed lower Miocene and higher strata lap progressively farther landward onto the basement. On the oceanic side, strata become increasingly deformed toward the fore-arc ridge, and that deformation includes both arcward-directed thrusts and folds and the diapiric rise of shale into folds; basement generally is not defined by reflection data. Depocenters of successively younger stratal packages are displaced arcward. This displacement is better documented by published data for the fore-arc basins of Peru and Chile (Coulbourn and Moberly, 1977) and Luzon (Lewis and Hayes, 1984). I have seen proprietary reflection profiles on which it appears that deep strata now tilted arcward on the oceanic side of the Sunda fore-arc basin were deposited as units prograded trenchward in deep water, before their basement was raised to define the basin. The Aleutian fore-arc basin similarly evolved as its front was raised (Harbert and others, 1986). The basement beneath the outer parts of both the Sumatra (Kieckhefer and others, 1980) and Java (Naomi Benaron, 1982, written commun.) basins has velocities typical of oceanic, not continental, crust, although the thickness of crust of such velocity in the Sumatra sector is much greater than is typical of oceanic lithosphere.

I integrate these features for this and other modern fore-arc basins, the features of the fore-arc ridge noted previously, and characteristics of some ancient analogs to infer that the fill of a fore-arc basin is deposited across the boundary between continental crust and a narrow strip of oceanic upper lithosphere that is attached to the front of the overriding continental plate. The basin is formed primarily by the raising of the thin, oceanic leading edge of the overriding plate as accretionary-wedge mélange and packets of sediments are stuffed under it. Depth of the basin is augmented by elastic downflexure behind that raised leading edge. The fore-arc ridge is the crest of accretionary-wedge debris accumulated in snowplow fashion in front of the overriding leading edge. Debris that overtops the leading edge is imbricated gravitationally arcward over the shallow strata of the basin. As tectonic erosion trims the leading edge of the overriding plate, the fore-arc ridge migrates arcward relative to that plate, and the fore-arc basin is narrowed.

Fore-arc basins of similar characteristics are common along subduction-system margins of continents and mature island arcs. The ridge and basin may be displayed in bathymetry as well as structure (as in the modern Sunda system and in the paleobathymetry and longitudinal deposition of the Lower Cretaceous part of the "Valley Facies" of California) or may appear as a bathymetric shelf underlain by structural ridge and basin (as, modern Chile and southern Alaska and much of the Upper Cretaceous and Paleogene parts of the "Valley Facies"). Basal strata in such fore-arc basins are generally pelagic sediments and abyssal-fan strata that predate the inauguration of the basins and of the subduction systems that bound them.

Exposed basement of the outer parts of fore-arc basins consists of oceanic crust [for example, Cretaceous California (Hamilton, 1978b; Ingersoll and Schweickert, 1986) and middle Tertiary Luzon (Bachman and others, 1983; Karig, 1982)] and is arguably in most cases of marginal-basin origin. A similar origin of the basement of modern basins, including the Sunda system, accords with geophysical data. The leading edge of overriding continental plates may commonly be a strip, 100 km or so wide, of oceanic lithosphere. As noted below, such a strip likely forms behind a migrating oceanic island arc which then collides with a continent or another arc, the strip then being left attached to the enlarged crustal mass when reversal of subduction polarity took place.

Lack of Shortening. Sunda and other fore-arc basin fills and their thin upper-plate–lithosphere basements are not commonly shortened compressively across their width, although they are subjected to tectonic erosion and rumpling at their trenchward sides. Thick and undisturbed basin-filling strata can be seen on reflection profiles across many fore-arc basins in Indonesian and other active subduction systems. This lack of deformation disproves the common assumption (for example, Hutchinson, 1980) that the leading edges of overriding plates are crumpled against subducting plates. Extreme shear imbricates the surficial accretionary wedge pushed in front of an overriding plate, but that plate itself commonly is not shortened. Slight to severe extension, not shortening, occurs across most modern magmatic arcs, perhaps because the steeply sinking subducting slabs displace underlying mantle downward, resulting in extension of the mantle, asthenosphere, and lithosphere above the slabs.

Relation to Arc Reversal. Subduction systems typically are inaugurated by reversal of subduction polarity following a collision between thick crustal masses. Subduction can no longer occur within the newly enlarged crustal mass, and as convergence continues, a new subduction system breaks through on an oceanic side of the enlarged landmass. The break commonly occurs not at the boundary between thick and thin crust, but within oceanic lithosphere 100 km or so oceanward of that boundary, so that a strip of oceanic lithosphere thus becomes the thin leading edge of the newly defined overriding plate. In the case of a reversal following an island-arc collision, this oceanic strip is the youngest part of the back-arc–basin lithosphere formed by the migrating arc, hence is only slightly older than the collision itself. Such an explanation is best documented for the case of latest Jurassic California (Ingersoll and Schweickert, 1986) but accords with data from many other arcs, including Sumatra and Java (Hamilton, 1988b). (Contrary views are expressed by Karig, 1982.)

High-Pressure Metamorphism. The only high-pressure metamorphic rocks yet known within Neogene mélange in the Sunda system are blocks of garnet amphibolite found on Nias by Moore and Karig (1980). (Glaucophane schist is known in Neogene mélange farther east, in the Banda sector.) High-pressure metamorphic rocks, of blueschist and locally eclogite or garnet amphibolite facies, are widely known in pre-Neogene Phanerozoic subduction complexes in the Indonesian region and elsewhere about the world. The petrology of such rocks requires that they have been metamorphosed mostly at depths of 25–45 km at relatively low to moderate temperatures, then returned to shallow depths before equilibration of geothermal gradients to normal values for such depths; this apparently occurs as a return-flow by-product of subduction (for example, Cloos, 1985, and Wang and Shi, 1984). I infer from the geologic relationships of many occurrences around the world and from the geometry of modern wedges that such metamorphic rocks never form within an accretionary wedge between trench, fore-arc ridge, and subducting lithosphere but, rather, that they form only where crustal and supracrustal materials have been subducted beneath the overriding plate.

Sediment on subducting plates can partly bypass the accretionary wedge and ride far beneath the overriding plate. This is shown directly where anticlinal windows in southern California broadly expose metamorphosed oceanic sedimentary and crustal rocks (termed Pelona, Orocopia, and Rand Schists) that were subducted in latest Cretaceous time beneath lower continental crust.

Reasoning by analogy with Mesozoic California and other deeply eroded ancient systems of accretionary wedges and fore-arc basins, I infer that beneath the sub-basin leading edge of the overriding Sunda plate, mélange is now being metamorphosed at blueschist facies, and perhaps eclogite facies, and that beneath this metamélange is metamorphosing crust of the subducting oceanic lithosphere. The thick zone with oceanic crustal velocities beneath the basin fill, as defined by Kieckhefer and others (1980), may represent a sandwich of thick arc-type ophiolitic overriding-plate basement to the basin, metasedimentary rocks beneath that, and crust of the subducting Indian Ocean plate still deeper.

Magmatic Arc. Sunda volcanoes now erupt in a belt about 100 km above the top of the inclined Benioff zone of mantle earthquakes, or about 130 km above the midplane (Hamilton, 1974a, 1978a; Hayes and Taylor, 1978). This magmatic arc changes along strike from continental in Sumatra to transitional in Java to a mature oceanic island arc in Bali, Lombok, and Sumbawa. Sunda-system volcanism did not begin until early Miocene time in Sumatra. Middle Tertiary volcanic rocks are widespread but poorly dated on land, but the inception and subsequent continuity of major silicic magmatism are defined, in sections drilled in the Gulf of Thailand, by voluminous volcanogenic mixed-layer clays in middle lower Miocene and higher shales. Volcanism, dated by the paleontologic age of intercalated strata in drill holes, was active by late Oligocene time in offshore southern Java; whether this magmatism records the Sunda system or an oceanic island arc that collided with the pre–Sunda-system continent is unclear, but the continuity of upper Oligocene and higher strata across central and western Java and the continental shelves to the north and northwest shows that region to have been a coherent part of Southeast Asia by then. The Paleogene of mainland Sumatra, inland from the collided arc noted subsequently, records pre-arc sedimentation across a low and stable landmass from Southeast Asian cratonic sources.

The volcanoes of the magmatic arc rise above a geanticline, within which are most exposures of pre-Miocene rocks of Java and Sumatra. Presumably, this geanticline is a product of magmatic inflation and thermal uplift of pre-existing crust. Continental Sumatra has much the higher geanticline of pre-volcanic rocks, and I infer that there, a crustal column was heated by intrusions to near-magmatic temperatures, with formation of voluminous migmatites, before much magma reached the surface to form volcanoes.

The compositions of the volcanic rocks vary systematically with the character of the crust through which their magmas have been erupted. The crust of Sumatra was continental by late Paleozoic time, when silicic, radiogenic granites were formed, and likely was so during the Precambrian, although no rocks of that age have been identified. The modern magmatic-arc rocks atop this continental crust are mostly intermediate to silicic in composition. They approximate rhyodacite (granodiorite) in bulk composition; there is little basalt. Lake Toba caldera, produced by collapse accompanying voluminous late Pleistocene silicic ignimbritic eruptions, is the largest caldera known anywhere and is about the same size and shape as what is perhaps the largest upper-crustal granitic pluton yet mapped, the Late Cretaceous Mount Whitney pluton of the Sierra Nevada of California. In Java, where the pre-Neogene crust is of near-continental thickness but consists of mélanges and mafic to intermediate magmatic rocks, young volcanic rocks are mafic to intermediate—mostly pyroxene andesite and high-alumina basalt, with subordinate dacite. Similar mafic and intermediate rocks characterize the mature oceanic island arc of Bali and Sumbawa, where exposed rocks are entirely of Neogene age. Farther east, in the Banda Arc sector discussed subsequently, the volcanic arc is younger and consists mostly of more primitive basalts, rocks much less evolved petrologically than those even of the mature oceanic part of the Sunda sector. Comparable transitions, from evolved and silicic magmatic rocks to more primitive and mafic ones, can be seen wherever about the Pacific continuous magmatic arcs cross from continental to oceanic lithosphere.

Indian Ocean lithosphere is being subducted beneath all of the Sunda sector, and presumably, the deep proto-magmas generated by subduction-related processes—melting of mantle consequent on dehydration of subducted hydrous rocks?—are similar olivine-rich basaltic melts along the entire length of the sector. The volcanic rocks which reach the surface have been profoundly modified by reactions in and with the crust through which they have passed. Even the primitive rocks farther east record magmas equilibrated at shallow depths; no deep-mantle magmas reach the surface without great modification.

Volcanoes north of the main Sunda magmatic belt show the marked variations, including increased potassium relative to silicon, that characterize eruptions above deep parts of subducting slabs.

Pre-Neogene Tectonics of Sumatra. The modern Sunda system, involving subduction of Indian Ocean lithosphere beneath Sumatra and Java, was inaugurated only in middle Tertiary time. Much of the older geology records subduction in quite different tectonic systems. Most of Sumatra has been continental at least since late Paleozoic time and belongs to the same system of late Paleozoic and early Mesozoic sutures and magmatic arcs as does the Malay Peninsula. Sumatra may have been rifted from what is now medial New Guinea in Middle Jurassic time, and a rifted-margin stratal wedge can be inferred from meager data to be present in Sumatra. Java, on the other hand, has been constructed entirely by post-Jurassic subduction-related processes of magmatism and tectonic accretion. Many reconnaissance data regarding the pre-Neogene geology of Sumatra have been released since the completion of my 1979 book, as 1:250,000 photogeologic maps constrained by sparse field traverses and brief rock descriptions (as, Bennett and others, 1981; Cameron and others, 1982; Rock and others, 1983). I interpret these works to show that the pre–Late Jurassic–age rocks of the old continental crust are bounded on the southwest by a broad belt of polymict subduction mélange and broken formation of late Mesozoic and(?) Paleogene age. This accretionary-wedge complex includes not only the small areas identified as mélange and serpentinite by these authors but also most of the larger terranes they designated as eastern Woyla Group and as Babahrot and Belok Gadang Formations, the brief descriptions of which indicate the presence of widespread broken formation and polymict mélange. (Rock-unit names applied in these reports have little lithostratigraphic significance.) This broad accretionary-wedge tract lies within the medial part of far northern Sumatra, where its distribution is complicated by the active right-slip Sumatran fault system, but closer to the southwest coast in central Sumatra; southern Sumatra lacks exposures of pre-Neogene rocks in the relevant coastal belt. To the west of the broad belt of probable mélange is a belt of volcanic, volcaniclastic, and sedimentary rocks, of island-arc type and of Late Jurassic and Early Cretaceous age at the few localities where dated paleontologically, which was assigned to the western Woyla Group by the mappers.

I interpret these relationships to indicate that a northward-migrating oceanic island arc collided with the margin of Sumatra, which had been a trailing edge since its mid-Jurassic separation from New Guinea, in Paleogene time. Convergence of Sumatra and Indian Ocean continued, and the subduction system that is now active broke through south of the continent as enlarged by the collision, leaving a narrow strip of marginal-sea lithosphere, which had been formed behind the advancing arc, as the leading edge of the new upper plate. (Bennett and others, 1981, and Rock and others, 1983, recognized the island-arc character of the southwestern rocks but interpreted them in terms quite different from mine.)

Pre-Neogene Tectonics of Java. The modern subduction system in Java was inaugurated no earlier than late Oligocene time. Exposures of pre-Neogene–age rocks are limited to small areas, in central and southwest Java, of polymict mélange of Late Cretaceous and early Paleogene age and of overlying middle or late Eocene through Oligocene quartzose clastic strata and shallow-water carbonates. Much more information has come from the subsurface of northern Java and the Java Sea shelf. Mélange of Cretaceous and early Paleogene age dominates the basement in a broad belt trending northeastward from Java across the shelf to southeast Borneo, where it is widely exposed. This mélange may be paired to wide-

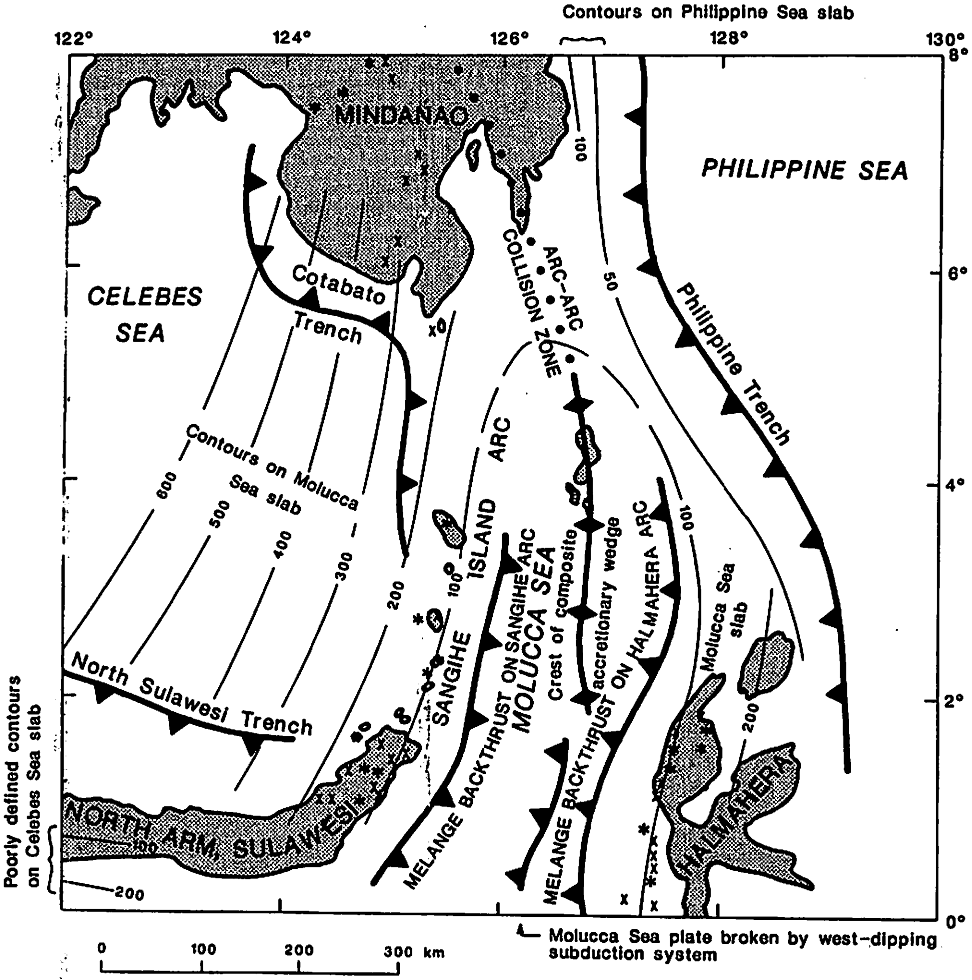

Figure 4. Plate-tectonic features of the Molucca Sea region. A collision between east-facing Sangihe island arc and west-facing Halmahera arc has progressed southward with time as the Molucca Sea plate has sunk (subducted) beneath them. The opposed accretionary wedges merged and backflowed onto the advancing arcs. The young Cotabato Trench has broken through on the west side of the old part of the aggregate; thrust earthquakes, but not a clearly defined Benioff seismic zone, are associated with it. The Philippine Trench, on the east side of the aggregate, has only a shallow west-dipping seismic zone, the relation of which to the east-dipping zone beneath Halmahera is unclear. The marked "collision zone" within Mindanao and the northern Molucca Sea may still be active as a left-slip transpressive plate boundary. Contours show depths to tops of subducting slabs, in kilometers; *, historically active volcano; x, Quaternary volcano. Adapted mostly from data and interpretations of Hamilton (1974b, 1979), but with modifications for data and interpretations of Cardwell and others (1980), McCaffrey (1982), McCaffrey and others (1980), and Moore and Silver (1982).

spread Cretaceous granitic and volcanic rocks to the northwest in Borneo and the Java Sea basement. During late Paleogene time, western and central Java and the Java Sea were tectonically and magmatically dormant and were fused to the subcontinent that included most of Sumatra and all of the Malay Peninsula, and subduction was beneath the opposite side of the small continent; South China Sea lithosphere was then being subducted southward beneath what is now northwest Borneo. If a northward-migrating arc collided with Java in Paleogene time, as might be expected from the interpretation just made for Sumatra, then it now lies offshore in the subsurface, where the upper Oligocene volcanic rocks drilled south of central Java may belong to such an arc. Eastern Java, Bali, Lombok, Sumbawa, and Flores project east of all known pre-Neogene complexes and expose only oceanic Neogene island-arc rocks.

Neogene Deformation. Popular conjecture, residual from geosynclinal theory, assumes great crustal shortening to be a precursor of arc magmatism. Such deformation is not recorded in the Sunda system or other modern magmatic arcs. In Java, middle Tertiary strata are openly folded; deformation decreases in intensity away from magmatic centers, about which structures tend to be concentric (as, Djuri, 1975), and gravitational spreading of magmatic chambers and edifices is likely a major cause of deformation. In Sumatra, middle Tertiary pre-magmatic strata within the modern volcanic belt but distant from local centers are subhorizontal or gently dipping and display normal faulting. Gravitational spreading related to magmatic crustal thickening can be inferred for Sumatra also. Normal faulting, not compressional deformation, is commonly seen in the old parts of mature island arcs. Where collisions of light crustal masses are involved, however, or where convergence is so rapid that an overriding continental plate drags on a gently dipping subducted plate, severe shortening and major crustal thrusting can result.

Banda Subduction System

The Banda Arc continues the great subduction system eastward from the Sunda sector. The character of the system changes greatly along strike. Oceanic lithosphere is being subducted beneath a continental plate in Sumatra, beneath transitional lithosphere in Java, and beneath another oceanic plate in the Bali-Sumbawa-Flores sector; in the Banda Arc, an oceanic arc is now colliding with the continent of Australia and New Guinea. That collision becomes progressively younger in the Neogene eastward, and as the arc complex has accreted to the continent, subduction has reversed beneath the south limb of the arc to become southward beneath it. The south limb of the Banda Arc is wholly of Neogene age, and it becomes progressively younger in age of inception of magmatism along its eastward trend; the arc has lengthened with time. In the eastern Banda Arc, trench, fore-arc ridge and basin, and volcanic arc all trend concentrically around a tight curve. A well-defined Benioff zone of earthquakes dips northward deep into the mantle from the accretionary wedge of the Sunda Arc and the south limb of the Banda Arc. The seismic zone curves in the east, concentric to the bathymetric features, to define a spoon-shaped zone that plunges gently westward but that can be traced unambiguously only to a little north of the geometric axis of the Banda Arc. Various conclusions of my 1979 and earlier reports have been replicated and expanded by others from much new geophysical data, some of which is cited herein.

Trench. Whereas the trench in the Sunda sector overlies oceanic lithosphere, the shallow trench in the Banda sector overlies continental crust around the entire curve of the arc. The continuity around the arc of the distinctive tectonic morphology of trench and accretionary wedge is shown by scores of reflection profiles. The trench marks the gentle dihedral angle between shallow-water strata bowed down from the Australia–Arafura–New Guinea continental shelf on one side and the toe of the accretionary wedge on the other. The accretionary front advances discontinuously as new thrust slices develop within the shelf strata (Karig and others, 1987). Continental crust is demonstrated by refraction data to extend beneath the accretionary wedge at least to the inner edge of the fore-arc ridge (Bowin and others, 1980; Jacobson and others, 1979). McCaffrey and others (1985) inferred that the thin leading edge of the continent has been subducted to a depth of 150 km in the Timor sector and that still deeper subducted oceanic lithosphere is detached and sinking independently.

Fore-Arc Ridge. The top of the accretionary wedge is wholly submarine from Java to Flores, but where it stands upon continental crust, it forms the large, high island of Timor; lower, smaller, and later-starting islands around the tight eastern curve of the Banda Arc; and large, high Seram on the north limb of the system. Continuity of the wedge around the arc as a thick aggregate of low-density material is indicated by its continuous gravity anomaly (Bowin and others, 1980). Descriptions of island geology that postdate Hamilton (1979) add details to my accretionary-wedge descriptions. The wedge consists of polymict mélange and broken formations imbricated, with generally arcward dips, with variably coherent strata that include strata from the continental shelf onto which the wedge has been ramped, strata deposited atop the wedge, abyssal pelagic sediments, and slices and fragments of both ophiolitic and continental crystalline rocks. Fore-arc–basin materials may have been imbricated into the wedge after tectonic removal of their overriding-plate basement. Quaternary reefs have been elevated as high as 1,000 m above sea level as the top of the wedge has been raised both by thickening of the wedge by accretion and imbrication and by ramping farther onto continental crust.

Berry and Grady (1981) described metamorphism of sedimentary rocks that decreases from uppermost amphibolite facies to greenschist facies away from an ophiolite mass at the north edge of central Timor. Potassium-argon ages of hornblende show the metamorphism to be of about late middle Miocene age. I infer from the relationships mapped by Berry that the temperature of metamorphism decreased downward beneath the ophiolite sheet, which I regard as the hot leading edge of the onramping island arc. (Berry and Grady inferred vertical or strike-slip tectonics and suggested no heat source.) The Tethyan region has many analogous ophiolite sheets that were emplaced while hot. Farther west in north-coastal Timor, upper Miocene tholeiitic and calc-alkalic basalt are thrust southward onto the wedge (Abbott and Chamalaun, 1981); again, I infer onramping of the advancing arc.

Fore-Arc Basin. The fore-arc basin is continuous (except at Sumba) around the Banda Arc. Little-deformed basin strata lap onto the fore-arc ridge on the outside of the basin and grade into volcaniclastic aprons of the magmatic arc on the inside. The bathymetric basin deepens symmetrically along both limbs of the Banda Arc toward the axis of its tight horseshoe curve to define the Weber Deep, the depth of which reaches 7.5 km precisely at that axis. I interpret the basin as formed by the elastic deflection of the thin leading part of the overriding lithosphere as its edge has been ramped up by the stuffing beneath it both of accretionary-wedge mélange and of continental crust. This depression is focused at the Weber Deep from three sides.

The basin is markedly narrower along northern and eastern Timor than elsewhere around the south limb and eastern curve of the Banda Arc. I infer tectonic erosion of the leading edge of the overriding plate, and the imbrication into the Timor wedge of what were strata deposited on that leading edge. There is no suggestion on reflection profiles of subduction within this or other sectors of the basin; narrowing (or, in the Weber Deep, deepening) by subduction cannot be proposed.

The concentricity of the Banda Arc deteriorates in the Buru–western Seram sector of the north limb. No fore-arc basin is present inward from that part of the fore-arc ridge. Islands of Pliocene volcanic rocks, which presumably represent the extinct magmatic arc and were erupted through silicic continental rocks (Abbott and Chamalaun, 1981), are separated from the ridge only by narrow straits. Tectonic erosion of the overlying plate may here also be part of the explanation.

The large island of Sumba rises within what is otherwise the fore-arc basin, and its almost undeformed Miocene to Quaternary strata are continuous with those of the basin; the island is a raised part of the basin, domed above a poorly understood complex of pre-Miocene–age crystalline and sedimentary rocks. I suggested (Hamilton, 1979) that the old rocks represent a crustal fragment rifted from the Java shelf, whereas Silver and others (1983c) suggested that they represent one of the crustal fragments in front of Australia, subducted beneath the basin.

Magmatic Arc. Although the magmatic arc is continuous around the south limb and eastern curve of the Banda Arc, its history varies systematically with position. The width and volume of the magmatic edifice decrease eastward along the south limb of the arc and correspond to a decreasing age of inception of magmatism, from early Miocene in the west to Pliocene in the east part of the south limb, and probably Quaternary within the tight eastern arc. (Data postdating my monograph include those of Abbott and Chamalaun, 1981, and Suwarna and others, 1981.) Around the sharp eastern curve, the magmatic arc is represented only by small, active-volcano islands atop a narrow and poorly continuous ridge. The volcanic rocks change correspondingly from andesites and evolved basalts in the older sector to more primitive basalts in the young sector. Volcanic rocks on the short, irregular north limb of the arc are of Pliocene age, but here, tectonic relationships are poorly understood. Volcanoes are currently active all along the south limb of the magmatic arc and around the eastern curve of the arc, except for a length of about 500 km, to the north and northeast of eastern Timor, and along the short north limb in the Buru–western Seram sector, in both of which activity ended in Pliocene time, apparently following the cessation of subduction beneath the Banda Sea as a consequence of the arc-continent collision.

Arc Reversal. Two sectors, each about 500 km long, of the south limb of the Banda Arc are now marked by trenches, the tectonic geometry of which indicates subduction relatively southward, at the north base of the volcanic arc. This polarity is opposite to that of the main Banda system. I (Hamilton, 1979) identified the trenches on reflection profiles and argued for arc reversal following collision of arc with continent. Breen and others (1986), Karig and others (1987), McCaffrey and Nabelek (1984, 1987), Reed and others (1986), and Silver and others (1983c, 1986) further defined the character and extent of the frontal and reversed trenches and the accretionary wedge from reflection profiles, side-scan mapping, seismicity, and other data. The eastern of these new trenches is north of central and eastern Timor and coincides with that part of the volcanic arc in which magmatism ceased in late Pliocene time. The western of the new trenches lies north of Flores, Sumbawa, and Lombok, where magmatism apparently belonging to the north-dipping subduction system is still active but appears to have decreased within late Quaternary time.

Banda Sea. The small but complex Banda Sea, enclosed by the Banda Arc, consists of the oceanic North and South Banda Basins and an intervening group of submarine ridges. These ridges are known from dredging to be fragments of continental crust (Silver and others, 1985).

Minicontinental fragments are exposed on the partly submerged platforms around the northern part of the Banda Sea—Buton in the west, Banggai-Sula in the northwest, and Buru–Ambon–western Seram in north-center (Hamilton, 1979; Pigram and Panggabean, 1983; Silver and others, 1983b; Silver and others, 1985). The age of formation of the oceanic crust of the two major Banda Sea basins is not yet constrained by drilling. I suggested (Hamilton, 1979) that the basins formed behind a migrating Banda Arc and are of Cenozoic age. Bowin and others (1980), Lee and McCabe (1986), Pigram and Panggabean (1983), and Silver and others (1985), by contrast, have regarded both basins as trapped bits of Mesozoic lithosphere. Their interpretation is plausible for parts of the North Banda Basin, which is discontinuously rimmed by fragments of pre-Cenozoic continental crust, although reconnaissance heat-flow measurements from the southern subbasin of the North Banda Basin are so high that Neogene rifting is likely there also (Van Gool and others, 1987). The old-crust interpretation is implausible for the South Banda Basin, for the Banda Arc, which defines the south edge of this basin, has lengthened during late Neogene time.

Interpretation. The age of inception of the Banda magmatic arc becomes progressively younger eastward along the arc, from early Miocene to Pliocene and probably to Quaternary; the arc has lengthened with time. The collision of the arc with the Australia–New Guinea continent also has progressed eastward with time, occurring earlier at Timor than around the axis of the tight curve in the east. Timor has not slid past Australia on strike-slip faults but has remained attached to it since the collision in that sector; Banda Sea lithosphere is beginning to be subducted southward beneath the continent, as enlarged by the accreted arc, at a new trench, even as subduction at the axis of curvature of the arc is relatively westward beneath the Banda Sea. Such relationships, to me, require that the crust of the South Banda Basin has formed by spreading behind a rapidly migrating Banda Arc or has been plated out by the fast-migrating arc itself. The Banda Sea does not represent an internally rigid plate neatly pre-shaped to slide into the Arafura concavity between Australia and New Guinea; rather, the Banda plate expanded as needed to fill a concavity which likely has itself changed shape as Jurassic oceanic crust attached to the continent sank in front of the Banda plate.

This much of the story is analogous to that in my 1979 book, but clearly, I erred there in picturing the entire Banda Arc and Banda Sea as a simple migrating arc paired to an extensional back-arc basin. The north limb of the arc (Seram and Buru), the North Banda Basin, and the submarine ridges require much more complex explanations. All observers agree that the continental fragments must have been torn from New Guinea, but details remain highly ambiguous. A viable solution must incorporate rapid northward motion of New Guinea and westward motion of Pacific plates, and probably southward motion of the Sunda system, and must account for the bewildering array of diversely oriented tectonic elements in and north of the Banda Sea, as well as for migration and lengthening of at least the southern and eastern parts of the Banda Arc.

Caribbean, Scotian, and Carpathian Arcs. Each of these three east-facing, horseshoe-shaped arcs is dimensionally and geometrically so like the Banda Arc and displays so many analogous features that similar origins are likely. Each can in my view (but not in the views of most local experts) be explained in terms primarily of eastward-migrating oceanic arcs. Caribbean and Scotia arcs collided with the Pacific sides of Central and South America and West Antarctica in late Mesozoic time but continued to migrate through the oceanic gaps between those landmasses, beaching arc material against north and south sides progressively eastward with time. The initial frontal collisions were followed by reversals of subduction polarity which inaugurated the Andean systems that have operated subsequently along the continental margins. The Carpathian arc migrated into a continental concavity during Tertiary time and also beached its flanks successively eastward with time; minicontinental fragments trailed behind.

Northern Indonesia and the Southern Philippines

Molucca Sea Collision Zone. A collision between inward-facing island arcs is under way in the Molucca Sea region, where the collision between the east-facing Sangihe island arc and west-facing Halmahera arc has progressed southward with time (Fig. 4). The suture zone is fully closed in the north and is exposed on land in Mindanao. In the central sector, the northern Molucca Sea region, the accretionary wedges of the two arcs have been joined by collision and have been thickened to at least 15 km, and the composite surface raised to near sea level and locally above it, in the medial zone. The overthickened composite wedge has flowed gravitationally across the inward-facing trenches and onto the arcs on both sides, so that surficial thrusting of mélange has the sense opposite to that of subduction. Following the collision, arc magmatism ceased in this central sector, and subduction polarity of the Sangihe arc was reversed. In the southern Molucca Sea region, the two accretionary wedges have met in the center, but subduction and arc magmatism are still active in their pre-collision sense.

This system of colliding arcs is important for comprehension of plate behavior and has been studied extensively, particularly by Eli Silver and his associates, since my work on it. Recent information on this collision system that in general documents the conclusions just summarized was reported by Cardwell and others (1980), Hall (1987), McCaffrey (1982), McCaffrey and others (1980), Moore and Silver (1982), and Silver and others (1983a). Weissel (1980) identified sea-floor–spreading magnetic anomalies of the southwestern Celebes Sea (the marginal basin opened behind the Sangihe arc but now being subducted beneath northern Sulawesi, southwestern Mindanao, and the northern Sangihe arc) as probably Eocene in age, whereas Lee and McCabe (1986) regarded them as of latest Cretaceous age.

The Molucca Sea plate is being subducted simultaneously relatively westward beneath the Sangihe arc and eastward beneath the Halmahera arc. A well-defined Benioff seismic zone dips westward beneath the Sangihe arc to a depth of about 650 km beneath the Celebes Sea, and another zone dips eastward beneath Halmahera to a depth of about 250 km. The active volcanoes of both arcs are concentrated about 100 km above the tops of the respective seismic zones, which merge beneath the Molucca Sea composite mélange wedge. This two-sided subduction cannot be explained in terms of subduction as a process of injection down fixed slots and requires that the subducting Molucca Sea plate fell away on both sides as overriding plates advanced over it.

Relationships around the southern Molucca Sea region are exceedingly complex and still poorly understood. Data and synthesis postdating mine were presented by Silver and others (1983b).

Aggregation of the Southern Philippines. The Philippine Islands are a collage of variably collided, reversed, oroclinally twisted, and magmatically overprinted components of island arcs—magmatic arcs, accretionary wedges, large and small ophiolitic masses, and sedimentary assemblages. The collided Sangihe and Halmahera arcs and intervening wedge come ashore in southern Mindanao, where suturing was completed during middle Tertiary time (Hawkins and others, 1985), and their products are being overprinted by arc magmatism paired to subduction relatively eastward from the Cotabato Trench, which was inaugurated by arc reversal following the collision. The Benioff zone inclined westward from the Philippine Trench extends only to shallow depth and has no obviously associated arc volcanoes south of Leyte (Cardwell and others, 1983); kinematic relationships of this Philippine Trench system to those of the rest of Mindanao are not yet clear. Farther west, the recently inactivated, northwest-facing Sulu island arc comes ashore as the Zamboanga Peninsula of western Mindanao, and the slow-subduction, southwest-facing Negros arc system apparently is closing southward against the Sulu-Zamboanga arc, colliding with its own earlier projection. Still farther west,

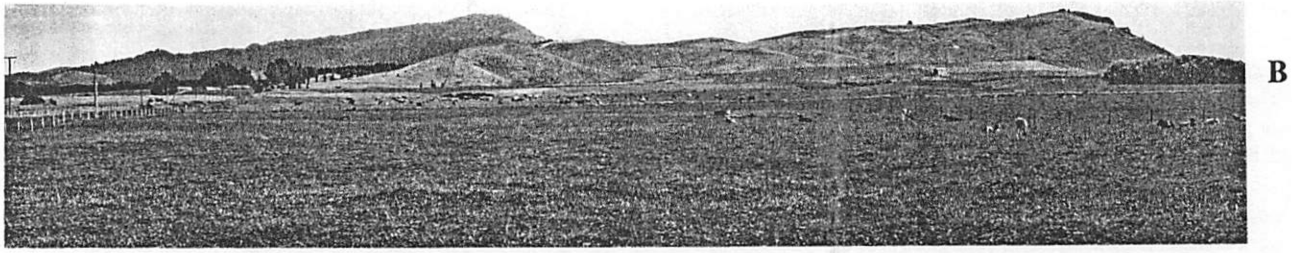

Figure 5. Volcanic rocks of the modern volcanic arc of North Island, New Zealand. A. Ruapehu stratovolcano of basaltic andesite, and Lower Tama Lake explosion craters, at nonextending south end of arc, which stands on geanticline. B. Normal faulted and rotated middle Quaternary ignimbrite sheets of silicic biotite rhyodacite, in the rapidly extending northern part of the arc, which is little above sea level. Paeroa Range, 25 km south of Lake Rotorua.

the Palawan island arc, beneath which South China Sea lithosphere was subducted during middle Tertiary time, comes ashore in the west-central Philippines, much complicated by a collision with a North Palawan minicontinent rifted from from China as the South China Sea was opened.

Six different middle and late Cenozoic subduction systems are thus clearly recorded in the southern Philippines aggregate. As arc-type materials are as old as Cretaceous in the southern Philippines, many additional complexities have yet to be understood. Other aspects of this accretionary history have been discussed by Hawkins and others (1985), Karig and others (1986), McCabe and others (1987), and Sarewitz and Karig (1986). It appears that many far-traveled arcs and fragments have here been aggregated entirely in an intra-oceanic setting; it is the ultimate fate of this composite mass to be accreted to a continent.

Collisions and Subduction

Examples such as those noted briefly in this section make it obvious that long-continuing, steady-state subduction systems are atypical; that complex sequences of collision, aggregation, reversal, rifting, and internal deformation are the rule; and that aggregates of collided bits can be assembled far from their final resting places. Histories and kinematics can vary dramatically along strike in continuous complexes. Collisions and reversals progress along strike with time, and strike-slip and oroclinal deformation are common. Collisions do not occur between neatly matched shapes; irregular masses meet, and highly variable deformation occurs before they are fully jostled together.

Large plates commonly continue to converge after a collision, and the result is the inauguration of a new subduction system on an oceanic side of the new aggregate; often, this represents a reversal of polarity of subduction as well as a jump in position. Subduction of oceanic lithosphere beneath a continental plate commonly begins as a consequence of a plate collision. Convergence between megaplates continues, but the light crust on the subducting plate is too low in density to be subducted, and so a new subduction system breaks through oceanward of the continental plate as enlarged by the subduction. Such post-collision reversals are now under way in the Timor and Molucca regions; dozens of others are recorded in circum-Pacific geology. The Solomon-Admiralty arc complex displays two reversals, one of which presently is progressing along strike as the arc slides past a trench-trench-transform triple junction (Hamilton, 1979).

Major plate-convergence complexes record subduction at rates on the order of 10 cm/yr, or 100 km/m.y. Large motions and great complexity are the common case. Subduction systems are as likely to be multiple as single and commonly vary greatly along strike and are linked by diverse boundaries of other types.

ROCKS OF ISLAND ARCS

Volcanic Rocks

Volcanic rocks of oceanic island arcs typically show a progression with time from primitive to evolved compositions. Rocks erupted in young arcs of small crustal volume are predominantly tholeiitic basalts, many of which differ from spreading-ridge basalts primarily in their lower contents of the high-field-strength elements titanium, zirconium, and hafnium. Rocks erupted in mature arcs of large crustal volume are typically calc-alkalic basalt, andesite, and dacite—rocks relatively rich in aluminum and calcium. Two-pyroxene basalt and andesite with plagioclase phenocrysts, with or without olivine, and pyroxene dacite are common types, although many andesites and dacites are hornblendic. The rocks of oceanic arcs mostly are primitive in isotopic compositions, and the significance of moderate departures from primitive isotopes is much debated. Arcs erupted through continental crust, or through thick terrigenous sedimentary rocks proxying for such crust, commonly are much more silicic in bulk composition and more evolved in their isotopes.

Some oceanic arcs contain also early rocks of a richly magnesian series, of which the mafic members lack plagioclase but the most common

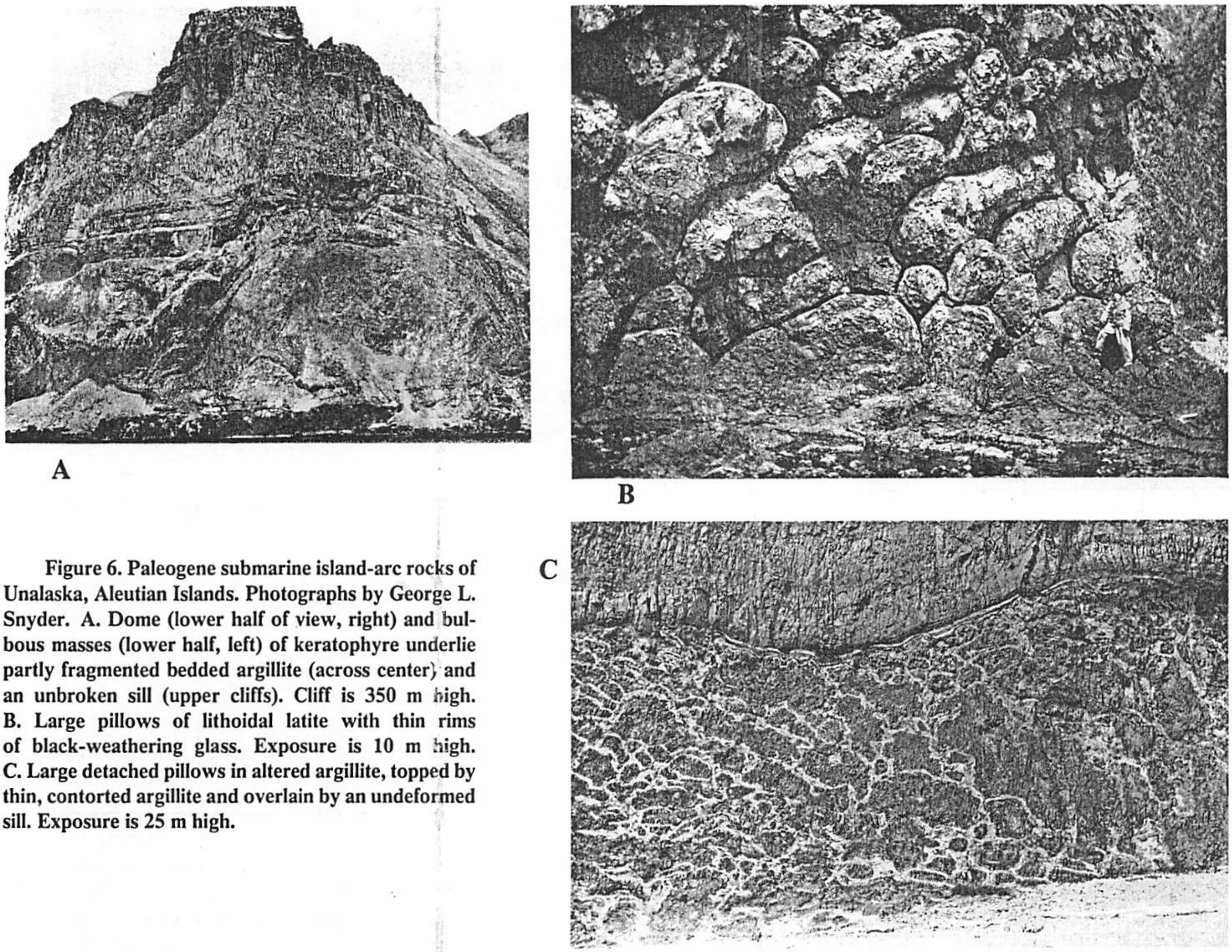

Figure 6. Paleogene submarine island-arc rocks of Unalaska, Aleutian Islands. Photographs by George L. Snyder. A. Dome (lower half of view, right) and bulbous masses (lower half, left) of keratophyre underlie partly fragmented bedded argillite (across center) and an unbroken sill (upper cliffs). Cliff is 350 m high. B. Large pillows of lithoidal latite with thin rims of black-weathering glass. Exposure is 10 m high. C. Large detached pillows in altered argillite, topped by thin, contorted argillite and overlain by an undeformed sill. Exposure is 25 m high.

member is magnesian andesite, boninite (Bloomer and Hawkins, 1987). These rocks are very low in the high–field-strength cations, and as these elements go preferentially from solids into partial melts, the boninitic and arc-tholeiitic magmas likely are derived largely from harzburgitic mantle that has previously undergone partial melting to yield ridge basalt (Bloomer and Hawkins, 1987; see also Fisk, 1986).

Magmatic arcs developed in continental or transitional crust contain more highly evolved volcanic rocks, as noted in the prior discussion of the Sunda system and the subsequent one of New Zealand.

Petrologic modeling, mostly cantilevered from the compositions of the final volcanic rocks, of various combinations of major and minor elements and of isotopes has in recent years yielded an array of hypotheses of origin of the mainline calc-alkalic rocks, involving partial melting of diverse mantle and subducted materials, fractionation at various levels, contamination, and magma mixing. Recent papers include those by Brophy and Marsh (1986), Crawford and others (1987), Davidson (1987), DeLong and others (1985), Gill (1981, 1987), Hawkins and others (1984), Kay and Kay (1985), Myers and Marsh (1987), Nye and Reid (1986), Wheller and others (1987), and White and Dupre (1986). The major point of agreement in these explanations is that the melting is somehow due to subduction.

Much of this mathematic-petrologic modeling incorporates such simplistic notions of one- or two-stage processes that it has little chance of achieving correct solutions. Melts rising in the mantle cannot be stable partial melts in equilibrium with specific wall rocks (O'Hara, 1985). Melts reaching the crust are already highly evolved, and complications such as those pictured by O'Hara and Mathews (1981, p. 237) likely are the rule as the melts evolve further in crustal chambers.

> If periodically replenished, periodically tapped, continuously fractionated magma chambers exist, they will evolve products whose phase petrology and trace element chemistry appear (in hitherto conventional interpretations) to require variable degrees of partial melting of inhomogeneous source regions for their petrogenesis. When the additional effects arising from assimilation by the magma of the roof of the chamber and from variation of mineralogy at the solidus of even a chemically homogeneous peridotite mantle are added, the scope for confusion is greatly increased. Moreover, these relationships cannot be inverted in order to deduce uniquely the magma chamber parameters or mantle source compositions from a knowledge of the erupted products.

O'Hara and Mathews were discussing the simplest of systems, that of spreading-ridge basaltic magmatism. Arc-magmatic systems add the great additional complications of progressively changing crust-and-mantle col-

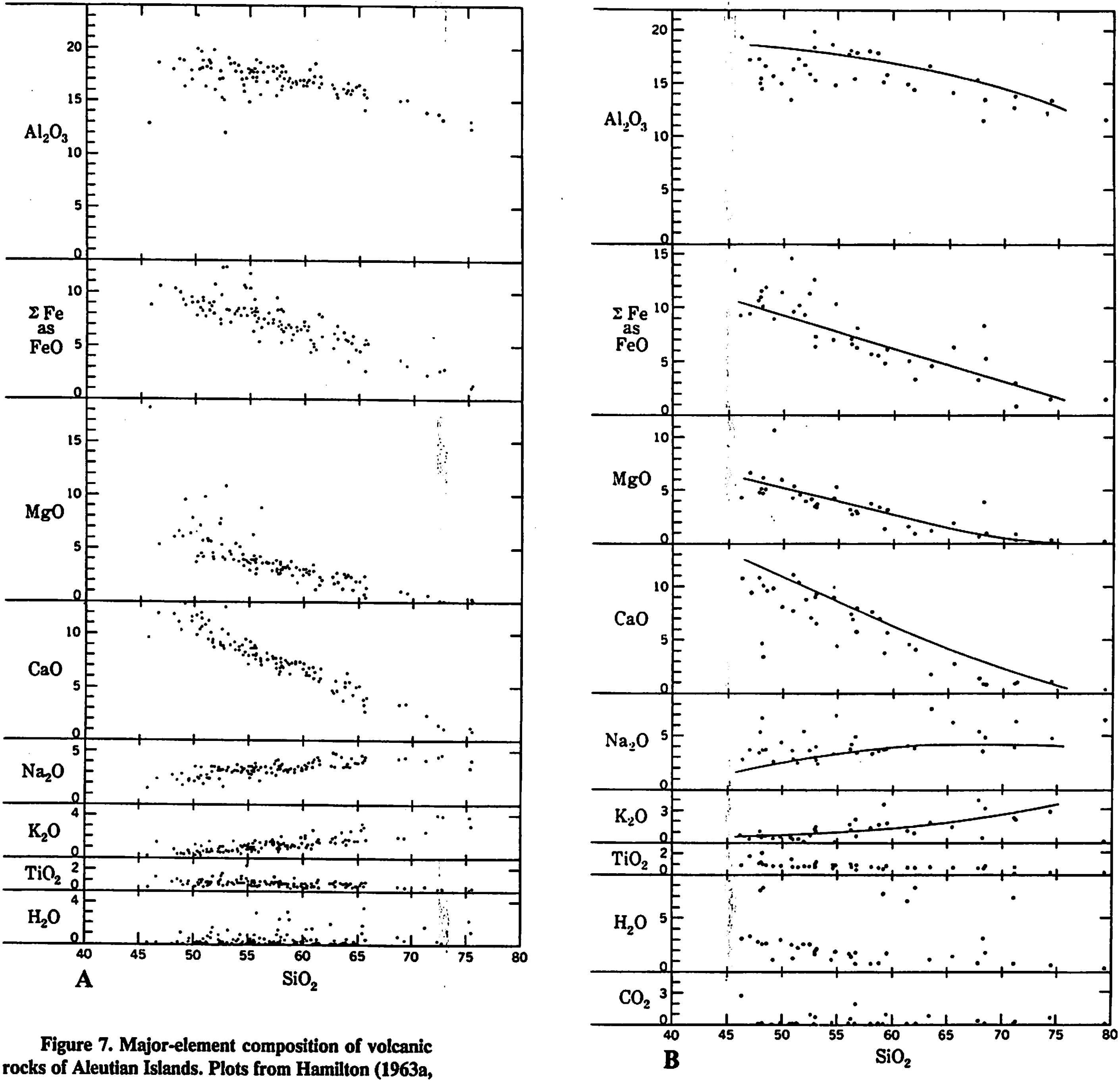

Figure 7. Major-element composition of volcanic rocks of Aleutian Islands. Plots from Hamilton (1963a, Figs. 65–67); data from U.S. Geological Survey reports, as cited by Hamilton. A. Silica-variation diagram of weight-percent analyses of subaerial volcanic rocks. B. Silica-variation diagram of weight-percent analyses of submarine volcanic rocks and contemporaneous intrusive rocks. Lines indicate variation trends in subaerial rocks (from A).

umns through which later magmas rise and evolve, with resultant systematic changes in composition of volcanic rocks along continuous arcs crossing crust of different type.

New Zealand System

A continuous, straight magmatic arc, 3,000 km long, trends north-northeastward from a terminus in southern North Island, New Zealand, across the continental shelf, and along the oceanic Kermadec and Tonga Islands. The arc illustrates not only the contrast between continental- and oceanic-arc magmas but the invalidity of some popular concepts regarding distinctions between arc and rift magmatism.

The modern arc lies above a continuous west-dipping slab of subducting Pacific lithosphere. Velocity of convergence and subduction decreases southward along the system, which gives way within New Zealand to a transpressive plate boundary. The New Zealand part of the arc is devel-

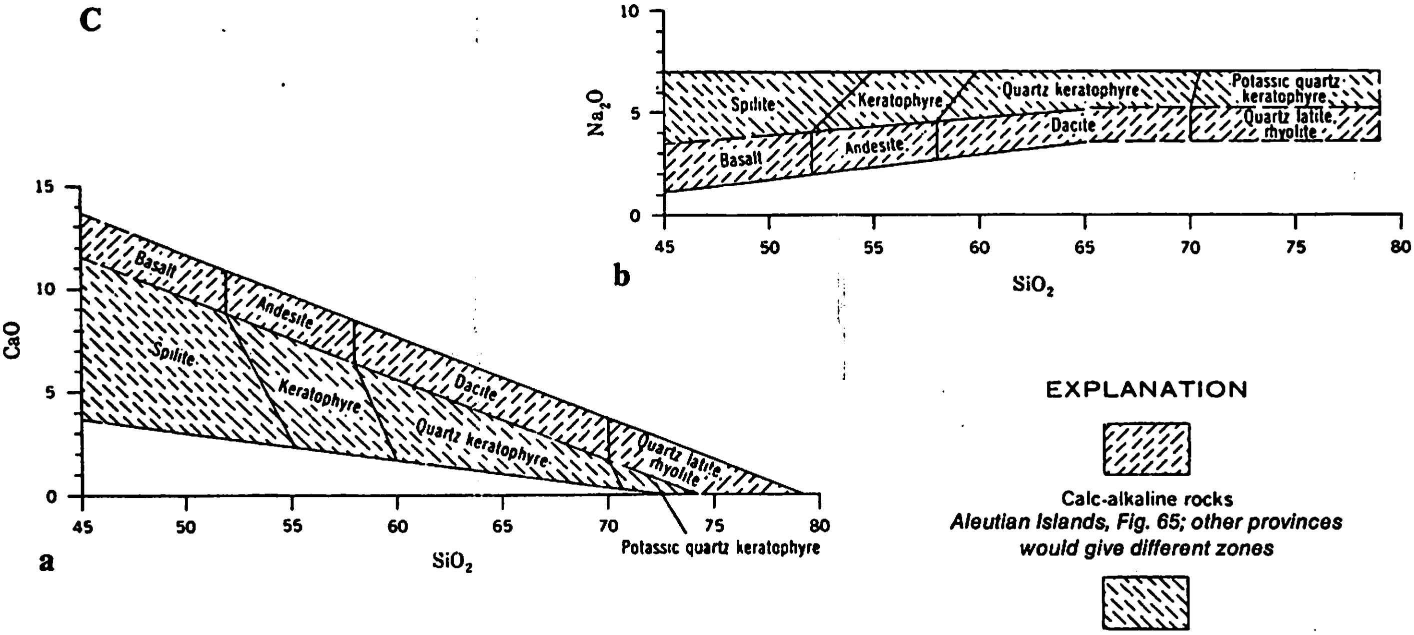

Figure 7. C. Schematic representation of members of andesite-keratophyre association as indicated by weight percents of CaO, Na_2O, and SiO_2.

oped on a crust of continental thickness but formed of Mesozoic accretionary-wedge materials, mostly variably metamorphosed terrigenous clastic sedimentary rocks. Along the oceanic Kermadec-Tonga part of the system, small volcanic islands rise from a submarine ridge. An oceanic back-arc basin has opened behind the migrating oceanic sector. The extensional zone rises southward onto the New Zealand continental shelf, and northern North Island is undergoing rapid, southward-decreasing extension and eastward-migrating, southward-lengthening arc magmatism (Stern, 1985).

Kermadec-Tonga lavas are typical of a mature oceanic arc—basalt, basaltic andesite, andesite, and subordinate dacite, all petrologically primitive and mostly of high-alumina types (Ewart and others, 1977).

Magmatism has only recently reached the south end of the modern arc in southern North Island, where there is little if any extension under way, and where large stratovolcanoes (Fig. 5A) are forming atop a low geanticlinal ridge that presumably is rising because of magmatic heating and inflation. The volcanic rocks are predominantly high-alumina andesites and basaltic andesites that display incorporation of continental materials—from the terrigenous strata of the accretionary wedge—in their minor elements and radiogenic isotopes (Cole, 1979; Ewart and others, 1977).

In north-central North Island, the arc is undergoing rapid extension synchronous with magmatism (Fig. 5B), and the predominant volcanic rocks are ignimbrites and flows of high-silica rhyodacite and quartz latite, with subordinate true rhyolite and much-subordinate basalt and dacite (Cole, 1979; Ewart and others, 1977). The isotopic similarity of the high-silica rocks to the underlying accretionary-wedge sedimentary rocks is indicative of a high degree of partial melting of clastic strata, likely as a result of heating of the deep crust by rising mantle diapirs and relatively primitive arc magmas. Extension is proceeding faster than the addition of magma from the mantle into the crustal column and the region is subsiding, and the northern part of the magmatic belt is below sea level on the subsiding continental shelf. Were this strongly bimodal magmatic assemblage met in an ancient setting, it would be regarded by most petrologists as evidence against a subduction setting—yet, it is in fact forming in a magmatic arc. Both the extending and nonextending parts of the onshore magmatic arc are at about the same height, 100 km, above the top of the subducting slab (Adams and Ware, 1977).

Submarine Volcanic Rocks

Oceanic island arcs are submarine ridges, built by magma, on which stand subaerial volcanoes that comprise a very small proportion of the crustal volume. The submarine rocks are erupted with compositions like those of the subaerial rocks but are variably altered by hydrothermal sea water to quite different compositions. Our petrologic data on arcs come overwhelmingly from the volumetrically minor subaerial rocks. Gill (1981) did not even mention submarine rocks in his generally excellent monograph on andesites. Ancient arcs accreted tectonically to continents are now exposed almost entirely at what were submarine levels, and so it is comparisons with submarine rocks that are relevant for paleotectonic analysis—but most geologists working with ancient accreted arcs mistakenly compare the petrology of ancient submarine rocks with modern subaerial rocks, and many reach invalid paleotectonic conclusions as a result. Submarine rocks commonly are exposed on some islands of mature island arcs, where they are raised, presumably, by magmatic inflation of the ridges. The submarine rocks commonly are altered to brown or green assemblages of fine-grained secondary minerals, and most petrologists and mapping geologists do little with them.

Much of our information on submarine rocks of still-active arcs comes from the reconnaissance study of the Aleutian Islands by U.S. Geological Survey geologists during the field seasons of 1946–1954, as reported particularly by Byers (1959), Drewes and others (1961), Fraser and Snyder (1959), Gates and others (1971), and Snyder and Fraser (1963). Subsequent Aleutian studies include those by Hein and others (1984) and McLean and Hein (1984). Eocene, Oligocene, and Miocene

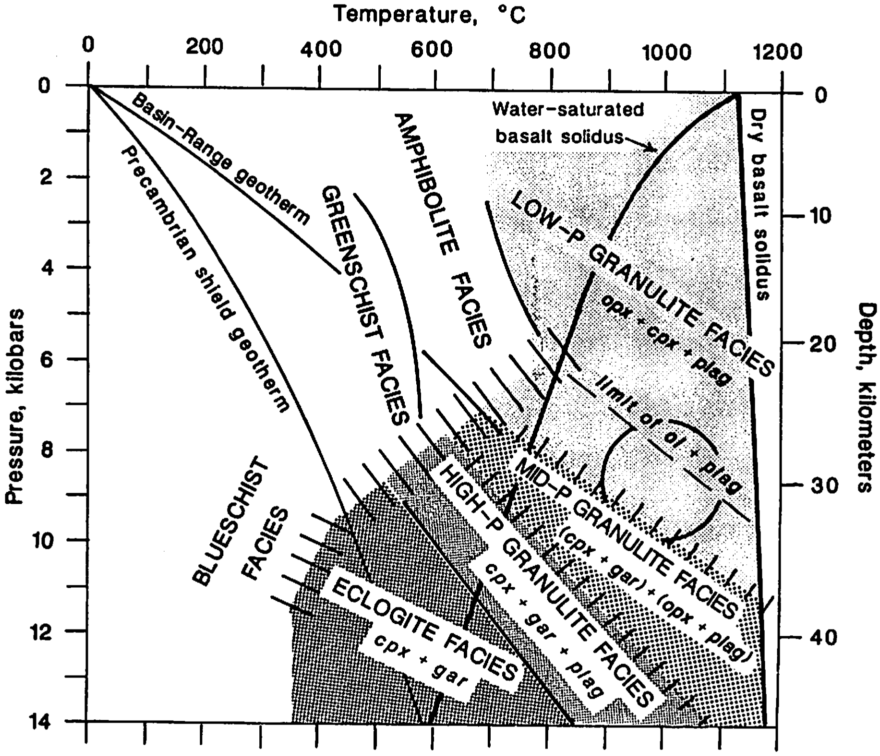

Figure 8. Generalized pressure-temperature diagram of mineral assemblages relevant to the crust of continents and mature island arcs. Boundaries approximate those for mafic and intermediate rocks but vary with bulk composition; coexisting minerals vary in composition across each facies. The boundary between amphibolite and granulite facies at pressures greater than about 5 kb shifts greatly with activity of H_2O, and a garnet amphibolite facies (not shown) of much-varying P/T width commonly intervenes. Abbreviations: cpx, clinopyroxene; gar, garnet; ol, olivine; opx, orthopyroxene; plag, plagioclase. Rocks of similar bulk compositions become progressively more dense going from low-pressure granulite to eclogite as plagioclase reacts with ferromagnesian minerals to produce successively denser phases; plagioclase reacts out successively with olivine, orthopyroxene, and clinopyroxene, although albite is stable in the higher T/P part of the blueschist facies, and sanidine is stable in high-T eclogite. Most igneous rocks in exposures of the upper part of the lower crust crystallized in or near the field indicated by the circle. From Hamilton (1988a, Fig. 2), where references are given.

submarine rocks are superbly exposed in the high seacliffs of the islands (Fig. 6). Near-source complexes are dominated by basaltic to dacitic lavas, pillow lavas, breccias including pillow breccias, and large and small sheets and nodular masses, intruded by gabbroic to granodioritic stocks and small batholiths. More-distal materials include volcaniclastic breccias and wackes, argillites, and cherts.

Severe alteration broadly affected the submarine volcanic rocks. Much of the alteration was diagenetic and much was hydrothermal, driven by heat from nearby plutons and by heat from the cooling flows and small intrusions themselves. Chlorite, epidote, albite, calcite, quartz, zeolites, clays, and oxides are widely developed. In addition to variable hydration, oxidation, and carbonation, much of the volcanic and hypabyssal assemblage underwent variable and often extreme change in bulk composition. The major-element change is defined particularly by enrichment in Na and depletion in Ca. (Systematic minor-element studies have not been made on interior submarine complexes of this or any other still-active arc so far as I am aware.) Contents of Na and Ca in the submarine rocks define a spectrum from amounts like those in the unaltered subaerial rocks of the island chain to extreme enrichment in Na and depletion in Ca (Fig. 7; Hamilton, 1963a). The rocks are compositionally basalt, andesite, and dacite and their Na-enriched, Ca-depleted equivalents, spilite, keratophyre, and quartz keratophyre. (The latter terms are often misapplied to greenschist-facies metavolcanic rocks of little-changed calc-alkalic bulk compositions in which plagioclase has been converted to albite, epidote, and other secondary minerals.) The aberrant, now-sodic rocks crystallized from calc-alkalic magmas, like those of the modern subaerial volcanoes, not from hypothetical sodic or hydrous melts. Relic clinopyroxenes are ordinary augitic varieties, relic high-temperature plagioclase is normal labradorite, and the voluminous albite has low-temperature crystal structure; the aberrant compositions are products of fluid exchanges under conditions comparable to those of low greenschist facies (Byers, 1959; Drewes and others, 1961; Wilcox, 1959). The reacting fluid must have had high activities of Na and CO_2 and a low activity of Ca, and must have affected submarine rocks selectively. Sea water is the obvious candidate, as Wilcox (1959) and others have emphasized. Brine concentrated from sea water produces the required albitization at low pressure and greenschist-facies temperature, provided other reactions release silica to the fluid (Rosenbauer and others, 1988).

Spreading-ridge basalts commonly display variable hydrothermal alteration by sea water, but the changes so far defined in bulk composition are far less severe than in many of the Aleutian rocks (Alt and others, 1986; Thompson, 1983). On the other hand, many on-land ophiolites—products of nascent island arcs?—display variable severe spilitization (Hawkins and Evans, 1983; Hopson and others, 1981; Lippard and others, 1986). Water depth may be a factor; contact between still-hot magmatic rocks and circulating sea water at the water depths, greater than 2.5 km, of spreading ridges may be inadequate to produce the observed arc-rock reactions. A possible explanation for the severe alteration of arc assemblages is that violent hydrothermal systems, involving great concentration of brines by boiling, are set up as submarine arc magmas cool in water shallower than the 2-km critical depth of water or are induced around plutons emplaced in shallow-water settings. The extreme variability of mineral-fluid reactions near the critical point of water may also be important. Further, the abundance of fragmental rocks in arc assemblages makes them highly permeable.

I showed that an ancient island arc now part of western Idaho had

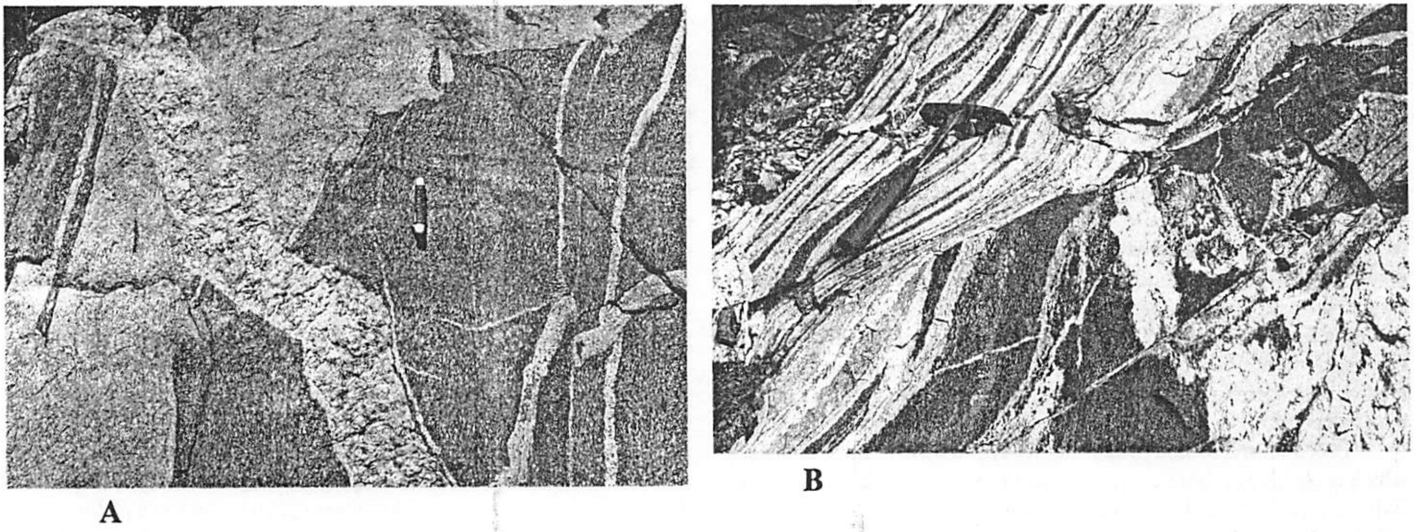

Figure 9. Middle-crust rocks of Mesozoic island arcs accreted tectonically to western North America. A. Dike of sodic pegmatite cutting light trondhjemite which migmatized tonalite gneiss. Sixmile Creek, Riggins quadrangle, west-central Idaho. B. Amphibolite migmatized by trondhjemite, which probably was derived by partial melting consequent on metamorphic dehydration of amphibolite. Near Diablo Lake, North Cascades, northwest Washington.

compositional variations, from calc-alkalic to spilitic-keratophyric, quantitatively like those of the submarine Aleutian rocks (Hamilton, 1963a). Various investigators (as, Roobol and others, 1983) have defined similar spectra in ancient submarine arc assemblages but then have argued that the sodic divergence from the compositions of modern subaerial volcanoes indicates alkaline magmatic associations.

Island-Arc Crust

Oceanic island-arc magmatism builds crust of continent-like thickness in mature arcs. Although this crust can be seen in exposure in various regions, its character has been minimally integrated in most petrologic modeling of arc magmas, which has been based primarily on the composition of subaerial volcanic rocks. The upper-crust substrates of volcanoes are widely exposed within still-active mature oceanic arcs and include abundant intrusive masses—dikes, sills, inflated pods, stocks, small batholiths—of gabbro, diorite, tonalite, and granodiorite and less commonly of more sodic granitic rocks. The plutonic rocks probably are on average more felsic than are the volcanic rocks. References to publications describing Indonesian and Melanesian examples were given by Hamilton (1979). Aleutian examples were described by Byers (1959), Drewes and others (1961), and others.

Rocks formed deeper in the crust of oceanic island arcs are exposed in some arcs accreted tectonically to continents and there deeply eroded. Figure 8 is a compilation of relevant crystallization facies for mafic rocks, applicable both to metamorphic and magmatic rocks. Facies designations herein accord with this figure, and not necessarily with the terminology of authors cited. Exposures of island-arc middle crust, beneath the levels of crosscutting mafic and intermediate plutons, in many cases are dominated by isotopically primitive amphibolitic, tonalitic, and trondhjemitic gneisses, the amphibolites becoming increasingly garnetiferous or pyroxene-bearing with depth; west-central Idaho and the North Cascades of Washington State provide excellent examples (Fig. 9). Trondhjemite (sodic leucotonalite; the term is misused by some geologists to include leucogranodiorite and andesine leucotonalite) may form primarily by partial melting, under lower-crustal conditions, of amphibolite of spilitic composition (Rapp and Watson, 1988).

Layered ultramafic and gabbroic complexes, fractionated both gravitationally and by fluid flow and contorted diapirically, are found in the roots of some arcs (as, Burns, 1985; Himmelberg and others, 1986; Irvine, 1974; Murray, 1972; Snoke and others, 1981). These complexes represent broad ranges of depth of formation, some having crystallized within the stability field of olivine plus plagioclase, others deeper (see Fig. 8). Clinopyroxene is the predominant pyroxene in most of these complexes, although orthopyroxene is abundant in many. Some of these mafic and ultramafic assemblages are associated with more felsic plutons.

An obliquely eroded north-dipping crustal section through a probable island-arc complex, of Cretaceous and early Tertiary age, which ramped southward onto northwest India in Eocene(?) time, has been studied in reconnaissance in Kohistan, northernmost Pakistan (Bard, 1983; Coward and others, 1982; Dietrich and others, 1983; Jan and Howie, 1981; D. E. Karig, 1988, written commun.; Tahirkheli, 1982). The much-deformed crustal section is perhaps 40 km thick, and mantle rocks extend as much as 5 km deeper to a truncation at the structural base of the section atop blueschist and mélange. Mafic and intermediate volcanic and volcaniclastic rocks, with abundant intercalated turbidite (Karig regards this part of the complex as of back-arc–basin origin) and downward-increasing stocks and small batholiths mostly of massive to gneissic diorite and tonalite, form the upper and middle crust, within which contact metamorphism on a regional scale increases downward from low greenschist through lower and upper amphibolite to garnet amphibolite facies. The lower crust consists of mafic granulites and mafic plutonic rocks, within which the grade of metamorphism, which is syn-plutonic with regard to some intrusions and post-plutonic with regard to others, increases downward from low-through middle- to high-pressure granulite facies. The variably metamorphosed plutonic rocks were fractionated from basaltic magmas and include norite, gabbro, and, in thin layers, anorthosite; magmatic olivine and plagioclase crystallized together in the upper part of the lower crust but not in the lower part. Rocks of intermediate composition are more abundant high in the lower crust than low in it. The mantle rocks at the base of the section consist of interlayered and injected residual, cumulate, and magmatic clinopyroxenite, peridotite, dunite, and subordinate olivine-free norite and gabbro, variably deformed and re-equilibrated at high-pressure granulite facies. Bard (1983) regarded the metamorphism as having occurred at much higher pressures than did the magmatism, but the facies relationships permit a contrary inference of isobaric magmatism and metamorphism.

A deep-crustal section of an isotopically primitive oceanic island arc, which probably was both crystallized and metamorphosed mostly within Early Cretaceous time, is exposed in far southwestern New Zealand (Mattinson and others, 1986), and includes Paleozoic components (Gibson and others, 1988). The rocks have been studied in reconnaissance by Blattner (1978), Gibson (1982), Gibson and others (1988), Mattinson and others (1986), Oliver (1980), and Williams and Smith (1983). The following synthesis represents my inference from their petrologic and structural data; they disagree variably with each other and with me. The crustal section was ramped up westward in Neogene time, as part of the transpressive deformation along the Alpine fault, and has been eroded obliquely. Gabbro, diorite, and tonalite dominate the deep, western part of the section, within which lenses of ultramafic rocks increase downward in abundance; leucogabbro, calcic anorthosite, and granodiorite are subordinate. Magmatic crystallization was in the high-pressure part of the low-pressure granulite facies (two pyroxenes; plagioclase stable with orthopyroxene but not with olivine; no garnet). At the deepest structural levels, these rocks were widely retrograded to gneisses in the middle- and high-pressure granulite facies and locally to eclogite facies; somewhat shallower rocks widely preserve igneous fabrics or were retrograded at garnet amphibolite facies. The facies relationships permit the inference that magmatism and retrogression were essentially isobaric and, for the deepest rocks exposed, occurred at a depth of about 35 km. Elsewhere in the complex, olivine and plagioclase crystallized together in mafic plutonic rocks, metavolcanic and calc-silicate gneisses are present, and retrogression occurred at amphibolite and garnet amphibolite facies; I infer isobaric magmatism and retrogression at depths of 20–25 km. Both massive and layered-differentiated plutonic rocks were present at both lower- and mid-crustal levels.

The character of crust in a nascent island arc was noted in the previous section on ophiolites.

Crust and Mantle

The lower crust of the two mature island arcs described above is dominated by mafic rocks in the Kohistan example, but by mafic, intermediate, and felsic-intermediate rocks in the Fiordland one. The high acoustic velocity and density of lower-crust rocks are due primarily to their granulite-facies mineralogy—to the presence of much of what would be plagioclase at lower pressure as pyroxene and garnet of granulite—and not necessarily to gabbroic bulk compositions. Similarly, mantle rocks include high-pressure plagioclase-free rocks as well as ultramafic rocks.

The Mohorovičić discontinuity exposed in the Kohistan section appears to be a gradational boundary within fractionated magmatic rocks, which are predominantly ultramafic beneath and predominantly granulitic and olivine-free noritic and gabbroic above. The discontinuity was constructed by arc magmatism and is not a fossil lithologic boundary. I have argued elsewhere (Hamilton, 1981) that this is the general character of the base of the crust in magmatic arcs—that the Mohorovičić discontinuity of continents and mature island arcs represents primarily the shallow limit of crystallization of voluminous arc-magmatic rocks of ultramafic composition or of plagioclase-free mineralogy. An example of similar relationships across the Mohorovičić discontinuity of a continental magmatic arc is given by the Ivrea zone of the northwest Italian Alps (Rivalenti and others, 1981). Arc magmas that reach the base of the crust have basaltic or even intermediate compositions, yet the protomelts generated deeper in the mantle likely are there in approximate equilibrium with olivine-rich rocks and hence likely are olivine-rich basalts, and so it follows that likely most of the ultramafic component of the primary magmas is crystallized within the mantle. Plagioclase-free rocks, formed at pressures too high for plagioclase to be stable, also are limited to the mantle. The mantle-crust boundary is a self-perpetuating density filter for rising melts, much evolution occurs within the mantle, melts that reach the crust are already highly fractionated, and those that reach the surface are more so. O'Hara (1985), Quick (1981), and Stolper and Walker (1980) made related points.

ACCRETION TO CONTINENTS

Island arcs migrate by back-arc spreading and are conveyor-belted toward subduction zones, so that island arcs sooner or later collide with one another and with continents. All island arcs older than middle Mesozoic have been accreted to continents, as have many much younger arcs. Collisions between continents commonly are preceded by long periods of subduction with complexly changing patterns, and collided arcs commonly are major components of the broad tracts of tectonic flotsam crunched between collided continents. Accreted arcs have now been demonstrated to occur within such tracts of all ages from the Archean onward. Among many examples are those discussed by Burchfiel and Davis (1981), Condie (1986), Dickinson (1981), Hamilton (1978b, 1979), Hanson and Schweickert (1986), Shervais and Kimbrough (1985), Silver and Smith (1983), Stoeser (1986), Sylvester and others (1987), and Windley (1984).

The complex histories of collisions, subduction reversals, rifting, and strike-slip and oroclinal deformation of the modern arc systems discussed earlier in this paper presumably have analogues, however difficult they are to decipher, in ancient accreted-arc terranes. Paleotectonic analysis of island arcs and other subduction-related complexes should, but too often does not, incorporate awareness of the complex variations and behavior of modern arc systems. Departures from actualistic models should record intent, not ignorance. The study of modern arcs, and the testing of predictions implicit in paleotectonic analyses in terms of modern analogues, are urged upon anyone who would interpret ancient arcs.

ACKNOWLEDGMENTS

This review draws on the published work of hundreds of geologists and geophysicists, only a relative few of whom can be cited, and on my discussions over the years with scores more. The manuscript was much improved as a result of helpful criticism by W. R. Dickinson, A. B. Ford, William Glen, J. W. Hawkins, and D. E. Karig.

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