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Oceanic Plateaus, the Fragmentation of Continents, and Mountain Building

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Many anomalous rises in today's oceans may be submerged continental fragments detached from previous continents, ancient island arcs, or basaltic piles formed by hot spots and spreading centers. These rises are embedded in their respective moving oceanic plates and are fated to be consumed at active margins. Where such rises are being consumed at present, e.g., the Nazca Ridge, they cause cessation of volcanism, disruption of the downgoing slab, and possible shifts in plate boundary configuration. Many past rises, including numerous continental fragments, have been recognized within mountain belts as allochthonous terranes. They constitute a large portion of the orogenic belts in the North Pacific from Mexico through western North America, Alaska, east Siberia, Japan and in New Zealand. The orogenic deformation in these belts is possibly the result of the accretion of the allochthonous terranes. Many terranes have been accreted with substantial deformation also in the Alpine chain, well before major continent-continent collisions. It is suggested, therefore, that the accretion of fragments may be the common process of the deformation phase of mountain building. Subduction of normal oceanic crust may be insufficient for deformation, whereas full continent-continent collision may not be necessary. The general validity of this conclusion depends critically on whether allochthonous terranes caused orogenic deformation in the Andes or not. Most of the accreted fragments with continental affinities in the Mesozoic-Cenozoic orogenic belts of the world can be traced back to the breakup of Gondwana, beginning with a Pacifica domain in the Permian through a larger India domain in the early Mesozoic and continuing through the separation of the Somalia plate in the near future. The reasons for this 250 million year breakup process are not known, but some kind of thermal process, possible of mantle-wide scale, is implied.

Introduction: From Oceanic Plateaus to Allochthonous Terranes

About 100 anomalous regions (Table 1) ranging in size from 1000 km down to a few kilometers are embedded in the earth's sea floor. These regions are typified by shallow water depth, thick crust, low upper crustal velocities, lack of clear magnetic lineations, and steep margins. They cover about 10% of the present day's ocean floor, with particular concentrations in the western Pacific and the Indian Oceans, as shown in Figure 1. Typically these regions are well embedded within their plates and show no evidence for relative motions. Such relative motions do occur, however, as the plateaus move into subduction zones where oceanic plates are consumed. The fate of plateaus upon arrival at consuming plate boundaries and their geological impact there are among the main questions considered in this paper. The other question considered is the origin of these rises, particularly those which are fragments of older continents. Specifically, we discuss the following topics: (1) what they are, (2) their past roles in circum-Pacific tectonics, (3) their role at present, (4) their origins, (5) their role and origin in continental breakup, (6) their role in continental accretion, and (7) their role in orogenic deformation.

The Nature of Oceanic Plateaus

Oceanic rises (Figure 1), which span a wide range of water depth and crustal thicknesses (Table 1), may be classified on the basis of information from drill holes, dredgings, multichannel seismic surveys, and core records: extinct arcs (e.g., Bowers Ridge, Aves Ridge), abandoned spreading ridges (e.g., the West Philippine Ridge), detached and submerged continental fragments (e.g., the Chatham Rise), anomalous volcanic piles (e.g., Iceland), hot spot traces (e.g., Cocos Ridge), and uplifted oceanic crust (e.g., the Nicoya complex in Central America).

Many of the large oceanic plateaus rise thousands of meters above their surrounding sea floor. Some, such as the Seychelles Bank, actually rise above sea level, whereas others, such as the Ontong Java Plateau, are submerged 1500 to 2000 m below sea level. Most of the plateaus for which seismic refraction and gravity data are available range in thickenss from 20 km to over 40 km, much more than usual oceanic crust (Figure 2).

Most plateaus exhibit weak or no magnetic lineations, suggesting that they are not formed as typical oceanic crust. Plateaus, as a rule, do not exhibit significant isostatic anomalies, implying that they are isostatically compensated. Although the nature of several plateau margins has been identified, e.g., an ancient subduction at the Bowers Ridge [*Cooper et al.*, 1981] and a rifted margin at the Ontong Java Plateau [*Kroenke*, 1972], the nature of most plateau margins is still unknown.

Geological evidence from some plateaus shows strong continental affinities. For example, Precambrian granitic basement is exposed in the Seychelles Islands in the middle of the Indian Ocean. Granitic basement was also found in the Paracel Islands in the South China Sea (K. O. Emery, personal communication, 1980), and dredging of the Agulhas Plateau yielded Precambrian or Paleozoic granite rocks [*Tucholke et al.*, 1981]. Consequently, some plateaus or parts thereof are probably submerged continental fragments. The causes for their subsidence are not known.

Other plateaus are of oceanic rather than continental origins. For example, the Cocos and Carnegie Ridges are probably the result of the continuous extrusion of basalts onto the Cocos plate, overriding an active hot spot. Other plateaus are of unknown nature. Drilling into the Ontong Java Plateau revealed a few meters of Lower Cretaceous basalt beneath a cover of more than 1 km of calcareous

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TABLE 1. Oceanic Plateaus: Distribution and Type

Name	Water Depth, km	Relief, km	Crustal Nature: Continent	Crustal Nature: Ocean	Crustal Nature: Island Arc	Crustal Nature: ?
Pacific Ocean						
Alaska Seamounts (Pratt-Welker and Kodiak)	1	3		x		
Bismark Archipelago	1–2	2				x
Campbell Plateau	0–1	4.5	x			
Carnegie Ridge	1	2		x		
West Caroline Ridge	0–1	4				x
Chatham Rise	0–1	4.5	x			
Cocos Ridge	1–2	3		x		
Coiba Ridge	1	2		x		
Colville Ridge	1.7				x	
Eauripik-New Guinea Rise	0–2	4				x
Fiji Plateau	0	3		x		
Galapagos Rise	3–4	1		x		
Hess Rise	2	3				x
Izu Ridge	0–1	4				x
Juan Fernandez	0–1	4				x
Kermadac Ridge	0.7–2.5	2			x	
Lau Ridge	1	2			x	
Louisville Ridge	2	3.5				x
Magellan Rise	3	2.5				x
Magellan Seamounts	2	3.5				x
Malpelo Ridge	0–2	3		x		
Manihiki Plateau	2.5	3				x
Marcus Ridge	1–2	4				x
Meiji Guoyt	3	2.5				x
Mid-Pacific Mountains	2	3.5				x
Nazca Ridge	1	3				x
Necker Ridge	2	2.5				x
Ontong Java	1.7	3				x
Shatsky Rise	2	3.5				x
Tehuantepec Ridge	2–3	2		x		
Three Kings Rise	1	2				x
Bering Sea						
Bowers Ridge	0.6	3			x	
Shirshov Ridge	1	2				x
Umnak Plateau	0.2	3				x
Coral Sea						
Bellona Plateau	0.2	3				x
Louisiade Plateau	2	2				x
Queensland Plateau	0	4				x
Torres Rise	1	3				x
Japan Sea						
Yamato Ridge	1	2	x			
Philippine Sea						
Amami Plateau	2	3				x
Benham Rise	2	3				x
Daito Ridge	1.5	4.5				x
Oki-Daito Ridge	1.5	4.5				x
Palau-Kyushu Ridge	3	2			x	
Philippine Ridge	5.0	1		x		
South China Sea						
Macclesfield Bank	0.2	4	x			
Paracel Islands	0	2	x			
Reed Bank Crustal Block (Dangerous Grounds)	0–1	4.5	x			
Tasman Sea						
Challenger Plateau	1	3	x			
Lord Howe Rise	1	3	x			
Norfolk Ridge	0–1	3.5				x
East Tasman Plateau	2	2.5	x			
South Tasman Rise	1–2	3.5	x			
Indian Ocean						
Agulhas Plateau	3	2	x	x		
Broken Plateau	2	2.5	x			
Chagos-Laccadive Ridge	0–1	3.5	x	x		
Crozet Plateau	0–1	4				x
Cuvier Plateau	3	2	x			
Exmouth Plateau	1.0	4.5	x			
Gribb Bank	1	3				x

TABLE 1. (continued)

Name	Water Depth, km	Relief, km	Crustal Nature: Continent	Ocean	Island Arc	?
		Indian Ocean (continued)				
Kerguelen-Gausaberg Plateau	0–1	3–4	x	x		
Madagascar Plateau	1	3	x			
Mascarene Plateau	0–1	3–4				x
Mozambique Ridge	2	3	x			
Naturaliste Plateau	2–3	3	x			
Ninety East Ridge	2–3	2				x
Roo Rise	2.5	2.5				x
Saya De Malha Bank	0	4	x			
Scott Plateau	1.0	4.5	x			
Seychelles Bank	0	4.5	x			
Wallaby Plateau	2.5	2.5	x			
		Atlantic Ocean				
Barracuda Ridge	3.5	2				x
Bermuda Rise	0	4.5		x		
Blake-Bahama Plateau	0–1	4				x
East Canary Islands	0	4				x
Cape Rise	2	2.5				x
Cape Verde Plateau	0–1	4				x
Faeroe Plateau	0–1	3	x			
Falkland Plateau	0–1	3	x			
Flemish Cap	1	3.5	x			
Galicia Bank	1	5	x			
Madeira Plateau	1	4				x
Orphan Knoll	2	2	x			
Porcupine Bank	0.5	4	x			
Rio Grande Ridge	1	3		x		
Rockall Plateau	1	2.5	x			
São Paulo Plateau	2	2		x		
N. Scotia Ridge	0–1	3	x			
S. Scotia Ridge	0–1	3	x			
South Georgia Rise	<2	3				x
Voering Plateau	1.5	2	x			
Walvis Ridge	1–2	3		x		
		Mediterranean				
Anaximander Seamounts	1	1				x
Cyrenian Plateau	1	2				x
Eratosthenes Plateau	1	1.5				x
Mallorca-Balearic Rise	0.2	2.5				x
Medina Plateau	2	1				x
		Caribbean				
Aves Ridge	1	3				x
Barbados Ridge	1	2			x	
Beata Ridge	2	2				x
Cayman Ridge	0–1	4.5				x
Curacao Ridge	0–1	4				
Nicaragua Rise	0–1	3				x
		Antarctic Ocean				
Balleny Island	0	3				x
Maud Bank	3	1.5				x
Peter Island	0	4				x
Thirty-East Spur	2	2.5	x			
		Arctic Ocean				
Alpha Ridge	1	3		x		
Beaufort Terrace	2	1.5				x
Chukchi Cap	1	3	x			
Gakkel Ridge	4	1		x		
Lomonosov Ridge	1	3	x			
Mendeleyev Ridge	2	2				x
Yermak Rise	1	2				x

sediments, indicating shallow deposition since Early Cretaceous time. The nature of the rock underlying the volcanics remains unknown.

Some constraints on the nature of the enigmatic plateaus may be obtained from their crustal seismic velocities (Figure 2). Much depends on the interpretation of compressional velocity $V_P = 6.0–6.3$ km/s in the upper 5 to 15 km in many of the plateaus. *Nur and Ben-Avraham* [1978] argue that

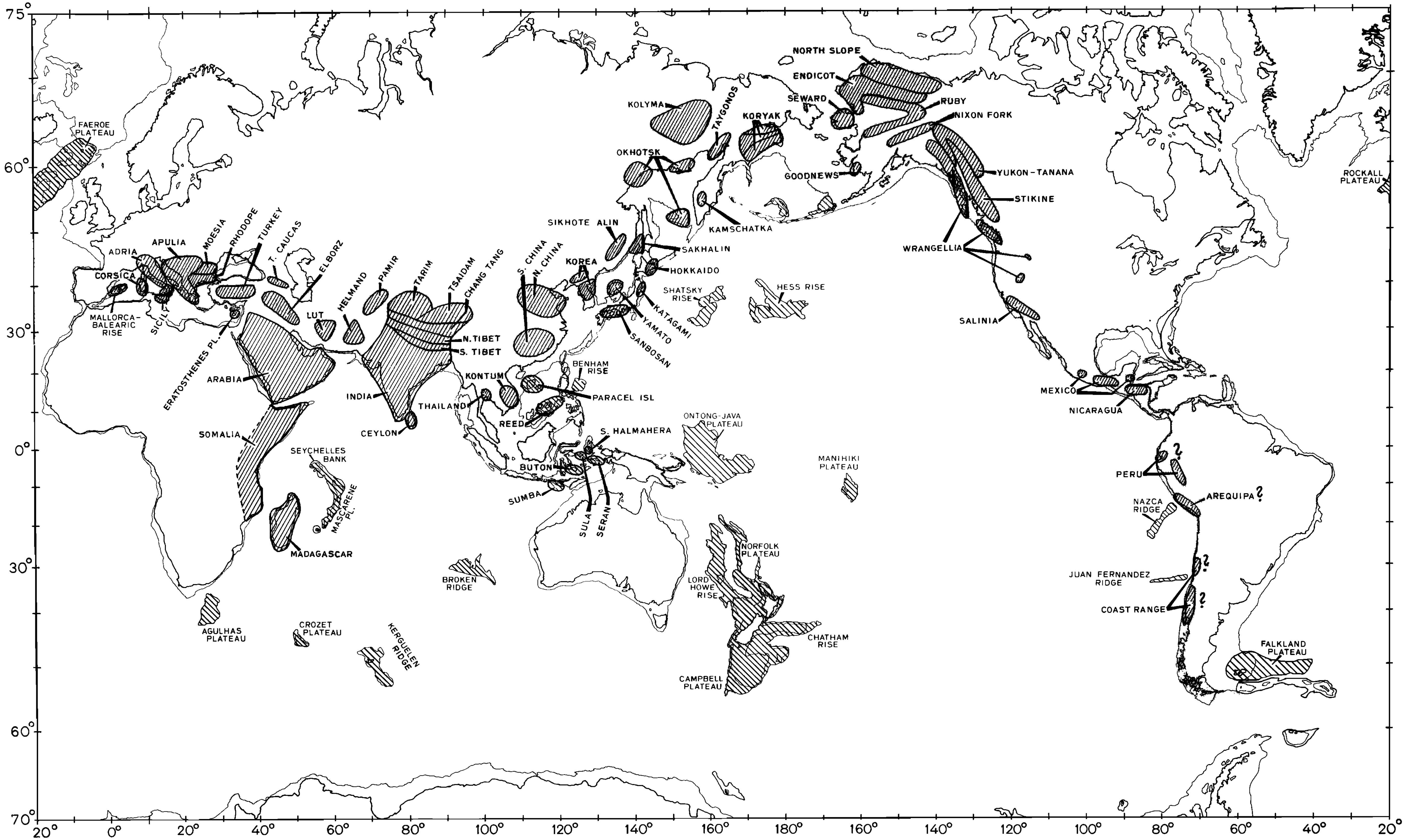

Plate 1. Sketch of past, present, and future allochthonous terranes, most of which are fragments of continents or have clear continental affinities. Shaded area indicates the Mesozoic-Cenozoic orogenic belts. Allochthonous terranes within the belt are most likely parts of Gondwana which have migrated toward and collided with Europe, SE Asia, and the Pacific margins. Oceanic plateaus, some of which are shown, are moving toward consuming boundaries, possibly to become accreted allochthonous terranes. Several fragments of Africa (e.g., Madagascar, Somalia) will probably collide with the Euroasian plate in the future.

Fig. 1. Worldwide distribution of the present day's oceanic plateaus (hachured). Many of these plateaus may be continental fragments, in spite of their situation well within oceanic plates. Others are of different origins such as extinct arcs and hot spot traces.

these values of V_P and thickness combined with the relief and gravity data, suggest a continental structure. *Hussong et al.* [1979] propose that these plateaus consist of normal oceanic crust expanded by factors of 5, 3.1, and 2.7 for Ontong Java Plateau, Manikihi Plateau, and Shatsky Rise, respectively. However, applying similar expansion procedure to the Canadian shield (Figure 3), we obtain a factor of 4.9 while typical continental platform gives a factor of 5.2. These numbers show there is no sound basis for *Hussong et al.*'s [1979] conclusion; their results simply follow from the fact that continental crust is four to five times thicker than oceanic crust. Based on detailed velocity analysis *Carlson et al.* [1980] conclude that the central part of the Ontong Java Plateau may actually be of continental affinity. By the same argument, the Manihiki Plateau, with crustal structure like that of Ontong Java, is also similar to continental crust. One of the concerns by *Carlson et al.* [1980] is the lack of a reasonable continental source in the western Pacific. However, in the Indian Ocean similar plateaus, which are considered continental fragments, originated from the breakup of Gondwana.

Houtz and Ewing [1976] and *Hussong et al.* [1979] have argued that the upper crustal velocities may be associated with oceanic basalts or with serpentinized peridotites. Figure 4 shows some available velocity-density data relevant to all three interpretations, taken at about 2 kbar confining pressure [*Press*, 1966; *Christensen*, 1978]. All three rock groups have similar V_P values in the density range 2.6 to 2.8. Consequently, a value of V_P = 6.0–6.3 km/s may be due to a granitic layer indicating continental crust or to basaltic rocks with porosity of 10 to 20% or to heavily serpentinized peridotite. Whether basalt can sustain such porosities at pressures and temperatures corresponding to depths of about 10 km for hundreds or even tens of millions of years is unclear. Secondary filling and pressure solution would in principle remove such porosity, but not enough data are available at present to resolve this question. If the foundations of the Ontong Java Plateau are basaltic, then origination as a volcanic pile at an active ridge similar to Iceland is suggested even though Iceland does not exhibit such deep Moho and thickness of the upper crust. Serpentinized peridotites may be responsible, but it is unclear where and why such large bodies are formed nor has an analogue been recognized.

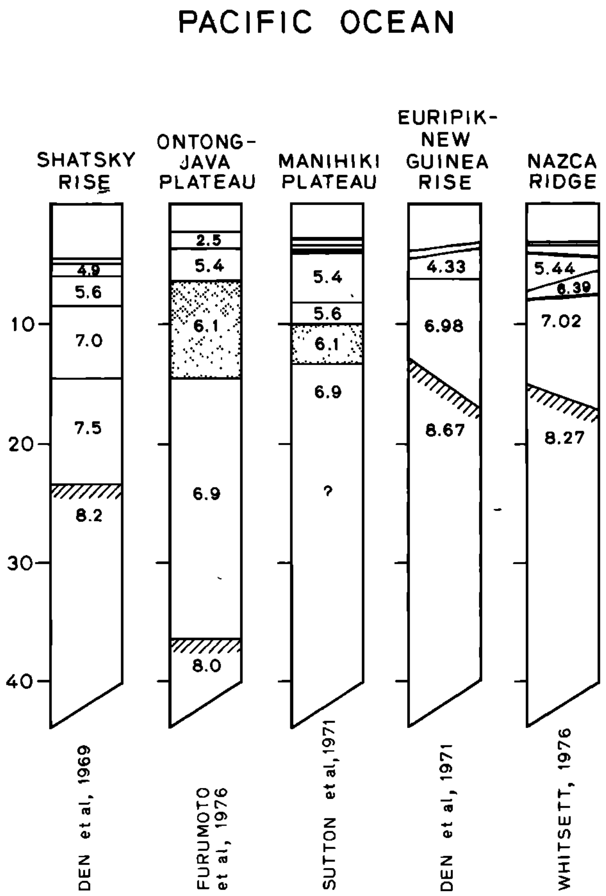

Fig. 2*a*. Summary of crustal structure data for oceanic plateaus in the Pacific Ocean. The vertical scale gives depth below sea level in kilometers; numbers in column indicate compressional wave velocities according to the references at the bottom of each column. Dotted zones indicate *p* velocities typical for continental basement rocks.

CONTINENTAL FRAGMENTS AROUND THE CIRCUM-PACIFIC

Tectonic and paleomagnetic data provide a record of the migration and consumption of oceanic plateaus in the northern rim of the Pacific Ocean and in adjacent mountain belts in Mexico, western North America, Alaska, Siberia, and Japan. Magnetic inclination measurements which yield the latitudinal component of motion [*Hillhouse*, 1977; *McElhinny*, 1973] show that many allochthonous terranes in Alaska and northeast Asia migrated several thousands kilometers over periods of tens of millions of years with inferred velocities of several centimeters per year [*Ben-Avraham et al.*, 1981]. Paleomagentic azimuths and declinations are often anomalous, suggesting that many terranes have also undergone substantial rotations [*Cox*, 1980]. The Cache Creek terrane [e.g., *Monger*, 1977] is one of the best examples for the incorporation of an ancient oceanic plateau. The terrane extends throughout much of the central part of the Canadian Cordillera well inland from the present continental margin. The presence of Tethyan Permian fusulinids led to the early recognization of this terrane as allochthonous [*Monger and Ross*, 1971].

The Cache Creek terrane is comprised of mafic and ultramafic rocks (ophiolites), chert, argillite, pelite, volcanic sandstone and tuff, and thick piles of fossiliferous carbonates, an assemblage which represents deposition within an oceanic environment. Locally, 2000 m thick carbonate banks formed plateau-like buildups that persisted from early Carboniferous until Late Permian time. Possible modern analogues of the Cache Creek limestone banks are large atolls or the Bahama Banks.

Some of the allochthonous terranes in northwest America (Figure 5) show strong continental affinities [*Coney et al.*, 1980]. A few of these terranes were probably parts of the North American craton and moved relatively short distances from their points of origin. Others such as Nixon Fork, the Ruby Mountains, the Klamath Mountains, or Wrangellia have no known parent continents or margins from which they were rifted. Wrangellia, for example, has an enormous accumulation of Middle to Upper Triassic subaerial basalts over an upper Paleozoic volcanic arc assemblage [*Jones et al.*, 1977]. The Triassic basalt is capped with Upper Triassic inner platform limestone and dolomite, overlain by basinal

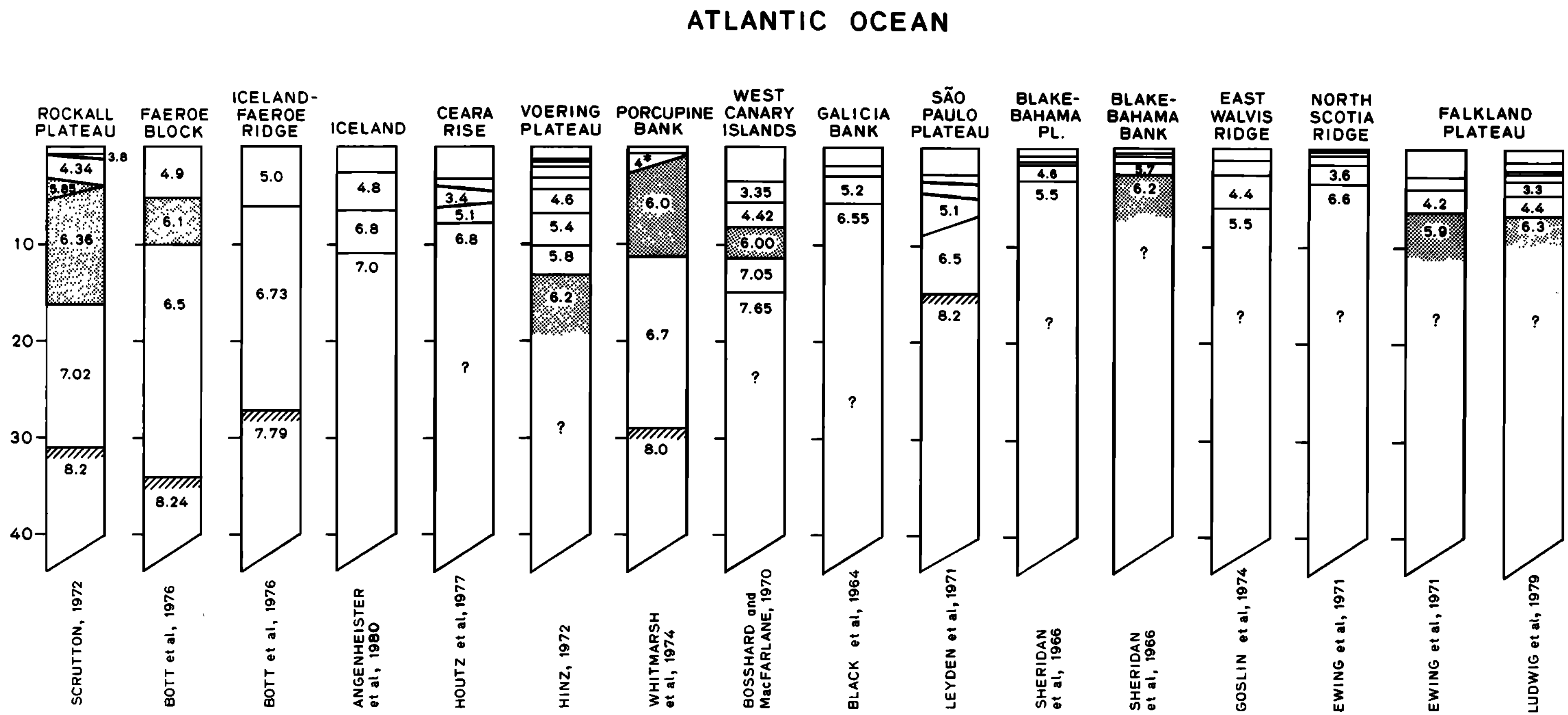

Fig. 2*b*. Summary of crustal structure data for oceanic plateaus in the Atlantic Ocean. See Figure 2*a* caption for details.

INDIAN OCEAN

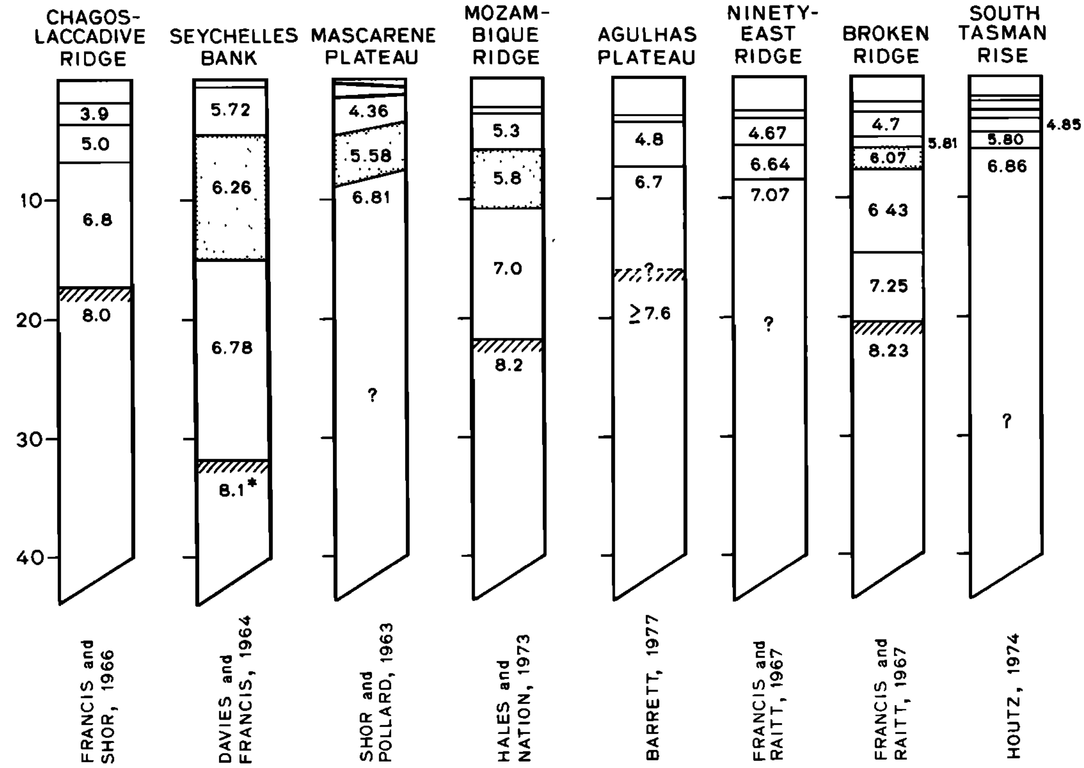

Fig. 2*c*. Summary of crustal structure data for oceanic plateaus in the Indian Ocean. See Figure 2*a* caption for details.

MEDITERRANEAN & CARIBBEAN

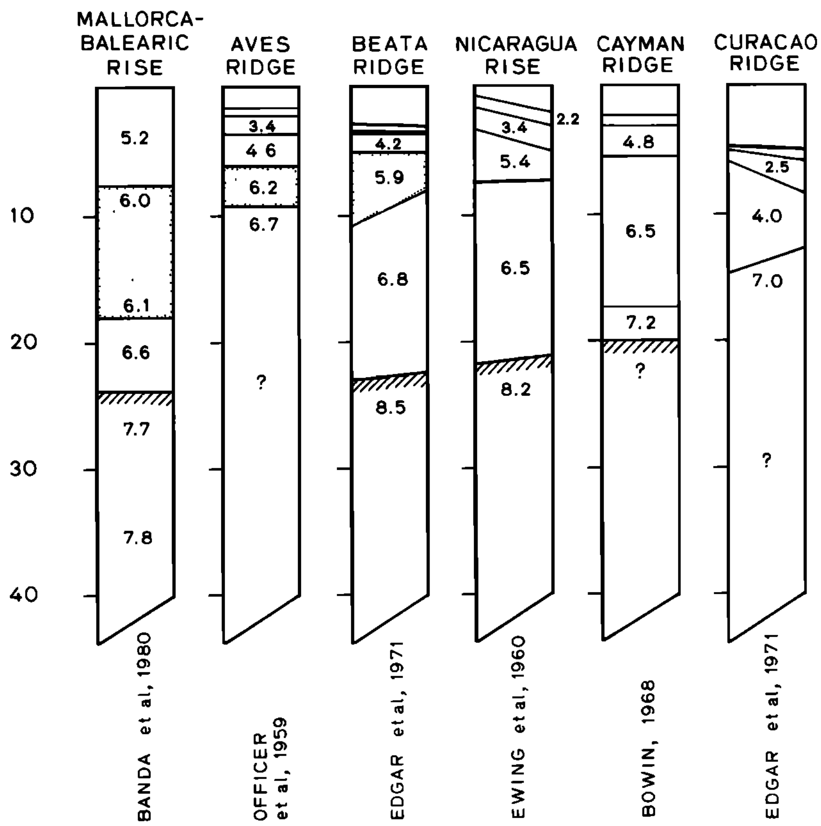

Fig. 2*d*. Summary of crustal structure data for oceanic plateaus in the Mediterranean and Caribbean seas. See Figure 2*a* caption for details.

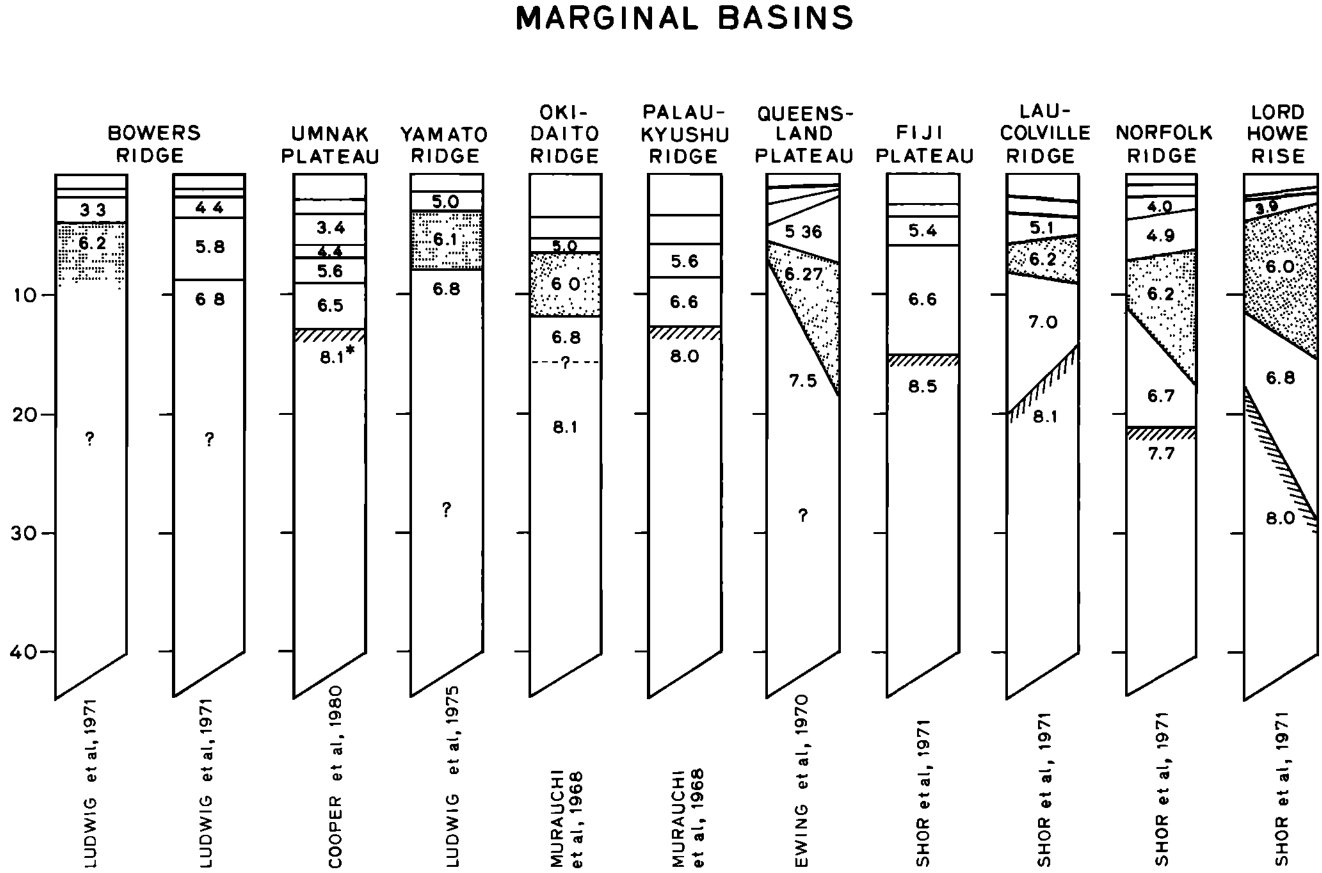

Fig. 2*e*. Summary of crustal structure data for oceanic plateaus in the marginal seas. See Figure 2*a* caption for details.

pelagic carbonates, siliceous argillite, and carbonaceous shale suggesting gradual subsidence with time. Continentally derived clastic material is wholly lacking indicating an oceanic setting. The basalt throughout Wrangellia probably represents rifting related to the commencement of a northward movement of the Wrangellia block from southern paleolatitudes, as inferred from paleomagnetic data [*Hillhouse*, 1977].

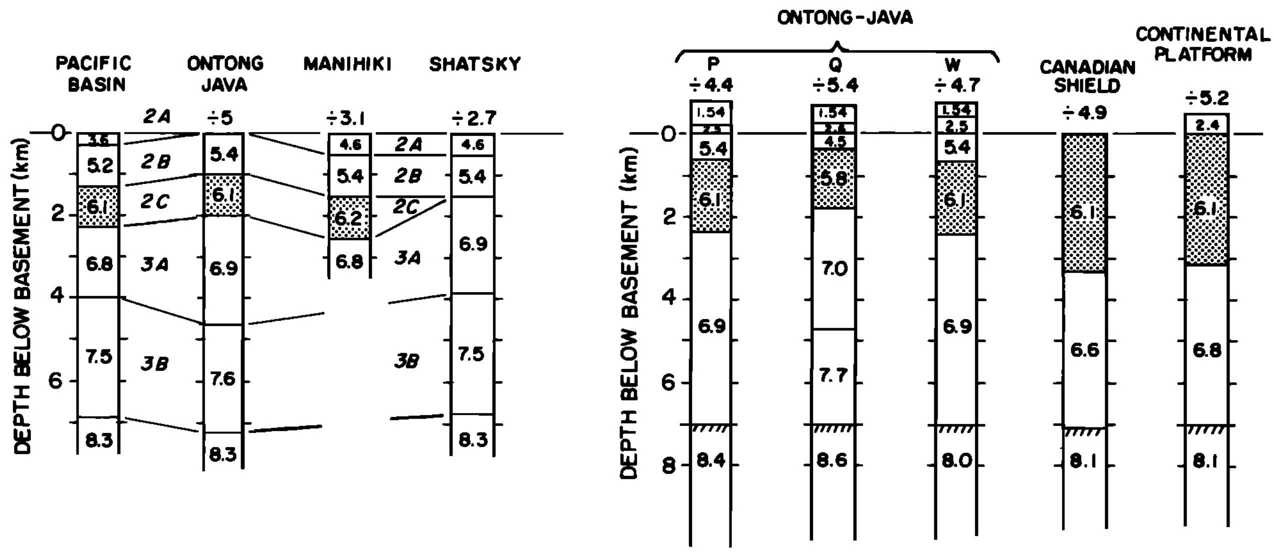

Fig. 3. Comparison between the so called 'reduced' crustal structures of Ontong Java, Manihiki, and Shatsky Rises (left, *Hussong et al.*, [1979]) and similarly 'reduced' structures for typical continental crusts (right). By dividing the Ontong Java, Manihiki, and Shatsky actual crustal structures by the arbitrary factors 5, 3.1, and 2.7 and comparing the results with typical Pacific basin structures, *Hussong et al.*, [1979] suggested that these rises consist merely of bloated normal oceanic crust. However, by dividing the Canadian shield and typical continental platform by the similar factors of 4.9 and 5.2, respectively, we obtain very similar sections. In particular the continental sections are very similar to the (*P*) and (*W*) sections of the Ontong Java Plateau. *Hussong et al.* [1979] have lumped sections *P*, *Q*, and *W* (reported by *Furumoto et al.* [1973] into a single average.

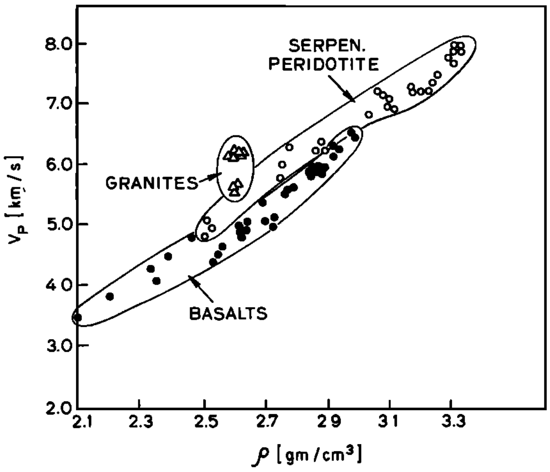

Fig. 4. Compressional velocity versus density measured at 2 kbar confining pressure for rock types which may be involved in oceanic plateaus. Note that basalts cover a wide range of velocities depending on their densities. The same is true for serpentinized periodities. Granites, on the other hand, display a narrow range of velocities and densities. All three rock types give a velocity of ~ 6 km/s for a density of 2.7–2.8 g/cm³. Data from *Press* [1966] and *Christensen* [1978].

Extensive accretion of micro-continents in other parts of the Pacific margins have also been suggested. It appears that northeast Siberia has evolved through the accretion by collision of several terranes (Figure 6) including the Kolyma micro-continent [*Fujita*, 1978; *Churkin and Trexler*, 1980]. *Fujita* [1978] suggested that a Kolyma subplate, which has separated from the Kula plate consists of two massifs which were in turn two older micro-continents: the Kolyma massif and the Omolon massif. Other microcontinents have also been recognized as having been involved in a series of accretion-type collisions until the end of the Mesozoic when the eastern margin of Asia was stabilized [*Markov et al.*, 1980].

Micro-continents have also played a major role in the tectonic evolution of the Japanese Islands. On the basis of paleomagnetic study of Permian greenstones and associated sediments from the inner belt of central Japan, *Hattori and Hirooka* [1979] suggest that parts of Japan were situated at equatorial regions in the late Paleozoic. They argue that a Japanese landmass, including part of its Precambrian basement, rifted away from an unknown continent, possibly Pacifica [*Nur and Ben-Avraham*, 1977], moved northward with the Far East microplate, and collided with Asia in late Mesozoic time. Based on the presence of exotic orthoquartzite clasts probably of Precambrian age in Japan's Shimanto belt which were supplied from the Pacific Ocean side, *Harata et al.* [1978] infer the existence of a large Kuroshio paleoland south of the Shimanto belt between late Cretaceous and early Neogene.

Collisions have been suggested also for the older Maizuru, Tamba, and other belts in Japan. The deformation of these older terranes started in late Paleozoic or early Mesozoic [*Shimizu et al.*, 1978] at the time when the Japanese landmass was presumably at an equatorial position [*Hattori and Hirooka*, 1979]. Collision events have also been suggested in terranes younger than Shimanto: the Miura belt [*Ogawa and Horiuchi*, 1978] and the Quaternary collision of the Izu Peninsula with central Honshu [*Matsuda*, 1978].

Evidence also indicates collision events in northern Japan. Late Paleozoic or early Mesozoic Australian fauna in the Kitakami Mountains in northeast Honshu [*Saito and Hashimoto*, this issue] is most notable. Hokkaido is now believed to contain an ancient collision zone between the west Hokkaido extension of Honshu and the east Hokkaido extension of the Okhotsk plate (S. Uyeda, personal communication, 1980). Several micro-continents, some on land with others just offshore, have been recognized in southeast Asia. In particular, the eastern Eurasian plate, including Sundaland, is probably composed of a number of continental blocks which may have come together only late in the Cenozoic [*Powell and Johnson*, 1980]. The data on land are insufficient to determine whether some of the old continental fragments within younger sedimentary strata were once true micro-continents. On the other hand, several micro-continents or fragments have been recognized offshore in this area (Figure 7). The Reed Bank area, the Calamian Islands, and the Cuyo Shelf [*Taylor and Hayes*, 1980; *Hamilton*, 1979], and the Paracel Islands and Macclesfield Bank [*Lud-*

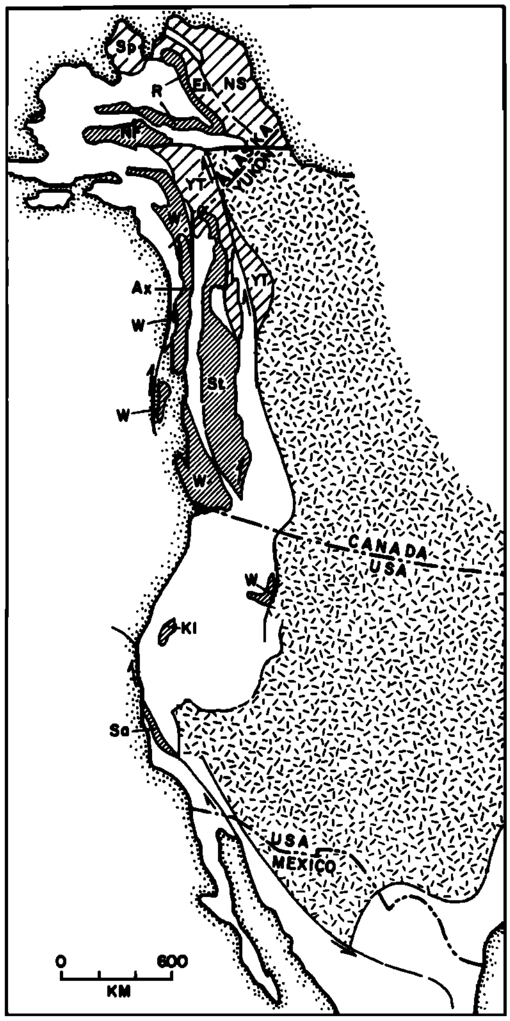

Fig. 5. Accreted terranes in western North America with clear continental origins or affinities (D. Jones, personal communication, 1980). Wide hachures indicate accreted terranes which have possibly been derived from the North American craton itself. Fine hachures indicate allochthonous terranes which have originated at other continents, definitely at more southern latitudes. The North American craton is indicated by pattern.

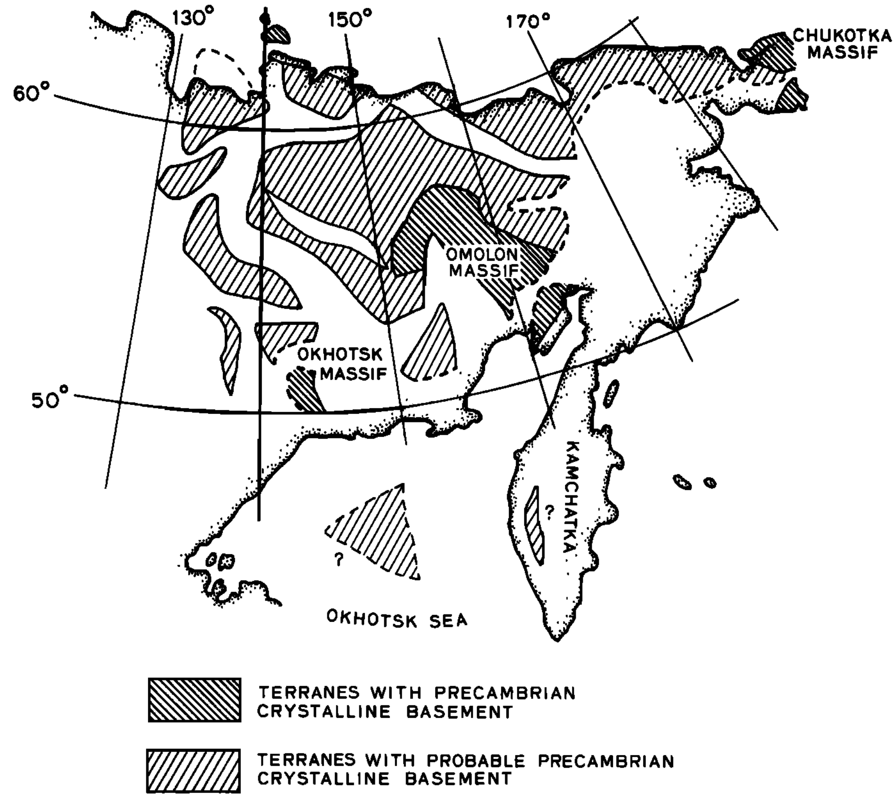

Fig. 6. Distribution of Precambrian rocks in northeastern USSR [after *Khain and Seslavinksy*, 1979]. Several have originated in more southern latitudes, as suggested by paleomagnetic evidence [*McElhinny*, 1973].

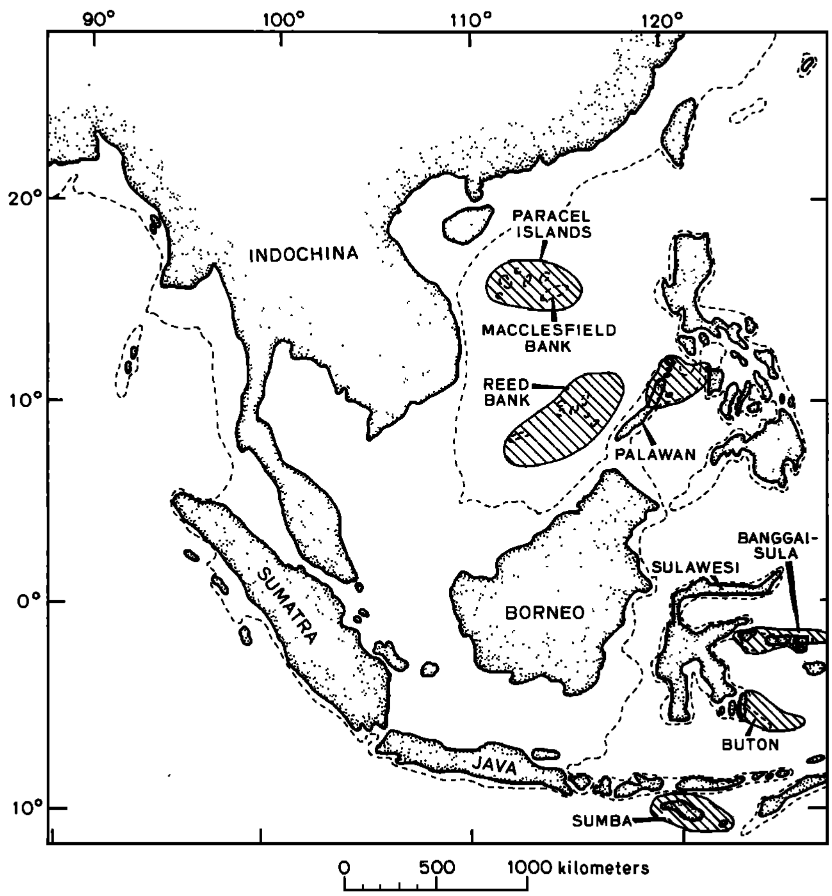

Fig. 7. Submerged continental fragments (hachured) in the seas of southeast Asia (from *Hamilton* [1979] and *Ludwig et al.* [1979*b*]).

wig et al., 1979*a*; *Taylor and Hayes*, 1980]. In eastern Vietnam, the Kontum massif is probably an accreted continental fragment.

The Banggai-Sula micro-continent off Celebes [*Hamilton*, 1979], presumably moved by a strike-slip fault in Middle Tertiary from New Guinea and is colliding with Celebes at present. Other fragments are the Buton micro-continent [*Hamilton*, 1979], also off Celebes, the Halmahera area in western Seram and Buru where Precambriam or Palezoic continental rocks are exposed, and south of the Banda Arc including the Sumba Island. *Hamilton* [1979] interprets this last fragment as a piece of the Java Sea.

The late Paleozoic and Mesozoic tectonic evolution of New Zealand involved the collision of micro-continents, as suggested by *Howell* [1980], *Kamp* [1980], and *Pirajno* [1980]. For example, the large Torlesse terrane is believed to be part of a larger continent which collided with New Zealand. It has even been suggested that the Pacifica continent [*Nur and Ben-Avraham*, 1978] served as a source for the sediments of the Canterbury Suite [*Kamp*, 1980].

We conclude that several Precambrian and Paleozoic continental fragments, many of unknown origins, are embedded in the circum-Pacific margins [e.g., *Hattori and Hirooka*, 1979]. The collision of these fragments, as well as noncontinental terranes, unquestionably played an important role in the evolution of these margins. Insight into the processes and effects of such collisions can be obtained from rises now in collision.

THE TRANSITION FROM OCEANIC PLATEAUS TO ALLOCHTHONOUS TERRANES

One of the most interesting results of active consumption is the creation of temporal and spatial gaps in subduction-related volcanism where oceanic rises are obliquely consumed, exemplified by the Nazca and Juan Fernandez Ridges in western South America and the Marcus Necker and Louisville Ridges in the western Pacific (Figure 8). We suggest that the oblique consumption of these ridges is responsible for the creation of temporal gaps in volcanic activity which trail behind the point of contact between ridges and the overriding plate [*Nur and Ben-Avraham*, 1981]. As seen particularly in the Nazca and Juan Fernandez gaps in South America, the normal pattern of seismicity in these gaps is also disrupted. It is likely that the arrival of the oceanic rise, with its buoyant roots, disrupts the coherency of the subducted normal oceanic lithosphere by flattening it or by slowing down the rate of its fall into the asthenosphere or by creating an actual tear in the plate. We have suggested that the inhibited subduction may cause the temporary cessation of volcanism due to a diminished supply of the water needed for the creation of partial melt.

The consumption of oceanic rises may also be associated with the emplacement of ophiolites. As summarized by *Ben-Avraham et al.* [this issue], several plateaus within or at subduction zones can be associated with ophiolite emplacement, e.g., the Benham Rise, the Ontong Java Plateau in the Pacific, and the Eratosthenes Rise in the eastern Mediterranean. Again, the buoyancy of the plateaus and their roots may be responsible for the obduction of slices of heavy oceanic crust which originally were adjacent to the margins of the plateau.

The result of the transformation of oceanic plateaus into allochthonous terranes may involve tectonic stress. In the

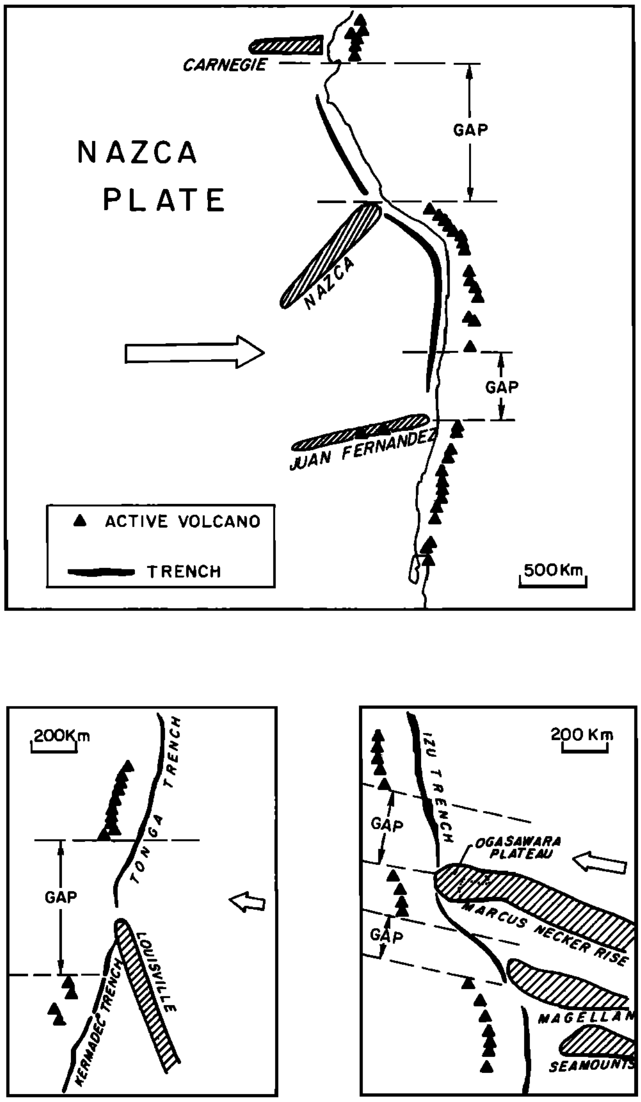

Fig. 8. The oblique consumption of the Nazca and Juan Fernandez Ridges in the eastern South Pacific and the Marcus-Necker and Louisville Rises the western Pacific is associated with volcanic gaps, possibly due to disruption of the subduction process. These gaps are temporary, trailing behind the moving contact between the ridge and the overriding plate [*Nur and Ben-Avraham*, 1981].

eastern Pacific where tectonic stress is high [*Uyeda and Kanamori*, 1979], colliding ridges may undergo extensive deformation during accretion with only small changes in plate boundary configuration. In contrast, plate boundary geometry may change significantly upon plateau collision in low stress regimes in the west and north Pacific. Here, where the subduction zones are not adjacent to a continent but rather to island arcs and marginal seas, plateaus or rises simply dock, causing subduction zone configuration changes by switching polarity or jumping to the oceanic side of the plateau [*Ben-Avraham et al.*, 1981]. Several marginal seas around the Pacific may have resulted from this docking process. For example, the creation of the Aleutian Trench may be the result of the consumption of the Bowers and Unmak Plateaus with the Mesozoic subduction zone in the Bering Sea [*Ben-Avraham et al.*, 1981; *Ben-Avraham and Cooper*, 1981]. The effects of consumption of a particular rise or plateau may also depend on its nature, whether it is oceanic in origin with thick, dense basalts or continental with light granitic rocks; therefore we need to consider the possible origins of plateaus and terranes.

ORIGINS OF ALLOCHTHONOUS TERRANES AND OCEANIC PLATEAUS

Four processes have been proposed to account for the presence of old continental crust in the circum-Pacific allochthonous terranes: (1) separation followed by the subsequent return and collision of continental slivers, (2) transverse motion of irregular continental slivers along transform faults such as the San Andreas Fault, (3) collision with and incorporation of island arcs, and (4) collision fragments separated from older continental masses like Gondwana in the past and Africa at present.

An example of the creation of continental fragments and their subsequent accretion is the history of the Indian Ocean. A complex pattern of rifting and ridge jumping [*McKenzie and Sclater*, 1973] produced a host of fragments and plateaus, including such fragments as Madagascar, the Seychelles Banks, and the Broken Ridge. Spreading finally concentrated along the Carlsberg Ridge, which gradually propagated northward, eventually separating the micro-continent of Arabia from Africa along the Red Sea. At present, while spreading along the Carlsberg Ridge-Red Sea axis continues and collision in the Himalayas and subduction in the Java Trench are well established, new rifting is developing in east Africa which could develop into a new spreading center. The east Africa rift has already led to the definition of the new, soon-to-be detached Somalia plate.

By analogy with the Indian Ocean Basin, we [*Nur and Ben-Avraham*, 1977] have proposed a hypothetical continental mass, possible intact before Early Mesozoic time, which broke up by the complex spreading process which eventually separated the Kula, Farallon, Pacific, and Phoenix plates. This process created continental fragments and oceanic plateaus which were carried toward subduction and eventually reached the active circum-Pacific continental margins. The fragments on the Kula plates collided with Alaska and eastern Siberia, the Farallon fragments collided with North America, and the Phoenix fragments, if they existed, collided with South America. Some of the fragments in the Pacific plate may still exist as the submerged plateaus present today in the western Pacific, such as the Ontong Java Plateau. Others are embedded as allochthonous terranes in eastern Asia and Japan.

CONTINENTAL FRAGMENTS, MICROPLATES, AND MOUNTAIN BUILDING

The role of continental collision, where two continental masses collide along a suture zone, in orogenesis has long been appreciated. However, the role of terrane accretion in mountain belts which directly face a vast open ocean, such as the cordillera of western North America, has only recently been recognized [*Nur and Ben-Avraham*, 1978; *Ben-Avraham et al.*, 1981].

Because of these two settings two types of mechanisms, collision and subduction, have been invoked for orogenesis. Collision is typified by the Alpine-Himalaya mountain chain. Subduction is typified by many of the circum-Pacific mountain chains, including Alaska, western North America, east Siberia, and particularly South America, where the Andes lent their name to this type of orogenesis.

As discussed previously and as might be inferred from Plate 1, it now appears that Andean-type orogeny in the usual sense of subduction of normal oceanic crust may not be the underlying tectonic process at the northern Pacific rim. In those sites where enough structural, stratigraphic, and paleomagnetic data have become available to demonstrate that allochthonous terranes are present, orogeny is intimately linked with the incorporation of these terranes. Although the occasional arc-continent collision orogeny has long been recognized, it now appears that many orogenic episodes aside from the Andean chain itself, may be the result of collisions. One possible implication might be that little or no orogenic deformation is expected where only pure subduction of simple oceanic crust has taken place.

Probably, accreted terranes have also played a leading role in orogenic deformation in the Alpine-Himalaya chain. In Table 2 we list some of the extensive evidence pointed out by numerous investigators for the extent of microplate incorporation in this chain. The list suggests that numerous terranes incorporated in most segments of the chain were associated with deformation well before full continental collisions have occurred. Examples include the Calabria, Adria, and Toscana microplates [e.g., *Kreuzer et al.*, 1979], now part of Italy; the Paikon, Palegonian, and Gavrono platforms [e.g., *Biju-Duval et al.*, 1977; *Giese et al.*, 1979]; the Apulian, Moesian, and Rhodopian fragments [*Burchfiel*, 1980] associated with the Carpathian and Balkan orogenic belts; the central Analtolian massif [e.g., *Durr*, 1975]; the Transcaucasus median mass [*Khain*, 1980]; the Rezaiyd micro-continent of northern Iran [e.g., *King*, 1973]; the Lut block in central Iran [e.g., *Gealy*, 1977], Gondwana fragments in the Herat and Panjchir sutures in Afghanistan [*Mattauer et al.*, 1980], and the Helmund block [*Gansser*, 1980], the accreted blocks in the Altyn Tagh and Kun Lun sutures in Tibet [e.g., *Burke et al.*, 1980; *Gansser*, 1980]. Sundaland [e.g., *Powell*, 1979], containing several massifs like the Tantum massif in Vietnam, probably was accreted in Cretaceous times. Finally, the South China platform [*Terman*, 1973] and Sikhote Alin also originated as separate terranes. Sikhote Alin has migrated approximately 30 degrees northward since Permian time [*McElhinny*, 1973].

Many of these continental fragments are thought to have rifted away from Gondwana, moved across the proto-Tethys, and accreted into northern continents, causing deformation and thrusting, without the actual collision between two full-sized continents. It is even possible, in view of the recent identification of the eastern Mediterranean sea floor as oceanic [*Ben-Avraham et al.*, 1979], that the Africa and European continents have not fully collided as yet. Even the most recent of these fragments, Arabia, is a subplate totally separated from Africa. It is therefore quite possible that the orogenic complexity in the Alpine chain is due to fragment consumption and not due to massive continent-continent collisions.

Most of the accreted continental blocks in the Alpine chain seem to have originated from Gondwana. The South European and Near Eastern blocks may have come from north Africa and Arabia, the Iran and Afghanistan blocks from east Africa [*Gealy*, 1977], and the Tibet-Himalaya blocks from northern India (see *Powell* [1979] for summary), as illustrated hypothetically in Figure 9. We also include Pacifica in this sketch, despite the vastly greater uncertainty of its location, to suggest the possibility that our originally

TABLE 2. Continental Fragments in the Alpine Orogenic Deformation

Area	Description and Reference
Western and Central Mediterranean	host of continental blocks and arcs, coalescing into present-day Italy and European platform: Calabria, Adria, Toscana, etc.; deformation in Apennines [e.g., *Kreuzer et al.*, 1979]
Hellenides	coalescence of 'African' fragments, e.g., Paikon platform, Pelagonian platform, Gavrono platform [e.g., *Biju-Duval et al.*, 1977; *Giese et al.*, 1979]
Carpathian/East Europe	at least three fragments of continental crust which lay between Europe and Africa accreted since Jurassic time: Apulian, Moesian, and Rhodopian fragments [*Burchfiel*, 1980]
Turkey	central Anatolian massif as microcontinent divided Tethyes into northern and southern parts; coalesced with Pontides in mid-Miocene [e.g., *Dürr*, 1975]; the Erthosthenes block is colliding with Cyprus [*Ben-Avraham et al.*, this issue]
Caucasus	the transcaucasian median mass, composed of Precambrian basement and paleozoic rocks; the mass probably closed an ocean basin in mid to late Mesozoic time [e.g., *Khain*, 1980]
Arabia	colliding at present with the collages of Turkey and Iran
Iran	the Rezaiyeh-Esfangeheh microcontinental complex in northern Iran, probably separated from Gondwana after Permian time [*King*, 1973; *Stocklin*, 1974]
Afghanistan	accretion of Gondwana(?) fragments into the Eurasian margin along the Herat and Panjchir Sutures [e.g., *Mattauer et al.*, 1980]; the origin of the Helmand block is established by paleomagnetic measurements [*Krumsiek*, 1976]; the Pamir block originated also at the same time [e.g., *Gealy*, 1977]
Tibet	the accretion of a series of Gondwana fragments, or micro continents beginning in Permian times; the Tarim block collided with Kazakhatan in Early Permian [*Burtman and Porshiakov*, 1973]; the Tsaidam block, Chang Thang, the N Tibert platform and S Tibert platform [e.g., *Chang and Cheng*, 1973]; the Altyn Tagh and Kun Lun lines define the sutures of the latter ones [e.g., *Burke et al.*, 1980; *Gansser*, 1980]
Southeast Asia	Sundaland, composed of several continental domains, was separated from South China in the Cretaceous [*Powell and Johnson*, 1980]; some of the blocks, e.g., the Tantum massif [e.g., *Klompe*, 1957], with old continental basement rocks; the massif was accreted from the east (?) [*Powell*, 1979]
China	the South China continental platform [*Terman*, 1974] has probably originated as a separate fragment; paleomagnetic data [*McElhinny*, 1973] suggest an origin 30° to the south; North China block; Sikhote Alin

proposed Pacifica fragments may be the eastern most Gondwana fragments. Unlike more westerly parts of the northern rim of Gondwana, Pacifica faced a vast ocean; therefore its fragments may have been more widely spread and may have travelled much greater distances.

In summary, it seems possible that Gondwana's northern and eastern margins were repeatedly fragmented at least since Permian times [*Boulin*, 1981]. This fragmentation, which continues today, supplied numerous continental fragments to the oceanic plates, fragments which eventually have been or will be accreted by collision into active continental margins.

Thus, the orogenic deformation in the northern Pacific rim may have been caused by collisions with accreted fragments and arcs and not by the normal subduction of oceanic lithosphere. Fragment collisions, rather than continent collisions, may also be responsible for orogenic deformation in the Alpine-Himalaya chain. In many instances, deformation has occurred in this chain upon the collision of a continent with a micro-continent or a continental fragment. Consequently, both orogenic systems, the Alpine and the circum-Pacific excluding the Andes, may have similar mechanical origins: collisions with fragments. In the Andes, unlike the rest of the circum-Pacific, there is no simple evidence of accreted terranes.

THE ANDES AND THE ANDEAN-TYPE OROGENY

The geological data for western South America are insufficient to determine whether the required allochthonous terranes are present now or where present in the past. Nevertheless, some evidence suggests the possibility that the orogenic history of the Andes may have involved accreted terranes.

As pointed out by *Zeil* [1979], the Andes are made up of several tectonically and stratigraphically distinct geologic assemblages which have been welded together over a wide range of geological time. Many paleozoic and Early Mesozoic structures run obliquely to the overall north-south structural trend of the Andes, including regions with penetrative deformation in continental basement rocks in late Paleozoic age. Deep crustal 'fractures' provide sharp boundaries between sections of the Andes. Some of these sections differ from one another in their geological history and rock types. In the northern Andes, these sections are characterized by rocks with oceanic affinities, whereas from Peru south the rocks have mostly continental affinities. Continental basement rocks, greatly deformed in Paleozoic and Early Mesozoic times but only mildly since, are exposed along the western coast from Tierra del Fuego to Peru, with ages ranging from 1.8 b.y. B.P. to 300 m.y. B.P. Many investiga-

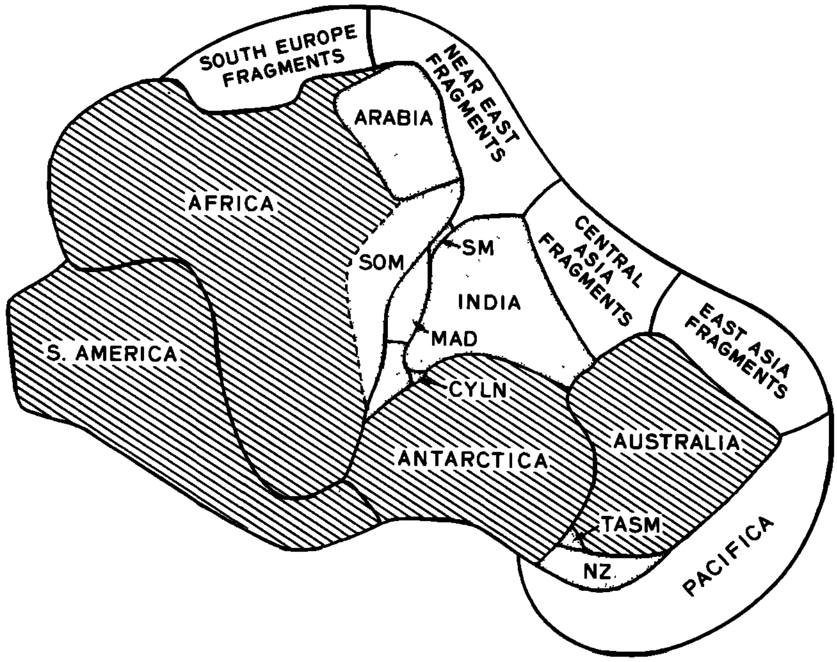

Fig. 9. Speculation about the origin of many of the accreted allochthonous terranes in the Alpine and Pacific Mesozoic-Cenozoic orogenic belts. Possibly the fragmentation of Gondwana and particularly its margins gave rise to a host of large and small fragments, which have become embedded in oceanic plates, moving toward subduction zones along the boundaries of other continental masses.

tors suggest that continental sources to the west of the Andes fed voluminous Late Paleozoic and early conglomerates and sandstones now found in the Andean chain. Arc terranes incorporated from the west have also been invoked [*James*, 1971] to explain the presence of old continental basement off the Peru coast.

These general observations suggest that the possible presence of allochthonous terranes cannot be excluded from the Andean orogenic belt, and given the abundance of these terranes and their impact elsewhere in the circum-Pacific, it would not be surprising to find accreted terranes also in the Andean chain. Therefore, we believe that the concept of Andean orogeny, resulting from subduction of normal oceanic crust beneath a continent, may be somewhat open to question. It may be that a sufficient condition for orogenic deformation everywhere on earth is collision with fragments.

CONCLUSIONS

We suggest that the role of fragments, particularly continental fragments, may be more important in both the breakup of continental masses and their growth by accretion than generally recognized. The breakup of northern and eastern Gondwana, continuing through the more recent breakup of Africa, illustrates the persistence and continuity of this process. From Permian fragments, which are now found for example in Tibet, through present Arabia and Somalia, a host of continental slivers, micro-continents, and related rises have migrated into Europe and Asia. Substantial orogenic deformation has resulted from the accretion of these bodies prior to continent-continent collision.

Numerous accreted continental fragments, as well as a variety of noncontinental rises, have been identified also in the cordillera of western North America, Alaska, east Siberia, Japan, and southeast Asia. As in the Alpine chain, the accretion of these allochthonous terranes involved extensive orogenic deformation, without full continent-continent collision. Although the sources of the multitide of these Pacific terranes remain unknown, many have migrated across open oceans, coming from older continental masses which underwent fragmentation processes such as Gondwana in the past and Africe more recently. One possible source configuration is Pacifica, an extension of Gondwana beyond New Zealand and Australia. Just as fragments of Gondwana and Africa are found today in the Alpine-Himalaya chain so are fragments of Pacifica or other continental source masses found in the northern and western circum-Pacific. Whether accreted terranes are both necessary and sufficient to cause orogenic deformation remains unresolved, until it is determined or not whether terranes have been accreted in western South America.

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