Subduction and Accretion in Trenches

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ABSTRACT

Although the reality of subduction has been greatly strengthened by recent investigations, there is little information dealing with the mechanisms by which material is subducted or accreted to the upper plate. An attempt to determine the gross evolution of subduction zones has been made, assuming that geographic variations in morphologic and geophysical characteristics of trenches can be transformed into temporal trends. Deformation associated with subduction extends across the lower trench slope, from the trench axis to the trench-slope break. This region is a rising tectonic element, but the upper slope is a subsiding region of sediment accumulation. An upper slope discontinuity separates this zone of subsidence from the rising frontal-arc block. Examination of very young trenches indicates that the upper-slope discontinuity marks the upper section of the continental or insular slope that existed before a subduction pulse began. As material is fed to the subduction zone, the distance between the upper slope discontinuity and the trench increases, and an accretionary prism develops, but its shape depends on the relative rates of sediment feed from the arc and from the offshore basin.

The lower boundary of the accretionary prism is the upper section of the seismic zone, which apparently widens and flattens as one or more accretionary prisms accumulate. The sediment cover on the downgoing plate and some of the igneous crust appears to be stripped off the plate before it reaches a point beneath the volcanic chain. Turbiditic sediments deposited in the trench axis are preferentially sheared off the underlying pelagic sediments and are accreted to the lower trench wall. The pelagic sediments and crustal material are probably accreted at deeper structural levels.

Where turbidites overlie pelagic sediments in the trench axis, the turbidites are stripped off in fold packets with axial surfaces having very low dips. These dewatered and rigidified structural units move up the lower slope, as subsequent packets are accreted. In trenches that subduct lithosphere carrying very thin pelagic sediment covers, accretion and uplift of crustal slabs seem to occur as topographic irregularities enter the trench. *Key words: marine tectonics, island arcs, subduction, trenches.*

INTRODUCTION

One of the more controversial aspects of plate tectonics has been the assumption that large-scale subduction of oceanic lithosphere takes place along trenches. Early interpretations of gravity data (Worzel and Shurbet, 1955) and of seismic reflection profiles (Scholl and others, 1968; von Huene and Shor, 1969) have been cited as evidence precluding underthrusting in trenches (Beloussov, 1970; Carey, 1970; Meyerhoff and Meyerhoff, 1972). However, these interpretations have been shown to be erroneous by more recent results using these same techniques (Grow, 1973a; Holmes and others, 1972; Beck, 1972) and by data from the Deep Sea Drilling Project (Kulm and others, 1973b; Ingle and others, 1973, 1975), as well as by the results of earthquake seismological studies (Isacks and Molnar, 1971; Barazangi and others, 1972).

It is now apparent that the oceanic lithosphere is subjected to large-scale underthrusting at trench axis and that some of the uppermost material is transferred from the lower to the upper plate in the process. In some trenches, tectonic erosion of the upper plate during subduction has been suggested (Scholl and others, 1970); but this process is neither well documented nor necessary (Karig, 1974a).

Accretion of oceanic sediment and deeper crustal material onto the upper plate during subduction has been postulated using several different approaches (Dewey and Bird, 1970; Gilluly, 1972; Moore, 1973; Burk, 1965; Hamilton, 1969; von Huene, 1972), but as yet the variations in the accretionary process and in the resultant geologic structures remain almost completely unknown. In large part, this void results from a lack of data from the inner trench wall where accretion is suspected to occur. Acoustic methods cannot adequately resolve the geomorphic detail or the internal structure of the constituent rocks, and the conventional bottom sampling too often collects only recent sediment overlying the accreted material.

This paper reports the results of a broader scale approach to the problem of accretion at subduction zones. Digitized bathymetric profiles across almost all Pacific and Indonesian trenches (Fig. 1) were computer-reoriented, perpendicular to the associated trench, and plotted at similar horizontal and vertical scales. These profiles, integrated with available seismic reflection profiles and other geophysical data, provide insights to the variations in subduction-zone structures which were not obvious from analysis of scattered separate data sets presented at different scales and vertical exaggerations. The basic assumption utilized in our analysis is that morphologic variations among the arc systems can be interpreted in terms of evolutionary trends.

TECTONIC FRAMEWORK OF SUBDUCTION ZONES

The uniformity of geological and geophysical features among the various island-arc systems has often been noted (Hess, 1948; Umbgrove, 1947) and has since been amplified (Karig, 1971a; Karig and Mammerickx, 1972; Grow, 1973a, 1973b; Dickinson, 1973b). A generalized terminology (Karig, 1970, 1974b) based on this uniformity is utilized, for the most part, in this paper (Fig. 2). Modification is required chiefly in the slope area between the crest of the frontal arc and the trench, where the greatest variability within the arc system is observed.

The slope between the trench and frontal arc, in all but very young trenches, consists of two sections (Fig. 3). The upper section is relatively smooth, reflecting a little-deformed sediment cover, and contrasts with a steeper, less regular lower section where sediments are either deformed, acoustically unresolvable, or absent. The two slope sections are separated by a ridge, bench, or slope break, which, because of its variable aspect, has received a number of designations. In the Indonesian arc system, where it forms a ridge that occasionally breaks sea level, this boundary has been termed the tectonic arc (Vening-Meinesz, 1964), outer arc (Umbgrove, 1947), or nonvolcanic outer arc (Van Bemmelen, 1949). The basin thus formed in the upper slope area has been referred to as the interdeep (Van Bemmelen, 1949). In some areas, sufficient sediment has been deposited behind the boundary to fill the upper slope basin and to produce topographic benches, which have been called terraces (Gates and Gibson, 1956) or deep-sea terraces (Hoshino, 1969; Tayama, 1950). Recogni-

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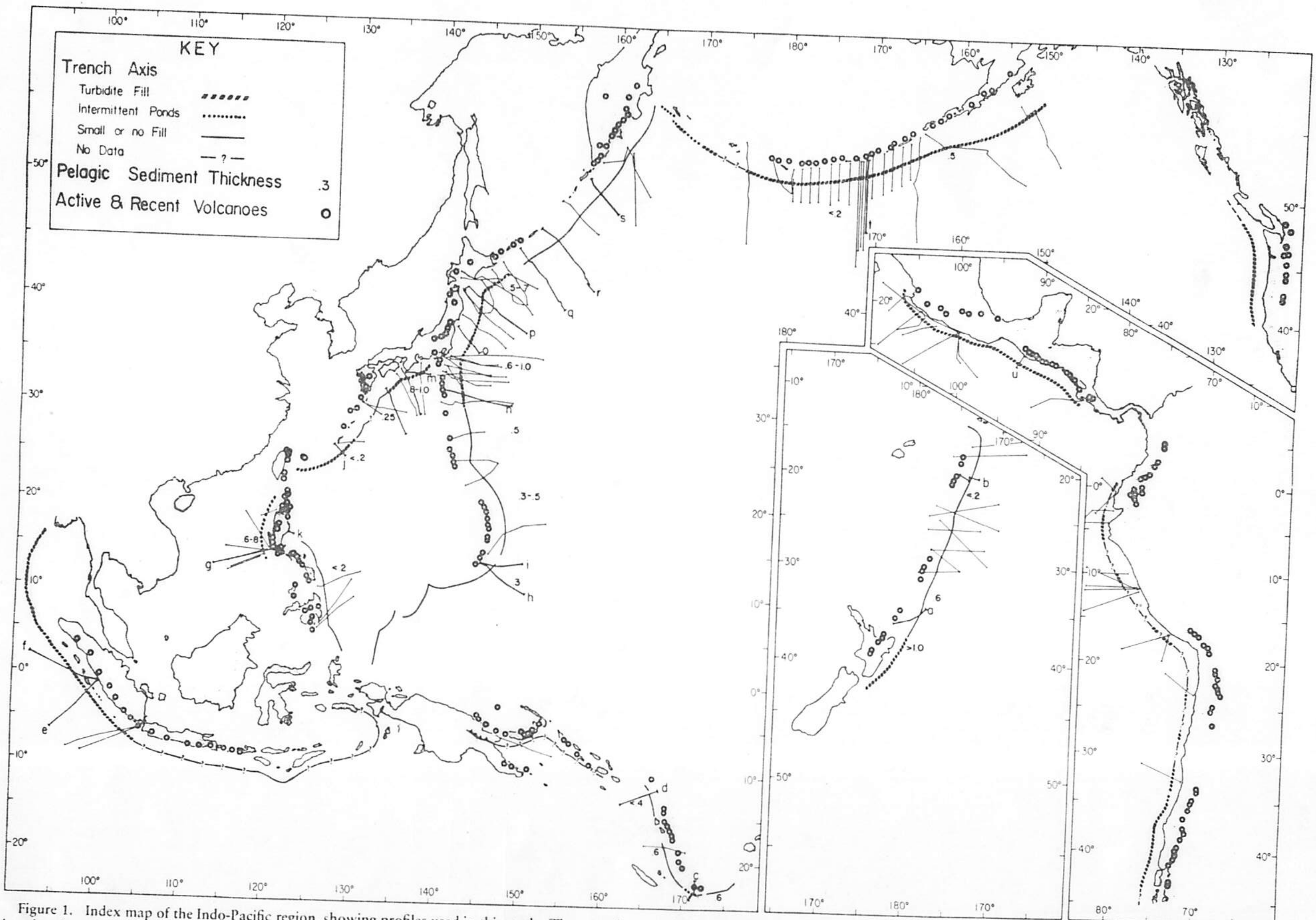


Figure 1. Index map of the Indo-Pacific region, showing profiles used in this study. Those used in other figures in this paper are shown by heavy lines. These are oriented perpendicular to the trench and at 20× vertical exaggeration, and are located on Figure 1 by small letters. Other symbols are shown on the explanation. Profiles are from Scripps Institution of Oceanography (S.I.O.) and Navy digitized sounding lines deposited in the S.I.O. data bank, along with a few hand reoriented profiles from references cited in the text. Sediment thicknesses are from the same sources and from Initial Reports of the Deep Sea Drilling Project.

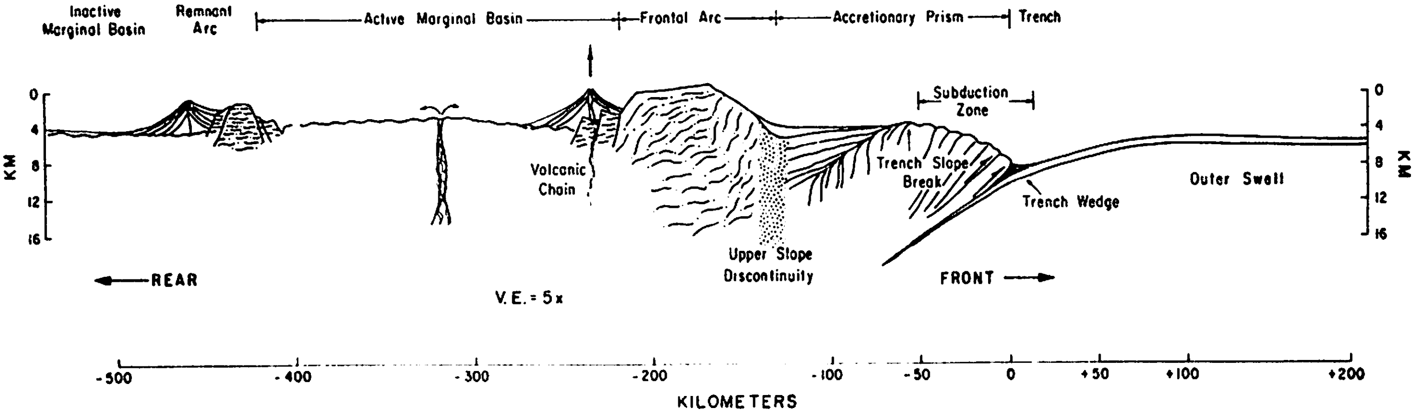


Figure 2. Cross section of a typical island-arc system, showing tectonic units and terminology used in this paper (revised after Karig, 1970, 1971a).

tion of the variability of the morphology in this two-part slope has led to the more generalized definitions of midslope basement high (Karig, 1971a) and "slope break" (Dickinson, 1971). A nongenetic term, "trench-slope break," has been generally agreed upon to cover all aspects of the boundary between slope sections (Dickinson, 1973a) and is used here.

Trench Slope Break and Lower Slope

Direct observations of the trench-slope break are restricted to the few areas where the feature emerges as islands. The best examples are Barbados (Caribbean arc system; Baadsgaard, 1960; Mesolella and others, 1970; Steinen and others, 1973; Lohman, 1974), the Mentawai Islands (Sumatra arc system; Van Bemmelen, 1949; Hamilton, 1973; D. E. Karig, unpub. field work data), and Middleton Island (Aleutian arc system; Miller, 1953; Plafker, 1969). All show rapid tectonic uplift of Quaternary reefs or wave-cut terraces. The bedrock beneath the surficial carapace of reef or terrace deposits consists of either highly deformed, steeply dipping clastics which may contain slices of basalt or ultramafic rocks, or less steeply dipping, nondisrupted clastics or carbonates. On the Mentawai Islands and Barbados (Lohman, 1974), slope deposits overlie more highly deformed rocks. This relationship is amplified by seismic reflection profiling in many arc systems that show that upper slope sediments are openly folded over an opaque basement core at the trench slope break (Hilde and others, 1969; Ludwig and others, 1967; Grow, 1973a, 1973b; Karig, 1973a).

Deformation near the trench slope break apparently marks the upper boundary of a zone of active deformation that extends to the base of the inner trench slope. Available data indicate that the maximum rate of deformation occurs very close to the foot of the lower trench slope (Ingle and others, 1973; J. C. Moore and Karig, in prep.) and continues at a decreasing rate up the slope to the crest of the trench-slope break (Kulm and others, 1973b; Creager and others, 1973). This zone of deformation between the trench-slope break and the trench axis limits and probably defines the surface expression of the subduction zone.

The rocks dredged or cored from beneath the surficial sediments of the inner trench wall are identical or similar in lithology to those at the trench axis or on the oceanic crust (Kulm and others, 1973b; von Huene, 1972; Fisher and Engel, 1969; Hawkins and others, 1972; Ingle and others, 1973). Basement rocks on the Mentawai Islands and on Barbados can also best be interpreted as having originated in those areas. This implied upward displacement of the deformed material continues to the crest of the trench-slope break. However, down-to-the-rear faulting and folding, and rearward tilting of the upper slope sediments near the trench slope break (Fig. 3; see also Figs. 4, 16, and 18 of Ross and Shor, 1965; von Huene and others, 1971) suggest that the upper slope area is not rising as rapidly as the trench-slope break and may even be subsiding relative to sea level.

The sediments of the upper slope, between the trench-slope break and the frontal arc, are usually synformal or show a homoclinal tilt toward the frontal arc. These sediments may reach a thickness of several kilometers (Ludwig and others, 1966, 1967; Grow, 1973a; Den and others, 1968). In contrast, the frontal arc is strongly emergent, especially along its seaward edge (Fitch and Scholz, 1971; Plafker, 1969, 1972; Mitchell, 1969). To a close approximation, the frontal arc is a rising and rearward-tilting or rotating block, with little internal deformation. There is, therefore, a strong tectonic discontinuity between the frontal arc and the upper-slope sediment pile.

Upper Slope Discontinuity

The boundary between the frontal arc and the upper slope takes several different forms, all of which will be referred to as the upper-slope discontinuity (Figs. 2, 3). In the Japan and eastern Aleutian arc systems, the upper-slope discontinuity is a fault zone (von Huene and others, 1971) or a steep contact without significant morphologic expression (Fig. 3). Arc systems having a deeper upper-slope trough or apron (such as the central Aleutians, Marianas, and Luzon systems) display the upper-slope discontinuity as the downward extension of a steeper upper-slope section, along which the sediments are faulted, strongly flexed, or lapped against the frontal arc (Fig. 3; Grow, 1973a; Ludwig and others, 1967). The upper-slope discontinuity in the New Hebrides, Solomons, and similar arc systems without upper slope sediments (Fig. 3) is placed at the upper section of the steep trench slope, where it forms the forward boundary to the frontal-arc platform.

The upper-slope discontinuity in most arc systems describes a smooth map trace about 75 km in front of the volcanic chain. In the eastern Aleutians and Hikurangi areas, where sediment influx to the subduction zone is very high and the distance from the volcanos to the trench broadens, the volcanic-chain–upper-slope discontinuity separation also increases. In the Bonin arc system, where the frontal arc is composed of en echelon ridges (Karig, 1971a, and unpub. charts), the upper-slope discontinuity follows the frontal-arc offsets and has an irregular trace.

The fundamental structure of this important feature is not apparent. Small normal faults on the frontal arc of the Tonga arc system, interpreted as synthetic (Karig, 1970), may instead be antithetic, gravity-driven features. Grow (1973a) and Murdock (1969) discuss the possibility of high-angle reverse faulting along this zone in the Aleutian system. In this paper, only near-vertical basement displacement is assumed and the upper-slope discontinuity will be used to mark the forward edge of the frontal arc. That volume of material between the discontinuity and the trench will be referred to as the accretionary prism (Fig. 2). Use of this term will hopefully be justified in the following discussions.

BOUNDARY CONDITIONS IN ISLAND-ARC SYSTEMS

Determination of the quantity of material accreted, the rate at which accretion occurs, and the disposition of accreted material within the arc system are important in any study of subduction zones. However, there are several fundamental problems which must be attacked before these more specific questions can be answered. These concern the tectonic boundaries of the subduction zone and their stability over time, the initial condition of a subduction zone, and the extent of temporal continuity at consuming plate margins.

Temporal Continuity of Subduction

Although it has generally been assumed that tectonic activity in orogenic zones is discontinuous, the persistence of crustal extension along individual spreading ridges over periods of time often exceeding 100 m.y. requires that the assumption of discontinuous subduction be examined. Indirect evidence supporting episodic subduction is supplied by the discrete pulses of arc volcanism (Dott, 1969; Mitchell and Bell, 1970) and inter-arc basin extension (Karig, 1971b) along many arc systems. Unfortunately, lack of exposure and the difficulty in resolving deformation ages of rocks involved in the subduction zone prevent direct dating of subduction activity.

Major discontinuities can often be deduced from the geologic history along plate margins. These may result from regional effects, as the shift in subduction zones from one small plate boundary to another (for example, the Shikoku system; Ingle and others, 1975) or arc polarity reversal without collision (for example, New Hebrides; Karig and Mammerickx, 1972).

In addition to the reorganization of tectonism within arc systems and among a complex of downgoing plates, discontinuities in subduction might also be attributed to more general changes in plate motions (Coney, 1972; Larsen and Chase, 1972). For instance, steady-state extension along the East Pacific Rise could be coupled with sharp changes in subduction rates along the two sides of the Pacific basin.

Initial Configurations of Subduction Zones

Newly created or rejuvenated subduction zones should most nearly display the initial morphology and structure of the inner trench wall. The young trenches that appear to most closely approximate initial conditions are those of the Shikoku, East Luzon, New Hebrides, Solomons, and New Britain arc systems. All of these are newly occupied or strongly rejuvenated crustal interfaces of Miocene or younger age.

The west Melanesian trenches (New Hebrides, Solomons, and New Britain) are all similar in character. Instead of a distinct upper slope, these arc systems have a single steep slope leading from the edge of the frontal arc to the trench axis (Fig. 3; see also Hayes and Ewing, 1970, Fig. 11). Igneous rocks have been dredged from most of these slopes (Petelin, 1964). The 90- to 130-km separations between the trench axis and the volcanic chain are the smallest observed in contemporary arc systems.

The East Luzon and Shikoku arc systems represent a second style of initial morphology, with a small but well-defined trench-slope break and upper-slope sediment trough (Figs. 4, 5B). The characteristics of trench rejuvenation are especially well shown along the East Luzon system, which resumed subduction in the Quaternary (Fitch, 1972; Karig, 1973b and unpub. data). Because subduction has not yet propagated along the entire Luzon coast, pre-existing conditions can be observed off northeast Luzon (Karig and Wageman, 1975). This boundary became inactive in the mid-Tertiary and was subsequently the site of a moderate-sized continental rise wedge. Renewed underthrusting seems to have deformed this wedge and generated a small but well-formed accretionary prism (Fig. 4). Sediments on the lower slope or uppermost rise have been tilted westward toward the frontal arc (Luzon). More recent sediments have collected behind the accreted material to form an incipient upper-slope basin. In this case, the upper-slope discontinuity is clearly a remnant of the pre-existing continental or insular slope. A similar but more advanced situation can be observed along the Shikoku or southwest Japan system (Karig, 1975).

Following the rapid accretion of a continental or insular rise wedge, the rate of accretion would drop to a lower, more nearly steady state rate. Thus, the difference in initial configuration between the Shikoku-Luzon and west Melanesian types is explained by the greater sediment buildup at the slope bases of the larger continental masses. Different sediment feed rates to the subduction zone from the offshore basin and trench could also be contributory, but even several hundred meters of sediment subducted at a rate of 10 cm/yr or more since the end of the Miocene or longer has not begun to build an appreciable trench-slope break in the New Hebrides arc system.

These two types of young arcs may reasonably be used as initial configurations of subduction zones, and they suggest that accretion causes the enlargement of the area between the upper-slope discontinuity and

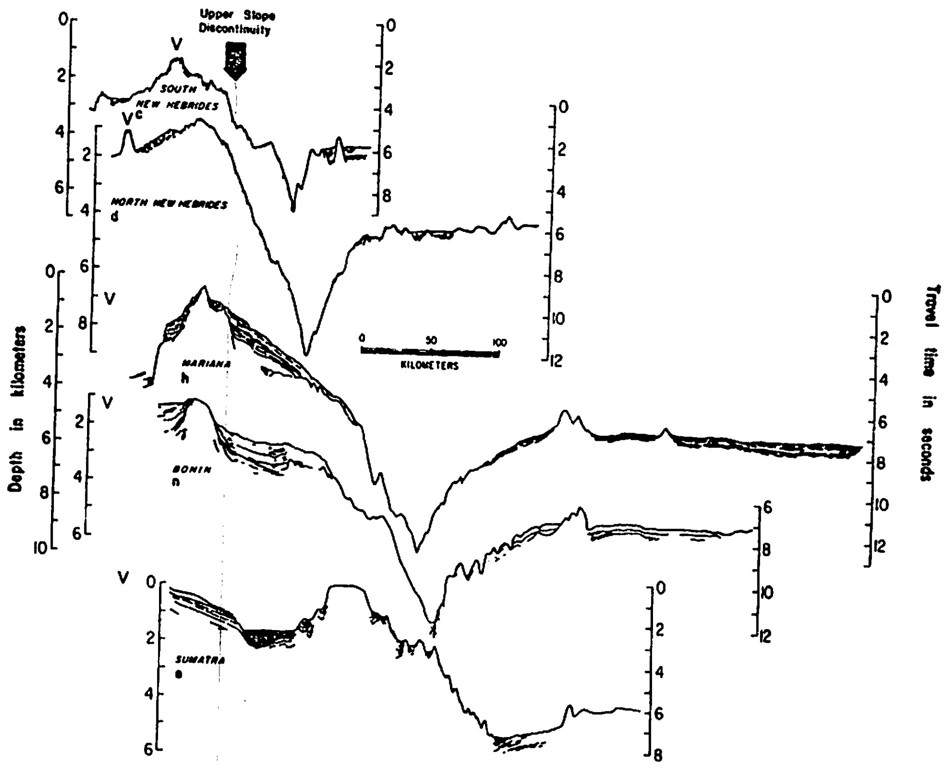


Figure 3. Seismic reflection profiles across the inner trench slopes of arc systems with varying ages and sedimentation characteristics. Profiles are normalized to the upper-slope discontinuity and show the wide range in width and shape of the accretionary prism. The axis of the volcanic chain (v) is also indicated. Profile *e* displays relative subsidence and rearward tilting of the upper slope sediments. Profile *d* (from Menard, 1964) was enhanced with reflection data from Hayes and Ewing (1970).

the trench. The accreted material also forms a basement upon which the upper-slope sediments can accumulate.

The Upper-Slope Discontinuity as a Tectonic Reference

Analyses of the youngest subduction zones leads to the indentification of the upper-slope discontinuity as the upper section of the continental slope which existed before the subduction pulse began. Morphologic relief between the frontal-arc platform and the upper-slope sediments in very young subduction zones is greater than 2 km and generally decreases with increasing age and growth of the accretionary prism (Figs. 4, 5). Low relief on older zones appears to strongly reflect high sedimentation rates on the upper slope and growth of the trench slope break as demonstrated along the eastern Aleutian, southern Kermadec, and Japan-Bonin systems. The juxtaposition of upper-slope sediments against frontal-arc basement is thus in part an onlap relationship and in part a result of structural displacement.

Although the upper-slope discontinuity quite clearly appears to originate as an upper continental slope, it is not at all clear that this boundary remains spatially fixed during subduction, or that there is a one-to-one correlation between pulses of subduction and positions of the upper-slope discontinuity.

If there were a steady trenchward migration of the upper-slope discontinuity, a thick section of upper-slope sediments should be exposed along the leading edge of the frontal arc. Such deposits have not been observed. Rather, the sediments overlying the frontal-arc basement are generally thin, shallow-water strata, and, together with reflection profiles which show no uplift of the upper-slope sediments relative to the frontal arc, they indicate stability of the upper-slope discontinuity for periods of 40 m.y. or more.

Upper-slope sediments appear to be incorporated into the continent within broad prisms of subduction materials. In the eastern Aleutians, Burk (1965, 1973) has described several such prisms, separated by steep faults that rotate the prisms away from the trench. These prisms become successively older toward the north and are attributed to progressive subduction, but data are lacking by which to interpret the significance of the individual prisms. Matsuda and Uyeda (1971) suggest a similar stepwise progression of subduction in Japan, in which the area between the volcanic front and the trench becomes the frontal arc during successive subduction.

In the Mariana system, the upper-slope discontinuity has remained fixed probably since the Eocene and perhaps longer (Karig, 1971a), but three pulses of subduction are suggested by the volcanic activity and marginal basin history. Along the Tonga-Kermadec system, and perhaps in other areas, the situation appears similar. The apparent contradiction in correlation of the upper-slope position with pulses might be explained either by the reactivation of the same trench interface in arc systems where the accretion rate is slow, or more likely, by attributing the pulses of marginal basin and volcanic activity to discontinuities in subduction rates rather than to absolute subduction halts.

In this paper, the upper-slope discontinuity is used as a stable rear boundary to the accretionary prism that is presently being developed. An upper limit to the time spanned by this accretion is given by the age of the youngest subducted and accreted rocks exposed on the frontal arc or by the oldest shelf sediments overlying them.

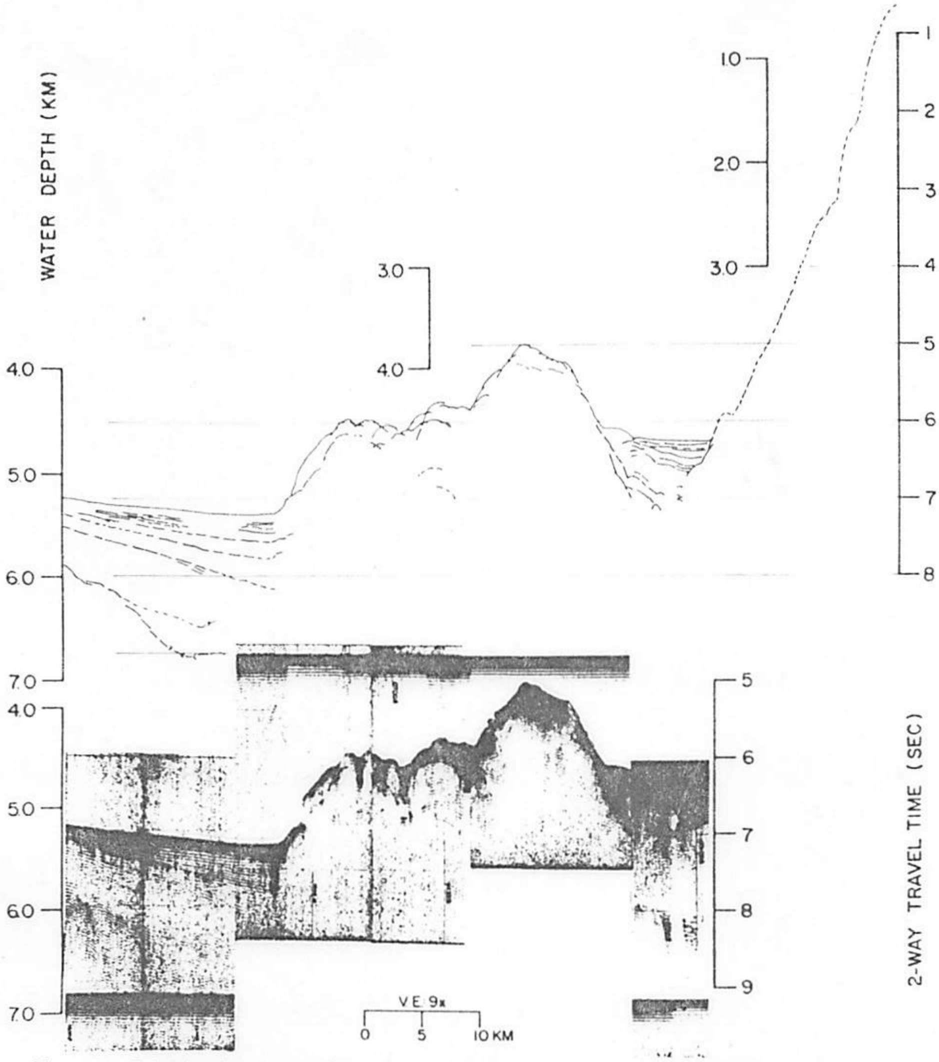


Figure 4. Seismic reflection profile and interpretation across the inner slope of a nascent trench east of Luzon. Notice the very great relief of the upper slope area. The small accretionary prism is built of deformed insular rise and lower slope deposits (unpublished core data from S.I.O. Cruise Tasaday). Younger deposits are ponded behind the small trench slope break.

The Volcanic Chain as a Tectonic Reference

A second possible tectonic reference for the growth of arc systems is the volcanic chain. This marker would be useful over longer time spans than the upper slope discontinuity would be and might provide information concerning the average rates of accretion.

The volcanic chain or front describes a remarkably smooth trace in most arc systems and generally lies above the 125- to 175-km-deep earthquakes of the seismic zone. Migration of the volcanic chain both toward (Matsuda and Uyeda, 1971) and away from (Dickinson, 1973a; Martin-Kaye, 1969) the subduction zone relative to the crust beneath has been proposed. Where arc systems have most clearly been accreting material and have not suffered internal tectonic disruption, the axis of maximum igneous activity has either remained fixed or has shifted rearward at average rates of up to 2 km/m.y. (Dickinson, 1973a;

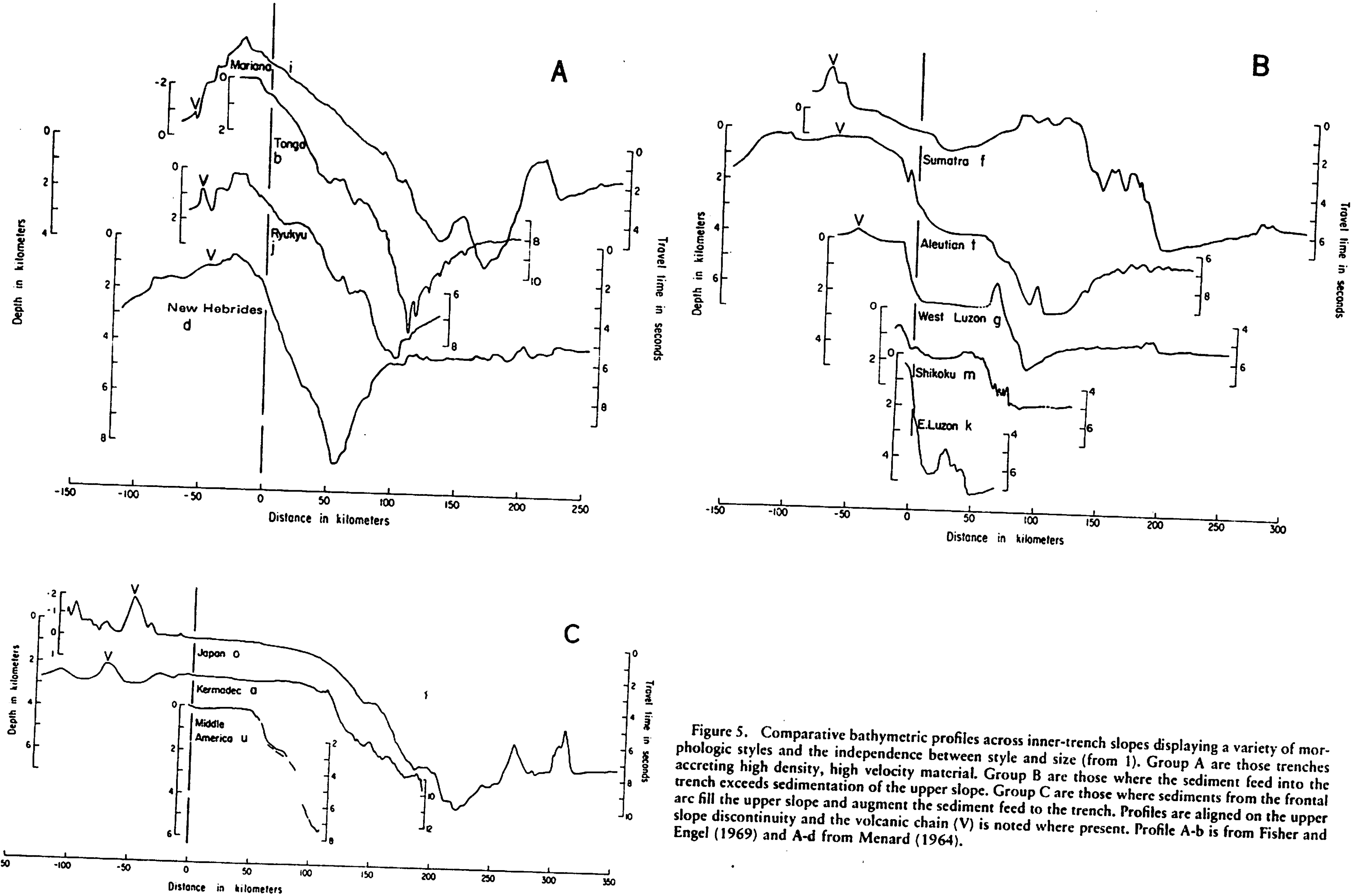


Figure 5. Comparative bathymetric profiles across inner-trench slopes displaying a variety of morphologic styles and the independence between style and size (from 1). Group A are those trenches accreting high density, high velocity material. Group B are those where the sediment feed into the trench exceeds sedimentation of the upper slope. Group C are those where sediments from the frontal arc fill the upper slope and augment the sediment feed to the trench. Profiles are aligned on the upper slope discontinuity and the volcanic chain (V) is noted where present. Profile A-b is from Fisher and Engel (1969) and A-d from Menard (1964).

Kawano and Uyeda, 1967; Peck and others, 1964).

The cause of the apparent rearward migration of the volcanic chain could be either a trenchward shifting of the frontal arc crust, relative to a volcanic source fixed relative to the mantle and Benioff zone, or a rearward shift of the seismic zone relative to the mantle and crust above. Dragging of the upper plate into the subduction zone is precluded by accretion rather than erosion on the inner trench slope. Some form of crustal extension along the volcanic chain is another alternative. Extension within and behind the volcanic chain, which results in the development of marginal basins, drives the entire arc system forward as a unit and does not appear applicable. Crustal extension resulting from plutonism beneath the volcanic chain does occur, but in the better mapped volcanic zones is not of the necessary scale (Peck and others, 1964; C. A. Hopson, 1974, personal commun.). Rearward shift of the 125- to 175-km-deep part of the seismic zone remains a possible solution but is not easily tested.

In general, volcanic chains can be fairly stable or tend to shift rearward during periods of as much as 50 m.y. or more. The increase of the volcanic-chain–trench separation is a function of both the migration of the volcanic chain and the growth of the inner-trench slope (Dickinson, 1973a). It is thus a poor reference by which to measure accretion.

GEOMETRIC VARIATIONS OF THE ACCRETIONARY PRISM

The accretionary prism, bounded by the upper-slope discontinuity behind and by the seismic zone beneath, is discussed most easily in two parts. The upper section, above the trench floor, is analyzed using morphologic, seismic reflection and refraction profiles, and geologic data. Analysis of the deeper section, for which far fewer data are available, centers on the behavior of the seismic zone beneath the prism during subduction.

Morphology and Shallow Structure

If the New Hebrides and East Luzon trenches approximate initial conditions of subduction zones, accretionary enlargement can assume one of three general configurations, or some morphologic transition between these (Fig. 5). The simplest type, represented by the Tonga, Mariana, and parts of the Bonin and Kermadec arc systems, displays a two-part slope, consisting of an upper slope apron that is separated from the steeper lower slope by a simple slope break (Fig. 5A). The acoustically opaque material constituting the basement on which the upper slope apron rests appears from available refraction studies (Murauchi and others, 1968) and from dredge hauls (Yagi, 1960; Fisher and Engel, 1969; Petelin, 1964) to consist largely of basalt and ultramafic rocks. Although ocean-floor pelagics have not been described from dredge hauls, these may be present but perhaps have been washed from the dredge during retrieval. On several profiles where the effects of down-slope sediment redeposition have not masked the internal structure of the apron, progradation of the sediment pile over an irregular but shallow-dipping basement is observed (Fig. 3; Fischer and others, 1971). The uppermost sediment unit spills over the trench-slope break, suggesting that the apron can extend trenchward only as the basement platform grows by accretion.

In a second major type of configuration, the trench-slope break is a ridge, behind which a sediment-filled trough develops (Fig. 5B). The Sumatra, Java, Luzon, central Aleutian, and Shikoku arc systems display this morphology. Seismic refraction studies (Ludwig, 1970; Raitt, 1967; Den and others, 1968) and the geology of islands on the trench-slope break indicate that the material underlying this form of accretionary prism is largely sedimentary and contains only minor amounts of igneous rock.

A third variety of inner trench slope displays a trench-slope break along the edge of a broad continental shelf, at depths up to several kilometers (Fig. 5C). The eastern Aleutian, Japan, and sections of the Middle America arc systems are in this category. A structural high at the shelf edge, forming the trench-slope break, is sometimes expressed morphologically but more often is discernable only on seismic-reflection profiles (von Huene and others, 1971; Ross and Shor, 1965).

There is no correlation between the type of prism morphology and the distance from the trench to the upper slope discontinuity (Fig. 5). The upper slopes in the Skikoku, Aleutian, and Sumatra systems all have ridge and trough morphologies, but with very different widths. The upper slopes of the Mariana and Tonga arcs, although seemingly primitive, are wider than the ridge-trough upper slopes of many arc systems. The relief of the upper part of the accretionary prism above the trench floor is as important as the width in determining its bulk. This relief varies from about 2 km in the Shikoku system to more than 6 km in the Mariana system. Relief increases roughly with the width of the upper slope area, but not in a simple way. The Tonga and Mariana systems have an accretionary prism whose upper section is relatively thick and narrow, whereas that of the Sumatra system is broad and thin.

Factors Affecting the Size and Shape of the Accretionary Prism

The most obvious factors affecting the amount and style of accretion are time and the availability of sediment. The upper-slope discontinuity–trench separation and other gauges of accretion generally increase with parameters that reflect increasing duration of subduction, but the great scatter in these relationships (Dickinson, 1973a) indicates large variations in rates of accretion. These rates of accretion depend on rates of sediment influx, which are only partly related to subduction rates. For instance, the southward widening of accretionary prisms in the Kermadec and Caribbean arc systems are clearly the effects of high sediment feed rates from the adjacent continents rather than of changes in the duration or rates of subduction along the arcs. The morphologic variations of the accretionary prism seem to be more dependent upon relative rates of sedimentation from the various sources feeding the subduction zone than on rate or duration of subduction. Sediment that passes into the accretionary prism at the base of the inner-trench wall can be derived from either side of the trench and by pelagic, hemipelagic, and density-flow mechanisms.

The basal section of the sediment pile entering the subduction zone consists of pelagic or terrigenous sediments deposited on the downgoing plate before it begins to descend. These vary in thickness with the age of the plate, with the productivity of the waters beneath which it has traveled, and with available terrigenous sources. Sediment thickness varies from less than 200 m on the young crust subducted into the Middle America Trench (Frazer and others, 1972; Riedel and others, 1961) to more than 3 km where the Bengal fan is subducted in the Sumatra Trench (Curray and Moore, 1971). The rate at which this sediment is fed into the subduction zone is a function of its thickness and the component of the subduction rate acting perpendicular to the trench axis.

As the downgoing plate, with its sediment cover, descends into the trench, it becomes covered by a wedge of clastic sediments that is fed to the trench from shallow depths through canyon systems and by other downslope mechanisms (Piper and others, 1973; Ross 1971a, 1971b; Anikouchine and Ling, 1967). In all but the most slowly subducting trenches, the clastic wedge is less than a few tens of kilometers wide and a kilometer or so thick. The majority of trenches have either no such wedge, or more likely, wedges so narrow that they are unresolvable by surface acoustic techniques (Fisher and Hess, 1963). Although the size of the clastic wedge may be quite small at any instant in time, the residence time of any piece of sediment in the wedge is quite short, so that the total quantity of sediment fed to the subduction zone may be large. A direct measure of the relative amounts of sediment supplied to the subduction zone by the wedge and by the downgoing plate cover is given by the

thickness of each type of sediment at the inner-trench wall.

The wedge will remain the same size if the sediment influx (sedimentation rate × wedge width) is balanced by the outflow (component of subduction rate in horizontal plane and perpendicular to trench × wedge thickness corrected for compaction). Changes in either sedimentation or subduction rate will be reflected by a change in the wedge size, but simple calculations show that the new equilibrium size will be logarithmically approached within a few million years in most cases.

The few available sedimentation rates in trenches (Table 1) indicate that there is no inconsistency between the size of the wedge and the rate of sedimentation, even assuming a steady-state condition. The conclusion that the wedge in the Peru-Chile Trench represented a time span much greater than that allowed by calculated subduction rates (Scholl and others, 1970) was based on less direct methods, which are felt to be less reliable.

Scholl and Marlow (1972, 1974) have suggested that the turbidite wedges are a result of lowered Pleistocene sea levels and of glacial erosion. They claim that, without these effects, most Pacific trenches would be devoid of turbidite fills. Although it is undoubtedly true that Pleistocene glaciation increased the supply of terrigenous sediment to the trenches, it does not necessarily follow that the observed abundance of terrigenous and volcanic-rich turbidites in mélange complexes of all ages requires a site other than the trench wedge for their origin.

Trenches with substantial turbidite wedges are not restricted to glacial regions or to those with broad shallow shelves, although such wedges are more common in those areas. Trench wedges occur in areas where there was little or no glaciation and where there are very narrow shelves (Fig. 1). A turbidite wedge more than 5 km wide and 400 m thick occupies sections of the axis of the southern New Hebrides Trench where the only terrigenous sources are the small recent volcanos of Matthew and Hunter Islands.

The predominance of turbidites in most accretionary prisms exposed along continental margins is most probably the result of preferential accretion of the more rigid trench wedge turbidites and subduction of the lower, highly porous section to deeper levels (Karig, 1974b). Such a décollement has been observed in DSDP Site 298 in the Nankai Trough off Shikoku (Ingle and others, 1975).

In oceanic arc systems, where the turbidite influx is relatively small, the accretionary prism should be constructed largely of pelagic sediments and igneous rocks, but accreted materials are very seldom exposed in these arc systems. Where collision processes have exposed accretionary prisms of oceanic arcs, as in eastern Mindanao (Melendres and Comsti, 1951; Irving, 1950, 1952; Hamilton, 1973; Karig, 1975), they do contain a large proportion of pelagic and igneous material.

The Franciscan complex, in which turbidites predominate over pelagic sediments and basaltic rocks (Bailey and others, 1964), is still best attributed to subduction in trenches. The nearly ubiquitous association of pelagic shales or chert with pillow basalts (Bailey and others, 1964) implies that these sediments were deposited in an ocean basin rather than on the upper trench or continental slope. The fact that these diagnostic pelagic-shale and pillow-basalt sequences are intercalated throughout a complex of highly deformed rocks constitutes a strong argument that the associated turbidites originated in a trench.

Another unresolved problem concerning turbidite sedimentation and deformation is the importance of slumping and gravity sliding on the inner trench slope (Chase and Bunce, 1969; Scholl and von Huene, 1970; von Huene, 1972). Shear strength tests (Ross, 1971b) have suggested that the pelagic and hemipelagic material deposited on the inner trench wall may be unstable and susceptible to slumping. Small mud balls and semi-lithified clasts incorporated in the turbidites cored from several trenches (Anikouchine and Ling, 1967; J. C. Moore and Karig, in prep.) are evidence that such displacement occurs. In sequences thought to represent trench-wedge sediments, slump folds have been described (Moore, 1973), but few instances of mass gravity movement of previously accreted material have been documented.

Von Huene (1972) has attributed irregular topography and tilted sediment ponds on the inner slope of the eastern Aleutian Trench to large-scale slumping and backward-rotating slide blocks. Because the eastern end of the Aleutian system receives a much greater sediment influx than do most other arc systems (Plafker, 1972), more deposition on the lower wall and more slumping of this material is expected. Near-bottom investigations in the central part of the Aleutian arc system (Grow, 1973a) and a detailed survey in the Nankai Trough (Ingle and others, 1975) found linear ridges on the lower trench wall rather than the equi-dimension topography suggested by von Huene (1972).

TABLE 1. SEDIMENTATION RATE AND TURBIDITE WEDGE SIZE IN TRENCHES

Example	Aleutian (von Huene, 1972)	Middle America (Ross, 1971)	Shikoku (Ingle and others, 1975)
Width of wedge (km)	30	13	17
Max. thickness of wedge (km)	0.8	1.25	0.7
Subduction rate (km/m.y.)	60	65 (Le Pichon and others, 1973)	20
Sedimentation rate (km/m.y.)	1 to 2 (observed)	1 (observed)	0.8 (calc)

The ponded and tilted sediments seem more likely to have been deposited between active thrust units (Fig. 7A). In both the Nankai Trough (Hilde and others, 1969; Ingle and others, 1975) and the eastern Aleutian Trench, the pond size and general slope sediment thickness increase upslope, which is to be expected if they develop in increasingly older thrust units upslope. It is assumed here that slumping of material from the inner wall is generally restricted to the unconsolidated cover and that it forms one end of the range of mechanisms by which shallow-water sediments are fed into the trench wedge. Other sources of feed into the trench, including pelagic and hemipelagic biogenous and detrital sediments, are generally less important than those already discussed.

The amounts and relative proportions of sediments fed into the subduction zone and to the upper-slope area from various sources determine the shape of the accretionary prism. Arc systems in which the accretionary prism is subdued and contains a large fraction of oceanic basement rocks (type A of Fig. 5) result from the subduction of lithosphere with a thin sediment cover, together with a low rate of turbidite influx to both the trench and the upper slope. In arc systems where the feed rate of sediments on the downgoing plate is higher and the turbidite influx from the frontal arc is relatively low, the trench slope break develops into a high ridge of deformed sediment (type B of Fig. 5). The deep trough behind reflects the inability of land-derived sediments to fill this trap. Those arc systems with high terrigenous feed rates pour enough sediment into the trench wedge to produce large accretionary ridges and also to keep the upper slope basin filled so that a shelf or terrace develops (type C of Fig. 5).

Configuration of the Seismic Zone and Deep Structure of the Accretionary Prism

The seismic zone, which forms the lower boundary of the accretionary prism, is assumed, in its upper section, to mark the zone of shearing between the two lithospheric plates (Isacks and Molnar, 1971). The trench marks the intersection of this interplate boundary with the ocean floor. Trench depth and position are functions of a surprisingly few variables. Rate of subduction does not appear to strongly affect trench depths. A large southward decrease in subduction rate is not expressed in trench depths along the Bonin and Mariana-Yap-Palau system or along the Tonga-Kermadec system beyond the influence of sedimentation from New Zealand. Shallow trenches, such as the Middle America and Java, are among more rapidly subducting examples.

The most clear-cut factor controlling trench depth is the general depth of the top of the downgoing plate before it descends into the trench. Thus, along one or more arc systems where the shape of the inner and outer trench walls are similar, the depth to the oceanic basement at the trench axis increases directly as the water depth in the basin being subducted (Le Pichon and others, 1973). Profiles along a given arc system, normalized so that the upper sections of the downgoing plate are superimposed, demonstrate that the trench depth and position are also functions of local differences in accretion along the inner-trench wall (Karig and others, in prep.).

The shape of the upper part of the downgoing plate, however, is not constant among the various arc systems (Fig. 6). Mechanical properties of the subducted lithosphere (Le Pichon and others, 1973; Watts and Talwani, 1974) are probably responsible for a part of this variation in shape. In addition, young plates and those of marginal basin origin have smaller radii of curvature than do older oceanic plates. The shape of the downgoing plate also appears to be strongly controlled by the loading due to the overlying accretionary prism (Karig and others, in prep.).

In nearly all arc systems, the seismic zone, regardless of its shape, is at depths of 125 to 175 km beneath the volcanic chain or front. Between the volcanic chain and the upper-slope discontinuity, the seismic zone begins to flatten sharply (Mitronovas and others, 1969; Karig, 1971b; Fedotov, 1968), but the range over which the flattening occurs and the shapes of this upper zone vary widely (Fig. 6). In the New Hebrides, the change in seismic zone dip from 70° at depth (Dubois, 1971; G. Pascal, 1974, personal commun.) to 8° at the trench axis (Fig. 6) occurs rapidly in horizontal distances of less than 100 km. In contrast, the seismic zones beneath the eastern Aleutian (Plafker, 1972; Lahr and Page, 1972; Lahr, 1973, written commun.) and southern Kermadec (Hamilton and Gale, 1968) systems begin to flatten sharply under the frontal arc and continue at dips of less than 20° for several hundred kilometers before surfacing at the trench with dips of 2° to 4° (Fig. 6). Some systems, such as the Mariana (Katsumata and Sykes, 1969) and Kermadec (Sykes, 1966) arcs, have very steep, deeper seismic zones and broad upper sections, but others with equally steep lower sections (New Hebrides; Dubois, 1971; and Solomons; Denham, 1969) have narrow upper sections. There appears to be no relationship between the dip of the lower part of the zone and the configuration of the shallower section.

The shape of the upper section of the seismic zone is constrained by the slope of the downgoing plate at the trench axis and by the position of the deeper seismic zone where hypocenters can be fairly well located. Shallow hypocenters seldom aid in defining the upper seismic zone because of scatter resulting from inhomogenous shallow velocity structure and from the lack of restriction of seismicity to the interface between plates. Some additional control for the position of the upper section of the seismic zone is obtained from seismic refraction profiles and from focal mechanisms.

The small depth range to the seismic zone beneath the volcanic chain or volcanic front implies that the upper end of the deeper part of the Benioff zone remains stationary or migrates slowly rearward over periods of up to 200 m.y. The width of the upper section increases directly as the separation between the trench and volcanic chain (Fig. 8). In part, this reflects the rearward movement of the volcanic centers, but it is predominantly a correlation with the amount of accreted material. There is also a correlation between the width of the accretionary prism and the width of the flattened zone, but, as illustrated in the eastern Aleutian system, the flattened section of the seismic zone spans several active and inactive accretionary prisms representing more than 150 m.y. of subduction (Burk, 1965). The correlation of the flattened upper section with the width of accreted material and with the outward migration of the gravity minimum related to the depressed slab (Karig and others, unpub. data) is the strongest argument favoring depression of the oceanic lithosphere by the weight of accreted material and upper slope sediments (Fig. 6).

The amount of material fed to the subduction zone that enters the accretionary prism can be determined, in principle, by comparing the amount of sediment with the increase in size of the accretionary prism from an initial configuration. The volume of the prism must be corrrected for sediment compaction during accretion and must be reduced by the amount of sediment

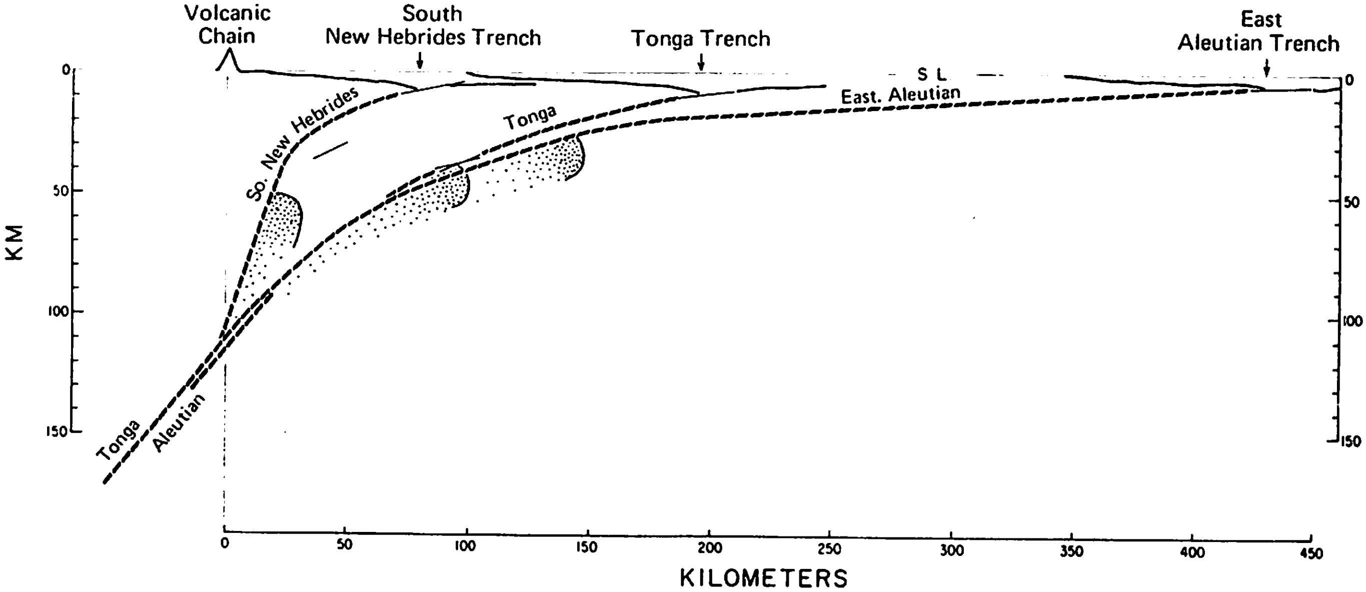


Figure 6. Configurations of the upper sections of three better-known Benioff zones, normalized to the volcanic chain, demonstrating the pronounced flattening with the growth of the accretionary prism. Control is provided by earthquake hypocenters (dotted areas) and by the dip of the downgoing plate at the trench axis and focal mechanism (thin lines). Data sources are, for the New Hebrides: Dubois (1971), Johnson and Molnar (1972); for the Tonga: Mitronovas and others (1969), Isacks and others (1968); and for the Aleutian: Lahr (1972, personal commun.); G. G. Shor, *in* von Huene (1972).

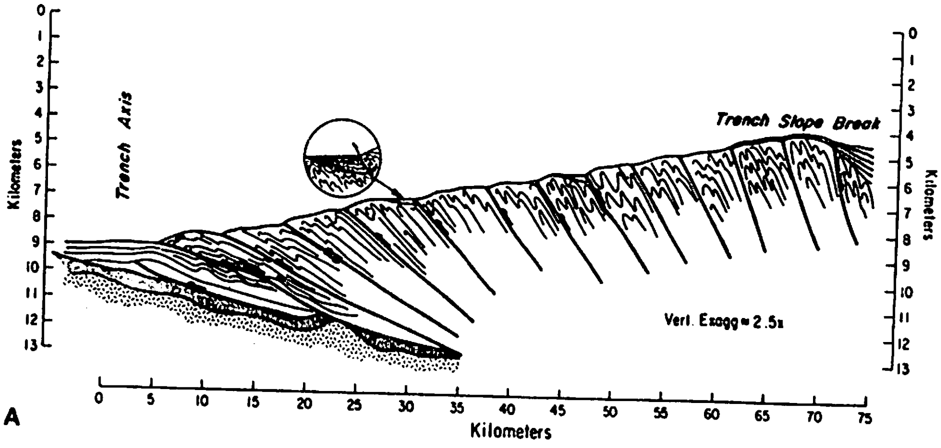
TABLE 2. ACCRETIONARY PRISM VOLUME CALCULATIONS*

Trench	E. Luzon	Shikoku	S. New Hebrides	Tonga	Mariana	E. Aleutian†
Duration of subduction pulse	<<1 m.y.	10 m.y.	3 m.y.	45 m.y.	45 m.y.	40 m.y.?
Average subduction rate	?	1.5 cm/yr	5 cm/yr	7 cm/yr	6 cm/yr	5 cm/yr
Average sediment thickness	2 km	1.5 km	0.6 km	≤0.4 km	0.4 km	0.5 km
Total sediment feed (40% sediment porosity reduction assumed during subduction)	30 km²	125 km²	50 km²	700 km²	600 km²	600 km²
Accretionary prism area (minus slope sediments)	50 km²?	550 km²	500 km²	1,200 km²	2,000 km²	1,200 km²

* Per unit length of arc.
† After von Huene, 1972.

deposited on the inner slope. Unfortunately, the present resolution of sedimentation and subduction rates and of the seismic zone configuration permits only approximate calculations.

The most reliable data show, however, that the accreted volume on the upper plate significantly exceeds the volume of sediment fed to the trenches (Table 2). Accretion of at least a part of the oceanic second layer, required by these calculations, would explain the thickened sections of high-velocity material below the inner slopes of the Shikoku (Den and others, 1968) and eastern Aleutian (G. G. Shor, *in* von Huene, 1972) and the magnetic sources beneath the central Aleutian slope (Grow, 1973a). It is very unlikely, therefore, that sedimentary material is carried down the seismic zone to the area feeding the volcanic chain. Effects of sediment on magma composition are more likely accomplished by interaction of the magma with earlier subducted metasediments at shallow levels.



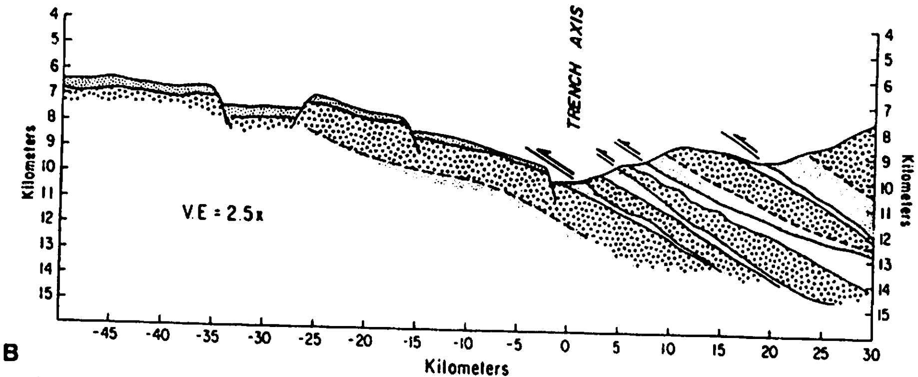


Figure 7. Speculative modes of deformation of accreted material on the lower branch wall (Karig, 1974b). A. Accretion of thick sediment cover or thick trench-wedge section. The upper turbidite section tends to be sheared off along the weak, high-porosity uppermost pelagic section and rides over the trench wedge, probably aided by high pore pressures. B. Accretion of thin pelagic sediment cover and oceanic crust. Slabs of the upper oceanic crust are intermittently sheared off when topographic irregularities enter the trench.

Mode of Deformation within the Accretionary Prism

Reflection profiles across active subduction zones and mapping in older exposed subduction terranes suggest a wide variation in the structural style and lithologic content of accretionary complexes. Some, such as much of the southern part of the Franciscan complex, show relatively little folding and much shearing and are comprised dominantly of turbidites and secondarily of pelagic sediments and basement rocks (Bailey and others, 1964; Hsü, 1969). Other examples show more intensely folded turbidites with only a small percentage of igneous rocks (Moore, 1973). Still others seem to be comprised predominantly of pelagics (Melendres and Comsti, 1951). This variation appears to reflect differences in sediment cover on the downgoing plate, in rates of subduction, and perhaps other factors, such as obliquity of subduction.

Processed multi-channel seismic reflection profiles over trenches that subduct thick sediment sections (Beck, 1972; Beck and Lehner, 1974) reveal that the sediments are stripped off the oceanic basement and support the idea that accretion occurs in fold or thrust packets (Fig. 7A; Chase and Bunce, 1969; Karig, 1974b). Deep-sea drilling and related investigations in the Nankai Trough (Shikoku system) demonstrated that trench-wedge turbidites are accreted in nearly recumbent fold units that are expressed on the lower slope as linear ridges (Ingle and others, 1975; Moore and Karig, 1975).

Dewatering and rigidification of the accreted sediments begins during the very early stages of deformation, even before the unit is effectively removed from the downgoing plate, in a proto fold region (Moore and Karig, 1975). This response, in which the well-developed folds sometimes face away from the trench (Silver, 1972), seems typical of the slower subducting trenches with thick sediment fills (for example, the Lesser Antilles, Shikoku, West Luzon, and Cascades). In more rapidly subducting trenches with high sediment feed, dewatering might not occur until more deformation had occurred, and then a different structural response could be expected.

By the time the deformed sediments are exposed on the trench-slope break, they form steeply dipping, generally isoclinal folds (Moore, 1973). In some cases (Tabor and others, 1970; Tabor, 1970, personal commun.; Stewart, 1970), the fold units, although internally deformed, are separated by zones of much more intense deformation. These shear zones may form during the initial décollement of trench-wedge turbidites or may reflect the decreasing intensity of deformation in increasingly competent material as it moves toward the trench-slope break. Subsequent accretion beneath and horizontal compressive stress

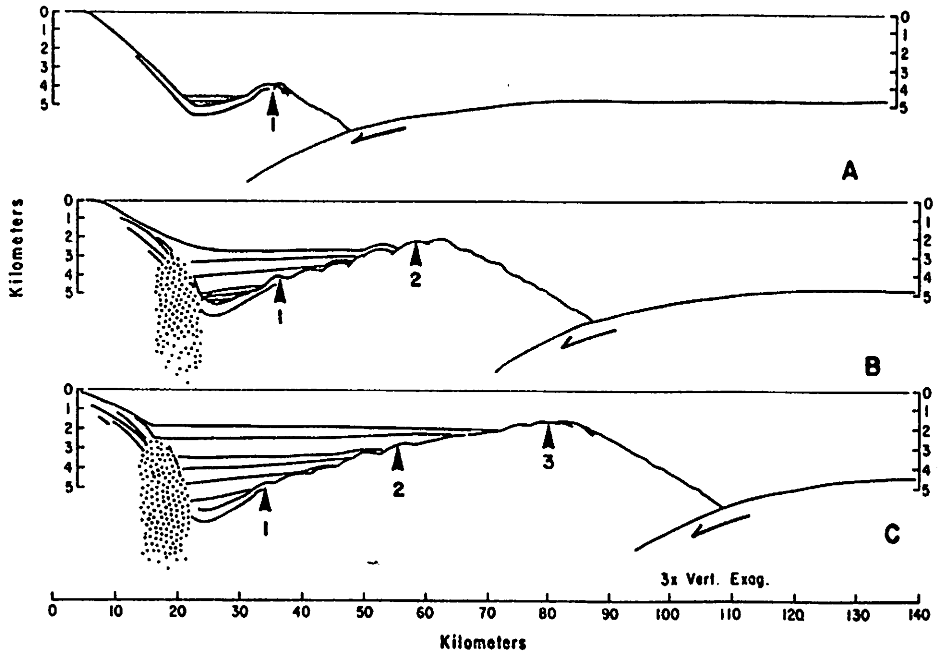


Figure 8. Hypothetical "building out" of accretionary prism, showing migration of the morphology over the accreted material. The original trench slope break becomes part of the subsiding basement of the upper slope area. Numbers mark arbitrary successive locations of the trench-slope break.

can explain both the marked rotation of the fold units and the rearward tilt of sediments in the ponds on the lower trench slope.

The style of deformation in arc systems which subduct plates with thin sediment covers may be similar to that displayed in the southern part of the Franciscan complex, with relatively unfolded and undeformed slabs of sediment and basement separated by shear or mélange zones (D. L. Jones, 1973, personal commun.; Karig, unpub. field mapping). Igneous rocks, dredged from the inner walls of this type trench, suggest that thrust slices which include crustal and sometimes mantle material are successively tucked under the inner wall (Fig. 7B). A linear ridge, more than 50 km long, which divides the Mariana Trench into a double axial trough near 13.5° N., 146.5° E. (Karig, 1971a) and another in the Peru Trench (Kulm and others, 1973a, 1974) may represent such thrust slices. Irregular basaltic bodies, some of which show columnar jointing, are imbedded in pelagic sediments in one southern Franciscan locality (Karig, unpub. mapping), suggesting that large-scale topographic irregularities might also be sheared off and accreted (Karig, 1974b).

The zone of uplift due to accretion does not extend far behind the trench slope break, where a progressively enlarging sediment body accumulates (Fig. 8). In the earlier stages of accretion, the upper-slope sediment body enlarges as the accreted mass builds upward and outward (Figs. 4, 5). Subsidence of the upper slope is only relative to the trench slope break. Subsidence relative to sea level does not seem to occur until the accretionary prism becomes quite wide and is best ascribed to the loading effects by the prism on the downgoing plate.

At this stage, the trench-slope break appears to mark the point where thickening of the accretionary prism is balanced by depression of the seismic zone. The cause of displacement along the upper-slope discontinuity is not obvious, but it is suggested that this boundary marks the mechanical leading edge of the upper plate and that the accretionary prism is nearly mechanically uncoupled.

CONCLUSIONS

Systematic profiles across the inner slopes of active trenches demonstrate the wide variation in size and style of accretionary prisms. When these morphologic variations are viewed together with other evidence, a logical dependence between morphological and structural factors and the type and rate of material feed is observed. The resulting rock mass, which preserves the record of subduction, will carry the effects of these variations, and, unless the correct relationship is known, correlation between contemporary arc systems and deeply eroded orogenic zones will be impossible.

The variations in contemporary arc systems also supply information bearing on problems of continental growth. Rather surprisingly, over time intervals of up to 50 m.y. or more, the volcanic chain does not migrate seaward, as does the trench. Instead, it often migrates to the rear (Dickinson, 1973a) and, together with the dominating effects of accretion, results in Benioff zones with very broad and flattened upper sections. In the eastern Aleutian system, no permanent seaward migration of the volcanic chain has occurred for more than 150 m.y., and the distance from volcanos to trench now exceeds 400 km. This displays the extent to which this process can proceed.

If the overstepping of the low P/T thermal regime (associated with the volcanic chain, over the high P/T zone, which probably exists beneath the trench slope break area) does occur, it must happen over a greater time span. Simple accretion has not persisted for such great periods of time along most plate edges. Rather, tectonic disruption by collision, longitudinal shifting of accreted zones during oblique subduction, and polarity reversals overprint the simple picture.

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