Sedimentary facies associations within subduction complexes

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Michael B. Underwood & Steven B. Bachman

SUMMARY: Sedimentation patterns within modern subduction zones are complex and variable, and do not necessarily follow models of submarine fan sedimentation. Environmental reconstructions within ancient subduction complexes should follow modern analogues as closely as possible and consider several criteria, including turbidite facies associations, vertical depositional cycles, regional palaeocurrent patterns, and in many cases, structural style and sandstone petrology.

Important variables in trench sedimentation include the volume and texture of sediment entering the trench and the distribution of major sediment sources, especially large submarine canyons. Sediment transport in the trench is commonly longitudinal, although locally, such as at the mouth of a submarine canyon, flow may be at a high angle to the continental margin.

Patterns of trench-slope sedimentation depend largely upon the topography of the slope. In general, coarse sediment is either trapped behind tectonic ridges (within slope basins) or bypasses the slope via submarine canyons. Background sedimentation is dominated by hemipelagic settling. Current directions are commonly at a high angle to the margin, but longitudinal flow may occur within large elongate slope basins. Major facies associations include submarine-canyon, slope, mature-slope-basin, and immature-slope-basin.

Classification schemes for turbidites and related resedimented deposits (e.g. Walker & Mutti 1973; Mutti & Ricci-Lucchi 1975; Ricci-Lucchi 1975) are applicable to deep-sea deposits regardless of the geometry of the depositional system. Turbidite facies are commonly used to describe specific facies associations, such as slope, submarine fan, and basin plain (e.g. Walker & Mutti 1973; Bouma & Nilsen 1978; Ingersoll 1978a; Walker 1978; Pescadore 1978). In these models, analogies are drawn between stratigraphic sequences of turbidites and modern depositional geometries. However, submarine fan models (Normark 1970, 1978; Nelson & Kulm 1973; Nelson & Nilsen 1974; Nilsen 1980) are not applicable to all modern sedimentary basins, particularly elongate troughs (e.g. Hsu et al. 1980; Pilkey et al. 1980).

Meaningful environmental reconstructions within ancient subduction complexes depend upon well-established modern analogues, and should, as closely as possible, be patterned after the geometry of those analogues. For this reason, we first discuss the diversity of sedimentary processes and depositional systems within modern subduction zones, where several types of sediment bodies, including submarine fans, are developed. The sedimentological characteristics of several examples of ancient trench and trench-slope deposits are also considered. We then model turbidite facies associations for the major depositional settings. Because many trench and trench-slope environments have not been adequately sampled, our facies associations in some cases are largely inferential, and designations are based upon the types of deposits logically expected for a given topography and sediment input. In this paper, turbidite facies terminology is used in only the most general sense (Table 1), following the classifications of Walker & Mutti (1973) and Ricci-Lucchi (1975).

The deformation associated with subduction and/or accretion commonly hampers the environmental reconstruction of ancient trench and trench-slope deposits. However, the scale of structural dismemberment, in many cases, is such that identifiable depositional cycles and facies changes are preserved. Nevertheless, several criteria must generally be considered before contrasting sedimentary environments (e.g. trench floor versus slope basin) can be recognized within structurally complex terranes (e.g. Bachman 1978, 1981; Moore 1979; Moore & Karig 1980; Moore et al. 1980).

Trench-floor deposits

Surface samples and Deep Sea Drilling Project (DSDP) cores show that modern trench sediments generally consist of varying proportions
TABLE 1. Classification of turbidites and associated deposits, after Walker & Mutti (1973) and Ricci-Lucchi (1975)

<table>
<thead>
<tr>
<th>Facies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Thick to massive, lenticular beds of coarse sandstone, pebbly sandstone, and conglomerate</td>
</tr>
<tr>
<td>B</td>
<td>Massive to thick-bedded, medium- to coarse-grained sandstone</td>
</tr>
<tr>
<td>C</td>
<td>Thick-bedded, classical sandy turbidites, with graded beds at base</td>
</tr>
<tr>
<td>D</td>
<td>Thinner-bedded and finer-grained turbidites, including lutite turbidites; basal graded beds absent</td>
</tr>
<tr>
<td>E</td>
<td>Thin- to medium-bedded, coarse- to fine-grained sandstone, with irregular wedge-shaped beds and cross-stratification</td>
</tr>
<tr>
<td>F</td>
<td>Chaotic deposits formed by slumps and slides</td>
</tr>
<tr>
<td>G</td>
<td>Hemipelagic mudstone and shale</td>
</tr>
</tbody>
</table>

Sedimentary sequences underlying the trench turbidites commonly include abyssal pelagic clay or biogenic ooze and hemipelagic sediments (Ross 1971; Kulm, von Huene et al. 1973; Piper et al. 1973; Kulm & Fowler 1974; von Huene 1974; Karig, Ingle et al. 1975; J. C. Moore & Karig 1976; Moore, Watkins et al. 1979; von Huene, Aubouin et al. 1980; McMillen & Haines 1981; McMillen et al. 1981). This sequence would not be expected, however, if large volumes of terrigenous turbidites are deposited on the abyssal floor seaward of the trench, as with the Bengal Fan (Curray & Moore 1974), or if the trench floor is starved of coarse terrigenous material, as is the Japan Trench (Langseth, Okada et al. 1978; Arthur, von Huene et al. 1981). The geometry of trench fill is dependent

Fig. 1. Bathymetric map and trench-axis profile of the Middle America Trench from Banderas Bay to Rio Balsas, Mexico. General bathymetry (in metres) is modified from Fisher (1961). Axial profile incorporates data from Fisher (1961), Ross & Shor (1965), and unpublished reflection records from the following sources: Scripps Institution of Oceanography cruises Scan-11, Cocotow-4, Iguana-1, Iguana-5, Lamont-Doherty Geological Observatory cruise Vema-28, and Glomar Challenger transit to Deep Sea Drilling Project Leg 66 drilling sites. Axial-depth values are in corrected metres. Sediment thickness was calculated using V = 2.0 km s⁻¹, such that 0.5 s penetration = 500 m of sediment. See Fig. 2 for explanation of symbols. Modified from Underwood & Karig (1980).
upon the interaction between sediment supply and convergence rate, the distribution and relative size of submarine canyons along the trench slope, and the bathymetric relief on the downgoing oceanic plate (Schweller & Kulm 1978; Underwood et al. 1980). The great bulk of terrigenous material reaches the trench floor via large submarine canyons that are deeply incised into the trench slope (Underwood & Karig 1980). The sand/mud ratio of trench deposits, in many cases, is thus dependent upon the proximity of submarine canyons to the site of deposition. After sediment reaches the floor of the trench, axial transport involving distances of hundreds of kilometres is indicated (Scholl 1974; Kulm et al. 1977; Schweller & Kulm 1978).

Submarine canyons and sediment bypassing

Large submarine canyons are prominent features along the landward slope of the northern Middle America Trench (Figs 1 & 2; Fisher 1961; Underwood & Karig 1980; Shipley et al. 1980; McMillen & Haines 1981; McMillen et al. 1981) as well as the Oregon-Washington continental margin (Carlson & Nelson 1969; Barnard 1978; Kulm & Scheidegger 1979) and the southern Chile Trench (Scholl et al. 1970; Hayes 1974; Prince et al. 1980). These canyons have been responsible for funnelling terrigenous sediment from the continental shelf directly to the trench floor, thereby bypassing the trench slope. Sediment bypassing was particularly effective during low stands of sea-level associated with Pleistocene glacial epochs (e.g. Scholl et al. 1977; Barnard 1978). Data from current-meter studies indicate that at least one of the canyons off Mexico (Rio Balsas Canyon) is still active (Reimnitz & Gutierrez-Estrada 1970; Shepard et al. 1979); by analogy, other prominent canyon systems that head on the narrow continental shelf (Figs 1 & 2) are probably active as well.

Sediment bypassing of the slope off Mexico is also supported by an axial profile of the Middle America Trench, which shows a strong correlation between the thickness of sediment and the location of large submarine canyons (Figs 1 & 2; Underwood & Karig 1980). These data suggest that the submarine canyons act as the

![Fig. 2. Bathymetric map and trench-axis profile of the Middle America Trench from Rio Balsas to Tehuantepec Bay, Mexico. Depth calculations and bathymetry are the same as for Fig. 1. Data sources, in addition to those cited in Fig. 1, include Karig et al. (1978), Shipley et al. (1980), and unpublished reflection profiles from the University of Texas Marine Lab (DSDP Leg 66 site survey). Modified from Underwood & Karig (1980).](http://sp.lyellcollection.org/Downloaded from at Oregon State University on June 8, 2012)
primary conduits for sediment entering the trench. Sediment thickness decreases in both directions away from point sources at the canyon mouths, indicating that bi-directional transport probably occurs on the trench floor. Seismic reflection data at the mouth of Rio Balsas Canyon show a thick wedge of sediment that is channelized along its upper surface; these appear to be distributary channels of a submarine fan (Underwood & Karig 1980).

Rates of sedimentation in the Middle America Trench (Ross 1971; Moore, Watkins et al. 1979) are not high enough to allow seaward progradation of submarine fans over the outer trench slope (Underwood et al. 1980). As a result, individual channels initially orientated perpendicular to the trench axis either shift their courses in response to the axial depth gradient or are deflected by the outer trench slope. Channelized transport on the trench floor appears to be very localized, as channels are no longer evident within a distance of approximately 30 km from the mouth of Rio Balsas Canyon (Underwood & Karig 1980; Underwood et al. 1980).

In trench systems with higher rates of sedimentation and lower convergence rates (e.g. the Oregon-Washington margin), submarine fans have built out over the seaward trench slope, masking the trench as a bathymetric feature (Karig & Kulm 1978). The Astoria Fan off Oregon, for example, has been used as a model of submarine-fan sedimentation (Nelson & Kulm 1973; Nelson & Nilsen 1974); in this case, the effects of tectonics on trench sedimentation appear to be minimal.

Large submarine canyons do not provide the only source of sediment to reach the trench floor. Secondary sources include background settling of hemipelagic debris and locally-derived mass flows, including slumps and slides (e.g. Piper et al. 1973; von Huene 1974; Moore et al. 1976; Karig et al. 1981). High pore water pressures resulting from tectonically induced dewatering at the base of the trench slope, combined in some cases with oversteepened slopes, provides a mechanism for recurrent slope failure (e.g. Carson 1980). Mass flows thus initiated may transport reworked slope sediments or accreted trench deposits to the trench floor, commonly via small submarine canyons that head on the lower slope (e.g. Karig et al. 1981). In general, hemipelagic deposition and locally-derived mass flows provide a significant source of trench sediment only if the terrigenous supply is low. Moreover, once slumps and debris flows reach the trench floor, redistribution of the sediment by longitudinal flow mechanisms may be expected (Piper et al. 1973).

Axial transport

Axial channels are prominent features in the eastern Aleutian Trench (Piper et al. 1973; von Huene 1974) and the southern Chile Trench (Scholl et al. 1970; von Huene 1974; Schweller & Kulm 1978; Underwood et al. 1980), and are locally developed in the Japan Trench (Arthur, von Huene et al. 1981), the northern Sunda Trench (G. F. Moore, pers. comm. 1980), and the Middle America Trench off Oaxaca (Shipley et al. 1980; McMillen et al. 1981). The spectacular channel off southern Chile is continuous for over 1000 km (Schweller & Kulm 1978); however, the extent of individual flow units has not been documented. The longitudinal distance and continuity of axial transport is thus poorly known.

Non-channelized longitudinal flow almost certainly occurs along trench floors in many cases. Axial channels are absent in the Middle America Trench north of Acapulco, for example (Ross & Shor 1965; Karig et al. 1978), but textural data and sedimentary structures suggest that turbidity currents transport sediment away from the mouths of submarine canyons (Ross 1971). Moreover, the continuity of the trench wedge, which maintains a thickness of over 300 m north of Rio Balsas Canyon (Figs 1 & 2), suggests that axial transport occurs for distances of 200–300 km between major point sources. Other trenches that do not display axial channels include the central Aleutian Trench (Scholl 1974), the Kuril-Kamchatka Trench (Scholl 1974), the northern California (Silver 1971), Oregon-Washington margin (Kulm & Fowler 1974; Barnard 1978), the Gulf of Oman (White & Klitgord 1976), the Peru Trench (Schweller & Kulm 1978), the Ecuador Trench (Lonsdale 1978), and the Middle America Trench off Guatemala (Seely et al. 1974; Ladd et al. 1978; Ibrahim et al. 1979).

The presence or absence of an axial channel is probably dependent upon several variables, such as the axial depth gradient, the texture of sediment reaching the trench floor, the rate of sedimentation, and the type of mass flow mechanism involved in axial transport. Where channels are lacking, coarse sediment is probably transported as sheet-like turbidites, in a manner analogous to sand-layer deposition within flat-floored basins along the Atlantic margin (e.g. Bennetts & Pilkey 1976; Pilkey et al. 1980). Individual sand layers in these abys-
Sedimentary facies associations within subduction complexes

Sal-plain basins are continuous for distances of up to 500 km (Elmore et al. 1979). Sand-layer thickness and the percentage of sand gradually decreases away from the source (Pilkey et al. 1980). Similar sheet-like flows in trenches are generally confined by the seaward and landward trench slopes, but in some circumstances, sand bodies may migrate up or overtop the outer trench slope (Damuth 1979; J. C. Moore et al. 1981).

Most trenches appear to contain a continuous wedge of turbidites. In some cases, however, sediment supplies are not large enough for sediment bodies to prograde over basement highs on the downgoing oceanic plate, such as seamounts, aseismic ridges, and fault blocks (e.g. Scholl 1974; Kulm et al. 1977). In the northern Middle America Trench, basement topography has created silled basins south of Rio Balsas Canyon (Fig. 3). Depth to the trench floor increases by over 200 m from the north side of an exposed basement ridge to the south side (Figs 2 & 3). South-directed turbidity currents emanating from Rio Balsas Canyon apparently filled the trench virtually to the crest of the basement ridge; subsequent flows could then spill over the ridge and continue down the trench axis. Farther south, near the DSDP Leg 66 drilling sites, closely spaced reflection profiles show that axial transport is locally blocked by basement highs (Shipley et al. 1980); low rates of sedimentation result in discontinuous and apparently isolated ponds of sediment (Fig. 2).

Ancient analogues

In spite of post-depositional deformation, sedimentary sequences up to hundreds of metres in thickness are preserved within ancient subduction complexes, such as the Coastal Belt Franciscan Complex of northern California (Bachman 1978, 1981). Inferred trench sediments within the Coastal Belt include all turbidite facies (Table 1). However, massive channelized sandstone (facies B) is locally dominant and closely associated with thin-bedded deposits of probable channel overspill origin. Chaotic fine-grained deposits (facies F) may represent hemipelagic material slumped off the base of the trench slope. Turbidite facies associations are consistent with upper- and mid-fan depositional settings, but outer-fan facies associations are generally lacking. Palaeocurrent data indicate that flow directions were parallel to the inferred continental margin; deposition may therefore have occurred within an axial channel on the trench floor. Elsewhere within the Franciscan Complex, mid- to outer-fan facies associations, consisting mostly of facies C and D turbidites, occur together with inner-fan deposits (Aalto 1976). These data suggest that trench fans were at least locally developed within the Franciscan trench.

Fig. 3. Single-channel seismic-reflection (air-gun) profile across the floor of the Middle America Trench south of Rio Balsas Canyon. Location of trackline B-B’ is shown in Fig. 2. Seismic profile is from DSDP Leg 66 transit.
Sedimentological data from other ancient subduction complexes demonstrate the diversity of possible transport processes and depositional geometries within trenches. Ordovician greywackes in the Southern Uplands of Scotland, for example, are interpreted as accreted trench deposits and consist primarily of facies B and C sandstones (Leggett *et al.* 1979; Leggett 1980). Localized conglomeratic units may represent point sources within a largely non-channellized trench-floor transport system (Leggett 1980). Permian to Jurassic strata in New Zealand include both melanges and coherent packets of strongly channellized thick-bedded sandstone and conglomerate (facies A & B) with associated levee deposits and overbank turbidites (Carter *et al.* 1978). Some of the channel-fill sequences probably accumulated in channels orientated parallel to the trench axis; localized point sources are also likely (Carter *et al.* 1978). Tectonically juxtaposed packets of accreted trench turbidites on Barbados are laterally continuous and up to 500 m thick; facies associations are consistent with deposition within middle and outer portions of one or more submarine fans (Speed 1981; Pudsey & Reading 1981). Inferred trench sediments on Kodiak Island, Alaska, were probably deposited within a basin-plain environment; dominant facies include fine-grained facies D turbidites and interbeds of facies G hemipelagic shale (Nilsen & Moore 1979). Regional facies relations and palaeocurrent data suggest that the basin-plain deposits represent long-distance axial transport and distal sedimentation within a major trench-floor system in SE Alaska (Nilsen & Bouma 1977; Nilsen & Moore 1979; Nilsen & Zuffa 1981).

**Sedimentary facies model**

Based upon the available data from both modern and ancient trench deposits, we propose a conceptual model for trench sedimentation which includes four major types of sediment bodies and corresponding facies associations. The four trench-floor facies associations are trench-fan, axial-channel, non-channellized, and starved-trench (Fig. 4).

Trench fans, in most cases, are not large enough to prograde over the outer trench slope, and the transition from more proximal to more distal facies associations takes place in a direction that is parallel to the trench axis. Submarine fans distorted by restricted basin geometries have been recognized within the geological record (e.g. Pescadore 1978). Trench-fan deposits include all turbidite facies and submarine-fan facies associations, and palaeocurrent patterns range from radial to longitudinal (Fig. 4). Vertical cycles should include typical thinning- and fining-upward sequences associated with channel migration and abandonment, as well as thickening- and coarsening-upward cycles associated with progradation of outer-fan depositional lobes (e.g. Ricci-Lucchi 1975; Mutti *et al.* 1978; Walker 1978).

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![Fig. 4. Conceptual diagram showing the turbidite facies and palaeocurrent patterns predicted for sediment bodies on the trench floor. See Table 1 for definition of facies terminology. Minor turbidite facies are shown in parentheses, and equivalent and/or similar associations, including submarine-fan facies associations, are also indicated. Adapted from Underwood *et al.* (1980).](image-url)
Sedimentary facies associations within subduction complexes

Trenches containing large axial channels do not fit well into a model of submarine-fan sedimentation. Thick sequences of channelized sandstone (facies B & C) are likely in such cases; these deposits would pass sharply into associated fine-grained levee and overbank deposits (facies E, with D & G). Palaeocurrents reflect longitudinal flow (Fig. 4). Facies associations are similar to those of inner- to mid-fan facies, but more distal fan facies associations are notably lacking. Basin-floor channels of this type have been described in the Alp and Apennines by Sagri (1979).

Evidence from seismic reflection data suggests that non-channelized sheet flow is common in modern trenches. Facies associations related to this style of sedimentation are probably similar to non-channelized outer-fan and basin-plain facies associations, although palaeocurrent patterns would be dominantly longitudinal (Fig. 4). Facies C and D turbidites and interlayered hemipelagic mudstones (facies G) are expected, but well-developed vertical cycles are unlikely. Analogies with modern abyssal-floor basins suggest a decrease in both sandstone/shale ratios and sand-layer thickness with increasing distance from the sediment source (Pilkey et al. 1980).

Trenches may be starved of coarse clastic material either because no terrigenous sands reach the trench or axial transport on the trench floor is blocked. The sedimentary facies associations expected with a 'starved' trench are similar to those of the slope or basin plain (Fig. 4); deposits are dominated by facies G hemipelagic muds and fine-grained facies D turbidites, along with possible facies F slump bodies.

Trench-slope deposits

The structure and morphology of forearc regions are diverse and variable (Seely 1979; Dickinson & Seely 1979). Large sedimentary basins such as the Aluetian Terrace (Marlow et al. 1973; Scholl 1974) and the Mentawai Trough, off Sumatra (Karig et al. 1980) are commonly located between the active magmatic arc and the trench-slope break. Several smaller basins or benches may develop on the upper trench slope, such as off Oregon-Washington (Barnard 1978; Kulm & Scheidegger 1979) and Peru-Chile (Coulbourn & Moberly 1977; Moberly et al. 1981; Kulm et al. 1977; Kulm et al. 1981). Models of forearc-basin sedimentation are well-established. Sedimentary sequences range from non-marine, deltaic, and shelf deposits to large complexes of coalescing submarine fans (Dickinson 1971, 1974; Ingersoll 1978b; Dickinson & Seely 1979). In this paper, forearc basins are considered only in so far as they affect sedimentation along the lower trench slope.

Sedimentary basins along the lower slope are generally elongate and bounded by tectonically active ridges (e.g. von Huene 1972, 1979; Kulm & Fowler 1974; Carson et al. 1974; G. F. Moore & Karig 1976; White & Klitgord 1976; Karig et al. 1979; Arthur, von Huene et al. 1981). Locally, slope basins may contain: (1) hemipelagic deposits or remobilized material slumped off adjacent bathymetric highs; (2) turbidites of shallow-water origin transported beyond the trench-slope break via submarine canyons; or (3) debris-flow deposits containing blocks of the underlying accretionary complex (G. F. Moore & Karig 1976). Any small basin or terrace is a potential site for the accumulation of sand-sized detritus, and sand layers have been cored in lower-slope basins off Kodiak Island (Kulm, von Huene et al. 1973; Howell & von Huene 1978; M. Hampton, pers. comm. 1979), New Zealand (Lewis 1981), and Oregon-Washington (Kulm, von Huene et al. 1973; Kulm & Fowler 1974; Barnard 1978; Kulm & Scheidegger 1979). Because of upslope blockage of sediment transport by tectonic ridges and deposition within basins located higher on the slope, the chances of coarse sediment reaching a lower-slope basin decreases with increasing distance down the trench slope (Underwood et al. 1980).

Where basins are not present, the apron of sediments covering the lower trench slope generally consists of hemipelagic muds and occasional thin beds of fine sand and silt (Ross 1971; Kulm, von Huene et al. 1973; Barnard 1978; Langseth, Okada et al. 1978; Moore, Watkins et al. 1979; Kulm & Scheidegger 1979; Krissel et al. 1980; von Huene, Aubouin et al. 1980; McMillen & Haines 1981; McMillen et al. 1981; Arthur, von Huene et al. 1981). In many cases, the slope muds overlie much coarser trench sediments that were accreted at the base of the lower slope (e.g. J. C. Moore & Karig 1976; Moore, Watkins et al. 1979). Tectonic loading and oversteepened slopes may cause sediment failure (slumps and slides) within the apron of slope muds (e.g. Hampton et al. 1978).

Upslope trapping

Small submarine canyons play an important role in the distribution of sediment along the trench slope by providing an effective transport route for coarse detritus. Most of the canyons...
on the landward slope of the northern Middle America Trench head downslope of the continental shelf (Figs 1 & 2; Fisher 1961), and, as a result, they probably do not receive a direct supply of terrigenous detritus with the present position of sea-level. It is likely, however, that sand-sized material entered the canyons during global low stands associated with Pleistocene glacial epochs. Moreover, unconfined mass movements (sediment creep, slumps,slides, debris flows) may carry coarse debris beyond the shelf break (Field & Clarke 1979; Nardin et al. 1979). Small submarine canyons can then intercept and funnel downslope the turbidity currents generated by mass movements occurring upslope or on the outer shelf.

Tectonic ridges and other bathymetric highs on the trench slope commonly cut off the paths of submarine canyons and block the transport of turbidites and other mass flows. The mechanics of upslope trapping are well-documented in the northern Middle America Trench, where detailed local bathymetry shows that the small canyons typically coalesce downslope into fewer and larger canyons (Karig et al. 1978; Underwood et al. 1980). As an individual canyon approaches a ridge, such as the trench-slope break, the canyon channel is blocked, the canyon gradient decreases, and sediment becomes ponded behind the ridge in a slope or forearc basin. Reflection profiles display far fewer submarine canyons below the trench-slope break (Underwood et al. 1980). In general, only the largest canyons continue across the active ridges of the trench slope (Underwood & Karig 1980). Approximately 80% of the submarine canyons off Mexico end without reaching the trench floor; most terminate above the trench-slope break (Figs 1 & 2). Where a greater number of active ridges are present, such as the Sunda Trench (G. F. Moore & Karig 1976; Karig et al. 1979), the effects of structural blockage of sediment transport are more pronounced, and the chances of submarine canyons maintaining their channels greatly diminishes downslope.

Ancient analogues

In general, differentiation of trench-floor and trench-slope deposits within ancient subduction complexes is difficult on the basis of sedimentary facies analysis alone, except in cases such as Barbados, where a clear lithological distinction exists between thin-bedded biogenic marls (slope deposits) and accreted trench turbidites (e.g. Speed 1981). Structural style is perhaps the most commonly used criterion for distinguishing between these two types of units, as trench deposits are generally more highly deformed than associated slope sediments (e.g. Bachman 1978; Moore & Karig 1980).

Perhaps the most complete record of lower-slope sedimentation is exposed on Nias Island, off Sumatra (Moore 1979; Moore & Karig 1976, 1980; Moore et al. 1980). Stratigraphic sequences exposed on Nias define an overall coarsening- and thickening-upward trend associated with basin uplift and the progradation of a submarine fan complex (Moore et al. 1980). Basal slope strata overlie melange (accreted trench deposits) and consist of hemipelagic marls and lutite turbidites (facies D & G). There is a pronounced increase upsection in coarser facies A, B, and C deposits, and small-scale vertical cycles suggest that deposition of coarser facies occurred within outer- to inner-fan environments (Moore et al. 1980). The stratigraphic record on Nias demonstrates the influence of tectonic processes on lower-slope sedimentation. Apparently, individual basins, initially isolated from sources of coarse detritus, were uplifted and eventually linked with downcutting submarine canyons which headed off the coast of Sumatra (Moore 1979; Moore et al. 1980). Continued uplift and deposition allowed progradation of submarine fans and the infilling of the slope basins.

Several examples of possible slope-basin deposits occur within the Franciscan Complex of California (Howell et al. 1977; Underwood 1977; Bachman 1978, 1981; Smith et al. 1979). These strata are relatively undeformed and generally dominated by thick sequences of channellized facies B sandstone, with associated deposits of levee/overbank origin (facies E, with minor D & G). Some sections in the Coastal Belt contain abundant facies C & D turbidites, but distal fan-facies associations are generally lacking (Bachman 1978, 1981). Facies associations suggest deposition within mid- to outer-fan channels and depositional lobes, or their facies equivalents (Howell et al. 1977; Bachman 1978; Smith et al. 1979). The predominance of thick-bedded sandstone can be attributed to selective trapping of the coarse-grained parts of gravity flows within restricted slope basins, while more turbulent fine-grained fractions were able to bypass the basins and settle farther down the trench slope (Bachman 1978; Smith et al. 1979).

Ancient trench-slope deposits on Kodiak Island consist primarily of thick sequences of facies G mudstone (Nilsen & Moore 1979). Chaotic deposits (facies F) and thick beds of channellized sandstone and conglomerate
(facies A & B) crop out locally and probably represent slump deposits and canyon/channel fill, respectively (Nilsen & Moore 1979). Trench-slope deposits on New Zealand contain deposits of low energy bottom currents (contourites) in addition to the dominant hemipelagic mudstones and lutite turbidites (Carter et al. 1978).

**Sedimentary facies model**

In our facies model for trench-slope deposits (Fig. 5), submarine-canyon and slope facies associations are generally the same as for tectonically inactive environments (e.g. Whitaker 1974; Kelling & Stanley 1976). Slope deposits are dominated by facies G hemipelagic mudstones and thin-bedded, fine-grained facies D turbidites (Fig. 5). The occurrence of chaotic deposits associated with slope failure (facies F) may be more common within subduction complexes, however, because of the related tectonic activity. Channel lag deposits from submarine canyons consist largely of coarse facies A, B, & C deposits; in large canyons, levee and overbank deposits (facies D, E, & G) may represent local deposition outside the channel thalweg. Slumps off canyon walls (facies F) may also become interstratified with canyon fill. Inactive canyons are filled largely with hemipelagic slope deposits and fine-grained turbidites (facies D & G). Palaeocurrents from canyon fill should be dominantly at a high angle to the margin (Fig. 5).

Because of upslope trapping, trench-slope basins near the base of the landward slope generally receive only fine-grained sediments derived from hemipelagic settling and dilute density flows (facies D & G). Slumps and slides derived from tectonically active bounding ridges are also likely, but such chaotic deposits would consist primarily of remobilized fine-grained slope sediments. In our facies model, basins that receive only fine-grained material are classified as 'immature' slope basins (Fig. 5).

Progressive growth of the accretionary prism generally causes uplift of trench-slope basins.

![Fig. 5. Conceptual diagram showing the turbidite facies and palaeocurrent patterns predicted for trench-slope settings. The terminology follows that of Fig. 4 (see Table 1). The terms 'mature' and 'immature' slope basin refer to the presence or absence, respectively, of a source of coarse terrigenous sediment, and are not necessarily indicative of any particular bathymetric position on the trench slope. Adapted from Underwood et al. (1980).](http://sp.lyellcollection.org/)
through time; this is associated with a decrease in tectonic activity with increasing distance from the active basal slope (Seely et al. 1974; Karig & Sharman 1975). As a result, bounding thrust ridges may become inactive during the uplift history of individual slope basins, thereby increasing the width of the basins through time (G. F. Moore & Karig 1976). The combined effect of these processes may be the sudden influx of coarse terrigenous detritus into previously isolated slope basins, as basin uplift is accompanied by progressive downcutting of submarine canyons (e.g. Moore et al. 1980). In our facies model, we define any such basin that receives a direct supply of coarse clastic material as ‘mature’, regardless of its actual position on the trench slope (Fig. 5).

The facies associations for mature slope basins are varied and depend largely upon the geometry of the basin. All of the submarine-fan facies associations may be present in large slope basins. In contrast, small narrow basins may selectively trap coarse material and allow fine-grained sediment to bypass the basin. Palaeocurrent patterns may also vary from radial to longitudinal (Fig. 5).

Discussion

The sedimentary facies models presented in this paper are somewhat speculative, due largely to the general lack of detailed sampling within modern subduction zones. The available data clearly indicate, however, that over-simplified models cannot account for the observed complexity and diversity of sediment bodies and patterns of sedimentation. We have attempted to stress the variety of possible facies associations and identify some of the variables that affect sedimentation within trench-floor and trench-slope environments.

Turbidite facies terminology is an important tool in the analysis of sedimentary strata, including strata exposed within ancient subduction complexes. However, turbidite facies associations within subduction complexes may be other than those of a submarine fan. The facies associations that do not fit well into the slope/fan/basin-plain model of deep-basin sedimentation include axial-channel, non-channelized (sheet-flow) trench-floor, starved-trench, immature-slope-basin, and certain associations within mature slope basins, such as small basins that selectively trap coarse detritus. Submarine fans also occur within subduction zones, but we believe that the use of terminology linked to submarine-fan morphologies is clearly not appropriate in all cases. The identification of submarine-fan deposits within subduction complexes should depend upon the documentation of appropriate palaeocurrent patterns, vertical cycles, and fan facies associations that are consistent with submarine-fan progradation or regression. In the absence of such documentation, facies association terminology should be linked with the geometries of the other types of sediment bodies observed within modern trenches, such as axial channels.

Our facies models have other implications for environmental reconstructions within accretionary margins, including the identification and differentiation of separate tectono-stratigraphic units. Because of the complexity and variability of sedimentation that is possible within a single trench, general lithologies and turbidite facies associations can change dramatically within a relatively short distance. For example, structural blockage of axial transport paths by a seamount on the downgoing oceanic plate could allow thick sequences of sandy turbidites to accumulate on one side of the blockage, with hemipelagic muds dominating the other side. Subsequent accretion and uplift of the seamount and trench fill could expose sections of strata that might appear to represent completely unrelated geological histories. The resulting juxtaposition of sandy turbidites, basalts, and mudstones could be erroneously attributed to large-scale tectonic events associated with accretion, rather than the original depositional geometry that existed on the trench floor. In other cases, it may be nearly impossible to differentiate between trench fill and trench-slope deposits. For example, abyssal sediments, trench sediments, and slope sediments could all be very similar if the trench is starved of coarse clastic material. If tectono-stratigraphic designations are based primarily upon sedimentary facies relations, then all of the resulting strata would be included in the same unit, and the designations would have little genetic meaning.

In addition to the predicted lithological variations and complexities, significant differences in sandstone petrology could result for trench-floor and slope-basin deposits that accumulate in different sites along the length of an accretionary margin. For example, both regional and local changes in source rocks and onland drainage patterns could introduce sands of differing composition into the submarine canyons that funnel detritus into different sedimentary basins. Moreover, long-distance axial transport in the trench could juxtapose detritus of one composition against sediments of a different
Sedimentary facies associations within subduction complexes

provenance that were transported via local submarine canyons. It is therefore important to integrate palaeocurrent data with data on sandstone petrology before reliable provenance determinations can be made.

We suggest that normal sedimentary processes, rather than large-scale tectonic events, may be responsible in some cases for lithologic and compositional changes recorded within many subduction complexes and accretionary margins. Clearly, the possible effects of penecontemporaneous or subsequent tectonism must be considered, but the possibility of relating observed changes or differences to a logical system of sediment transport and deposition cannot be ignored. The separation of strata into meaningful tectonostratigraphic units should depend upon several criteria, such as contrasts in sedimentary facies associations, sandstone petrology, structural style, palaeontology, and general physical properties.

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Sedimentary facies associations within subduction complexes


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