DAVID BLOOM Mon 9 Feb 87

Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America

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ABSTRACT

The term "mélange" is currently used to describe several different kinds of mudstone-rich rocks that are broadly characterized by an obscure stratigraphy, stratal disruption, or a chaotic, "block-in-matrix" fabric. Four types of mélange, which can be defined in outcrop on the basis of mesoscopic fabric and lithologic composition, are particularly widespread and distinctive. Type I includes sequences of originally interbedded sandstone and mudstone that record incipient to thorough disruption and fragmentation of strata accomplished largely by layer-parallel extension. Type II consists of similarly deformed, thin layers of green tuff, radiolarian ribbon chert, and minor sandstone originally interbedded with black mudstone. Disruption in both types I and II, which probably occurred while the sediments were incompletely consolidated, has been ascribed to either imbricate faulting in accretionary wedges or gravitationally driven deformation. Type III comprises inclusions of diverse shapes, sizes, and compositions enveloped in a locally scaly, pelitic matrix. The ultimate source of fragments is obscure, because the majority were not derived by either the progressive disruption of interbedded sediments or *in situ* tectonic plucking and abrasion of adjacent rocks. Although some type III mélanges may have originated deep within accretionary prisms, final emplacement as olistostromes (muddy debris-flow deposits) or mud diapirs seems likely. Type III mélanges are mechanically analogous to scaly, "sheared" serpentinites; many probably have been tectonically remobilized or even intruded into shallow-level fault zones. Type IV consists of lenticular inclusions bounded by an anastomosing network of subparallel faults. Their fabric records progressive slicing in brittle fault zones.

Each of the four types of mélange described here could, in theory, have formed in a variety of settings on or within an accretionary wedge at an active convergent margin; none can yet be singled out as a uniquely diagnostic "subduction mélange."

INTRODUCTION

In the short time since Hsü (1968) described parts of the Franciscan Complex in California as mélange, the term has been applied to many mudstone-rich rock bodies along the Pacific margin of North America from southwest Alaska to northwest Mexico. Where used in a general, descriptive way, the term conveys an impression of an obscure stratigraphy or a chaotic fabric typified by either obvious stratal disruption or blocks of various sizes and shapes dispersed in a fine-grained pelitic matrix. Although mélanges are characteristically problematical, they are widely regarded as an important or even diagnostic product of subduction.

Despite the widespread use of the term, it has been difficult to devise a generally acceptable definition. I believe that this difficulty has arisen because, in the Cordillera, the term is being applied in practice not to one, but to several types of rock bodies, each having distinctive structural and lithologic characteristics. After having worked in or visited many of these late Mesozoic and early Cenozoic mélanges along the Pacific margin (Fig. 1), I found that four types are particularly common and, in keeping with the connotations of the term "mélange," have controversial or unresolved origins as well.

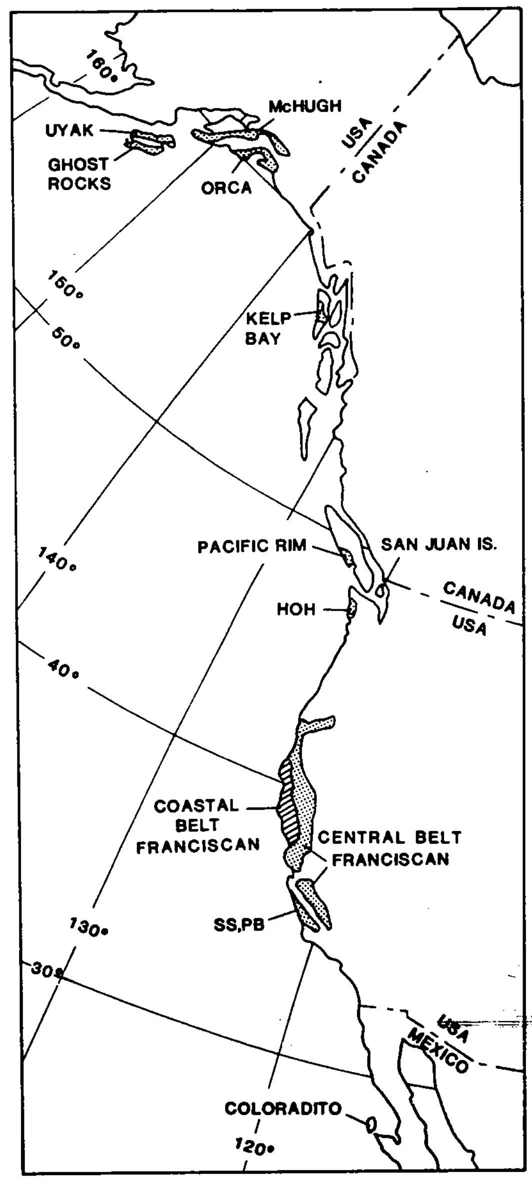


Figure 1. Map of the Pacific margin of North America locating specific mélanges discussed in the text.

Geological Society of America Bulletin, v. 96, p. 451–462, 10 figs., April 1985.

The purposes of this paper are to describe these common types, discuss the processes that may have given rise to their mesoscopic fabrics, and briefly evaluate how they might be related to subduction tectonics. In most cases, my own field observations are blended with material referenced from the literature. My main objective is to provide some examples, especially for geologists familiar with other orogenic belts, of how the term mélange is being currently and conventionally used in the western Cordillera. I am not striving to erect an all-inclusive classification; certainly, other varieties of disrupted or chaotic rocks, in addition to the four described here, have been called mélange. The particular categories I emphasize are not as important as the conclusion that, all controversies over definition and origin aside, Cordilleran mélanges are plural.

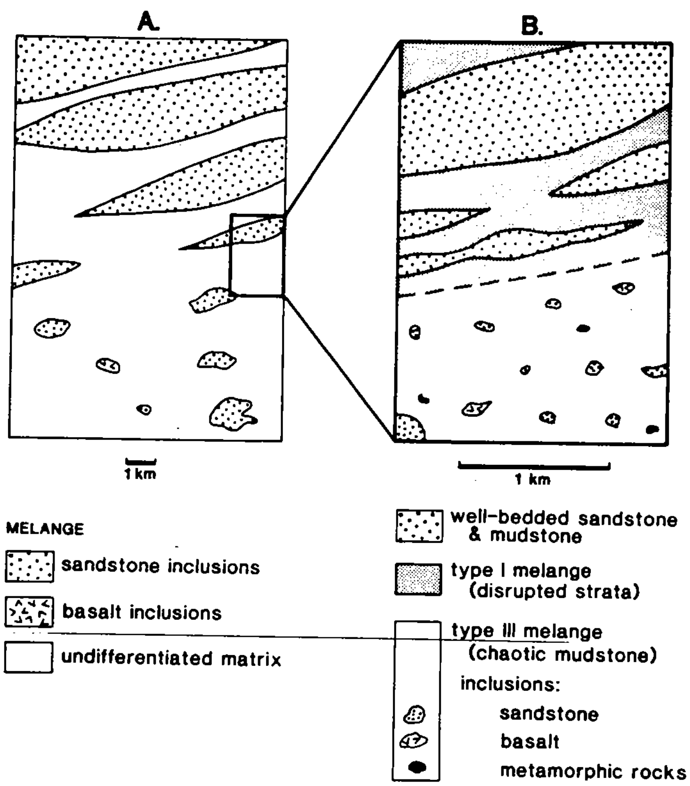


Figure 2. Geologic maps of an area underlain by mélange. Map-scale mélange in smaller-scale map (A) can be further differentiated in larger-scale map (B). See text for discussion.

In the following descriptions, I highlight some structural and lithologic criteria that, if apparent in hand-specimens or outcrops, might afford the easiest means of differentiating one type of mélange from another. Figure 2 schematically illustrates an important characteristic of mélanges and shows why the term can be applied descriptively to map units as well as to outcrops. The fundamental features used to define a mélange—*fragments*[1] enveloped by a finer-grained *matrix* of mudstone—are apparently independent of scale. That is, some fragments will be obvious, and theoretically mappable, given suitable exposures, at any scale of observation; the sizes and shapes of large blocks and slabs can only be portrayed on geologic maps. At conventional scales of 1:24,000 to 1:63,500 (for example, Cowan, 1974; McLaughlin, 1978; Worrall, 1981; Seiders, 1983), most maps and cross sections show map-units of mélange consisting of (1) inclusions, which are either outlined or merely located with symbols, and (2) "undifferentiated mélange," including the types described here, consisting of mudstone, highly disrupted strata, and inclusions too small to portray at these scales.

TYPE I: STRATIFIED SEQUENCES OF SANDSTONE AND MUDSTONE PROGRESSIVELY DISRUPTED BY LAYER-PARALLEL EXTENSION

Type I mélanges have a distinctive mesoscopic structural style that sets them apart from other types of deformed clastic strata. These mélanges, originally characterized by stratal continuity of interbedded sandstone and mudstone, show a spectrum of progressive stratal disruption (Fig. 3). Incipiently deformed sandstone layers display pinch-and-swell structure and boudinage, whereas the most intensely deformed rocks consist of isolated inclusions derived from dismembered sandstone layers and enveloped in a mudstone matrix. Disruption and fragmentation resulted largely from layer-parallel extension rather than from tight to isoclinal folding. Well-described examples of type I mélange in the western Cordillera include (Fig. 1) part of the Upper Cretaceous-lower Tertiary Ghost Rocks formation in the Kodiak Islands, Alaska (Byrne, 1985); part of the lower Tertiary Orca group in Prince William Sound, Alaska (Helwig and Emmet, 1981); much of the Upper Cretaceous-Paleogene Coastal Belt in the Franciscan of northern California (Aalto, 1982; Bachman, 1982); and Upper Cretaceous Franciscan rocks near Piedras Blancas Point and San Simeon in Central California (Cowan, 1982). Type I mélange in the Shimanto belt of Japan (Sakai, 1981; Taira and others, 1980) is usually referred to as "olistostrome" (T. Sakai, 1983, personal commun.).

Deformed rocks in this category were wholly derived by the *in situ* disruption of layered sediments. For this reason, some geologists would use a term that Hsü (1968) proposed for variably disrupted rock-stratigraphic units: "broken formation." Regardless of the possible merits of this term, it is a fact that two terms with different connotations are being used for the same rock units. Moreover, "broken formation" is also used to describe other rocks that are completely different from these disrupted sequences of sandstone and mudstone (see type II, below). The term "mélange" seems justified for type I, because some of the more thoroughly deformed rocks near one end of the spectrum have the familiar block-in-matrix fabric imparted by equant to lenticular (phacoidal) fragments of sandstone (Figs. 3B, 3C). Clearly, type I does not contain exotic (that is, foreign to the undeformed protolith) fragments, which, for some geologists, are an essential component of a mélange.

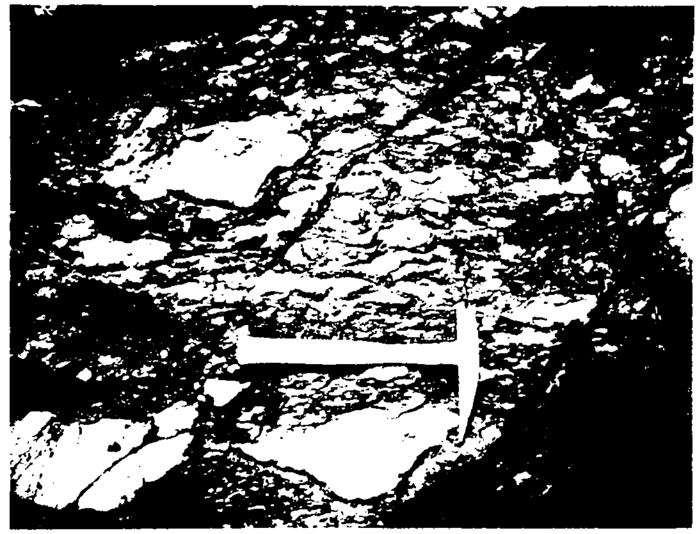
Mesoscopic Fabric and Mechanisms of Deformation

Perhaps the most distinctive feature of type I mélanges is their style of stratal disruption, which appears to differ fundamentally from styles observed in some conventionally folded tectonites. By definition, most of the progressive disruption in type I mélanges resulted from layer-parallel extension (Figs. 3, 4). Units comprising strata that were disrupted principally by the well-known processes of tight to isoclinal folding and transposition are excluded from this category in order to draw attention to an unusual and controversial deformational style. Although type I mélanges are characterized overall by a notable scarcity of folds, they typically include local zones of folded and disrupted strata that represent either significant zones of transposition or strata-bound intervals of synsedimentary slump folds. More extensive units of folded, transposed, and disrupted sandstone and mudstone occur in unmetamorphosed Coastal Belt Franciscan (Beutner and Hansen, 1975; Kramer, 1977) and higher-grade Franciscan tectonites to the east (Blake and Jayko, 1983).

Disrupted strata occur in tabular zones ranging from a few centimetres to hundreds of metres thick. On both outcrop- and map-scale, these

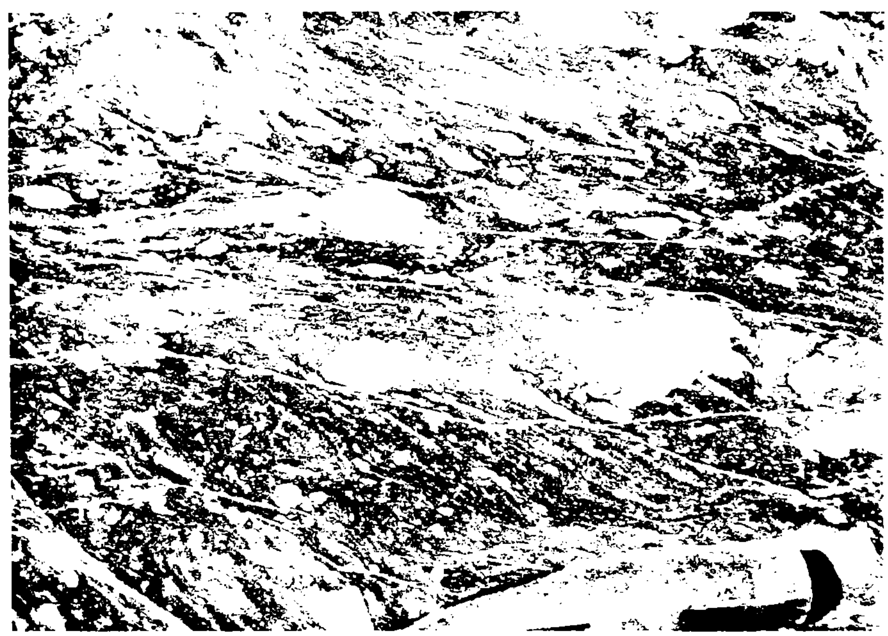
[1]There is no standardized nomenclature for the bodies of diverse shapes and sizes that are enveloped by matrix. In this paper, the terms "fragment," "inclusion," and "block" are used interchangeably and connote a range in size and shape. The terms "lens," "phacoid," and "slab" are used for elongate, tabular, or lenticular inclusions, but "slab" is reserved for those mappable at 1:25,000.

A



B

Figure 3. Three examples of type I mélange showing progressive stages of stratal disruption. A: Layer-parallel extension of sand beds accommodated by necking, boudinage, and shear fractures. Field of view ~60 × 95 cm. Franciscan Complex (from Cowan, 1978). B: Lenticular and irregularly shaped fragments of sandstone in mélange correlative with Pacific Rim complex on southern Vancouver Island, British Columbia. C: Fragments resulting from complete disruption of sandstone layers. Field of view ~24 × 40 cm. San Juan Islands, Washington.



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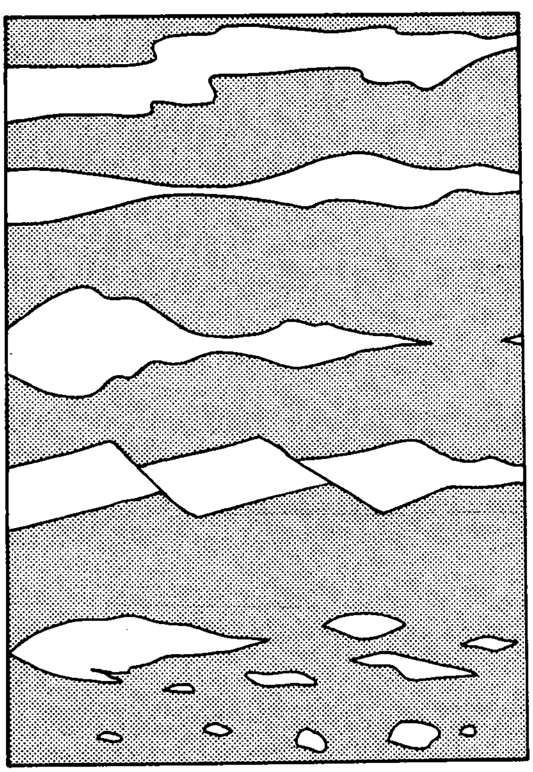


Figure 4. Schematic summary of principal mesoscopic structures in types I and II. Unpatterned areas represent layers of sandstone, chert, or tuff interbedded with a matrix of mudstone (shaded). Note that in spite of variable disruption, layers remain grossly parallel.

zones are grossly parallel to, and bounded by, less deformed or undeformed layers. Consequently, bedded sequences that were partly converted into type I mélange retain their over-all stratigraphy and layered architecture at these scales; hence, they are internally broken but stratiform. Larger, isolated fragments in disrupted zones typically have lenticular cross sections (Fig. 3b). The preferred orientation of elongate and lenticular sandstone fragments defines a foliation ("fragment foliation") subparallel to sedimentary layering on a larger scale. Mudstone locally has a weakly developed, hackly fissility or cleavage that also defines the foliation. In some type I mélanges, this early fabric has been folded, transposed, and overprinted by a slaty or crenulation cleavage during subsequent deformations.

Detailed studies of type I mélanges have documented how the sandstone inclusions formed. At Piedras Blancas and San Simeon, Hsü (1968) and Cowan (1982) showed that progressive layer-parallel extension in sandstone beds was accommodated principally by pinch-and-swell structure and boudinage; extensional shear fractures are less prevalent (Fig. 4). True boudins tend to be irregularly lenticular in cross section; inclusions bounded by shear fractures are more angular and lozenge-shaped. In the Ghost Rocks mélange (Byrne, 1985), some inclusions formed by boudinage and pinch-and-swell, but most were derived by what Byrne calls "layer-parallel dispersion." In this process, "layer-parallel shearing" disrupted sandstone beds into ellipsoidal inclusions which were progressively separated from one another and enveloped by mudstone. From the work of Cowan (1978, 1982), Bachman (1982), Byrne (1985), it is clear that the progressive disruption in type I mélanges was fostered by the different mechanical properties of sandstone and mudstone. In general, sandstone was less ductile and stiffer than the more pliant, mobile mudstone, which flowed on a mesoscopic scale and locally invaded fractures and re-entrants in sandstone layers and inclusions. Although these workers agree that disruption took place at low (sub-greenschist) temperatures without the development of synkinematic metamorphic minerals or a slaty cleavage, they differ in their interpretations regarding the microscopic mechanism of deformation and the physical state of the sediments during deformation. Kleist (1974) and Cowan (1982) concluded that the sediments they studied ranged from unconsolidated to partly lithified at the time of deformation; Cowan (1982) suggested that the diverse small-scale structures that accommodated layer-parallel extension reflect local variations in water content or pore-fluid pressure. In contrast, Byrne (1985) concluded that the widespread cataclasis in Ghost Rocks sandstones indicates that they were dewatered and also that they were deformed under high effective confining pressures.

Strain Path and Environment of Deformation

There are two outstanding questions regarding the origin of type I mélange. First, does the distinctive layer-parallel disruption record a coaxial, heterogeneous bulk flattening, or, instead, progressive noncoaxial deformation (simple shear) in localized fault zones? A second, related question is: in what sort of tectonic setting did deformation occur? Is deformation driven by gravitational spreading in shallow, unconfined environments or by imbricate thrusting in accreted trench sediments? Two quite different models proposed for the origin of type I mélange illustrate the quandary.

In one model, championed by Cowan (1982) for a Franciscan mélange at Piedras Blancas, type I stratal disruption results from gravitationally induced lateral spreading. Figure 5 illustrates the basic features of this model, which in some respects resembles one that Naylor (1981) developed for a disrupted continental-margin sequence in the Apennines. Type I mélanges, which are characterized by laminar, layer-controlled flow, may represent an initial stage in the progressive transformation of well-layered, undeformed sediments into more mobile, fluid, and internally mixed submarine debris flows that accumulate as olistostromes (see Abbate and others, 1970; Page, 1978; and Naylor, 1981, for descriptions of olistostromes). Cowan (1982) hypothesized that because layer-parallel extension apparently occurred in all directions in the plane defined by bedding, it records a coaxial strain history that is more compatible with vertical collapse and quasi-horizontal downslope creep in slope sediments than with strongly noncoaxial shear within confined fault zones. Underwood (1984), however, cogently argues that the sandstone-rich sequences in type I mélanges of the Coastal Belt are trench-floor or abyssal-plain turbidites deposited in environments that are not conducive to the pervasive gravitational failure postulated by Cowan (1982) and depicted in Figure 5.

Bachman (1982), Underwood (1984), and Byrne (1985) favor a different model in which the stratal disruption in type I mélange results from the accretion of trench sediments at and near the toe of the inner trench-slope. They envision zones of layer-parallel shear that presumably represent the actual thrust faults along which panels of less intensely disrupted trench sediments are scraped off the descending plate and are imbricated to form an accretionary prism. The "accretionary fault" model is attractive because it explains how stratified sequences might be concurrently disrupted, tilted, and structurally thickened (see Karig and Sharman, 1975). In my opinion, however, a major drawback to equating zones of type I mélange in general with faults is the rarity of the small-scale structures that characterize mesoscopically ductile rocks known to have been deformed along noncoaxial strain paths in shear zones: intrafolial isoclinal folds, rotated boudins, sheath folds, and asymmetric or sigmoidal features.

Given the evidence at hand, arguments can be marshalled both for and against each model. Perhaps type I, as defined in this paper, includes two or more superficially similar but genetically different kinds of sandstone-mudstone mélange. More complex models, in which sediments first experience a homogeneous bulk flattening and are subsequently imbricated along discrete faults, are possible. The origin of type I mélange is still a fertile field for research.

TYPE II: PROGRESSIVELY DISRUPTED SEQUENCES OF MUDSTONE, TUFF, CHERT, AND SANDSTONE

Type II mélange is analogous to type I in that it also formed by progressive stratal disruption and fragmentation. Type II, however, developed from lithologically distinctive sedimentary sequences consisting of black mudstone interbedded with thin layers of green tuff, white, gray, or black chert, and fine-grained sandstone. Green and black stripes and swirls are typically conspicuous in outcrop. These mudstone-rich sedimentary sequences are widespread in the western Cordillera and are typically inter-

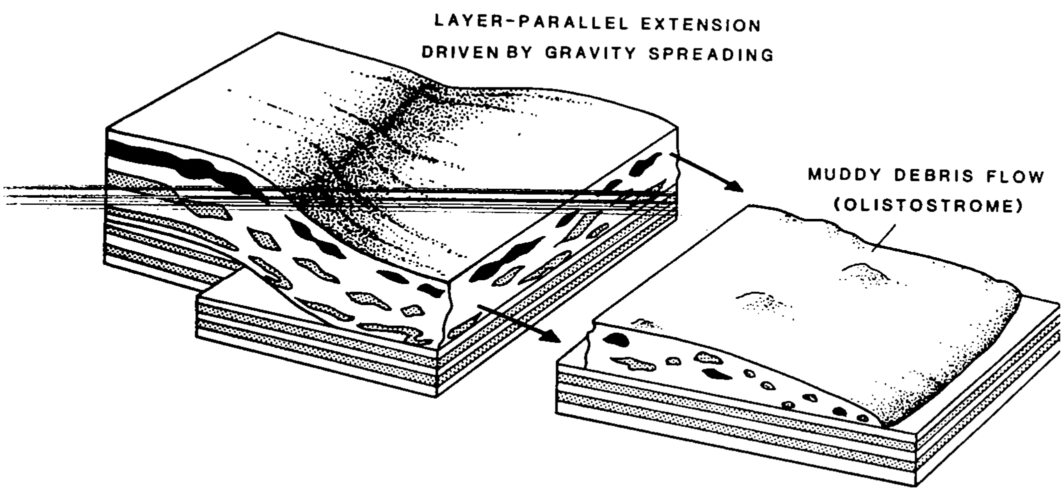
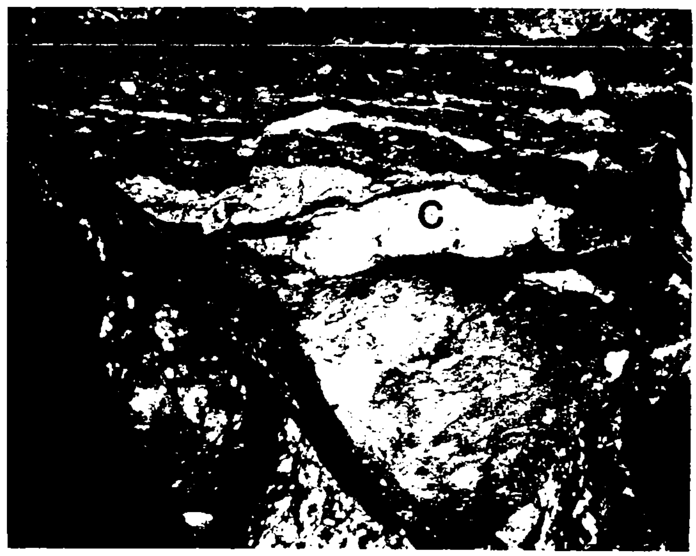


Figure 5. Model for the development of type I and type II mélanges. Strata are progressively disrupted by layer-parallel extension. Gravitationally spreading sediments may generate debris flows in which fragments of layers become widely separated and mixed.

A

B



C

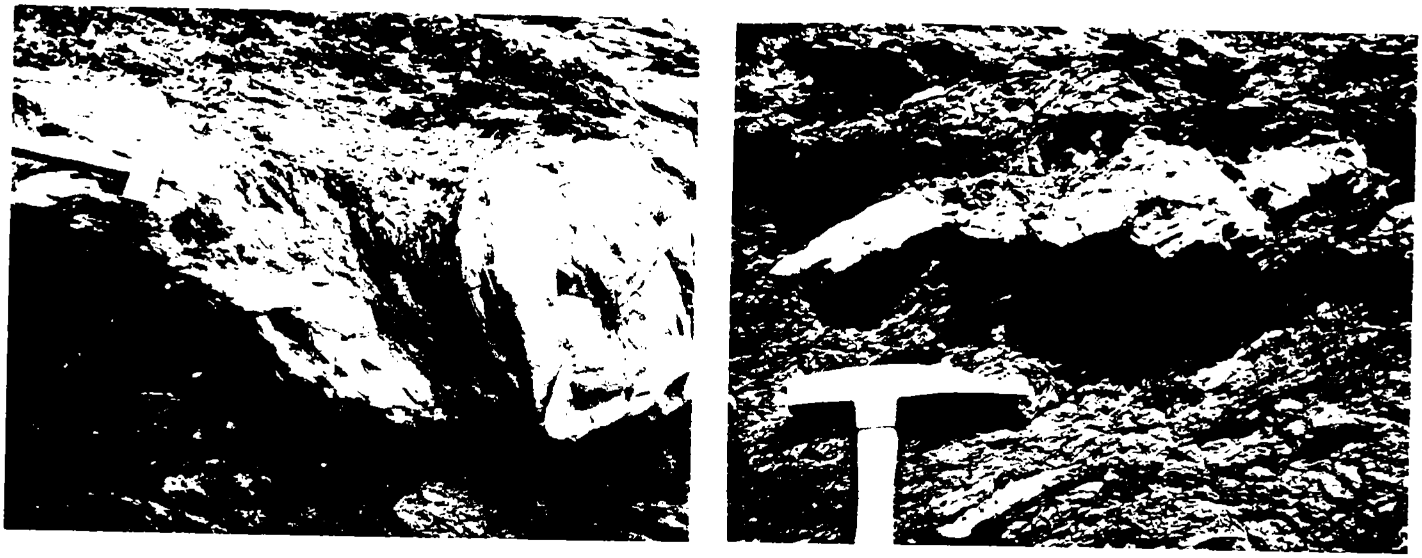
Figure 6. Mesoscopic structural styles in type II mélanges. A: Prominent lens of radiolarian ribbon chert isolated by boudinage, overlain by interbedded tuff and mudstone and underlain by a more highly disrupted zone containing smaller fragments of chert and sandstone. Uyak Complex. B: Green tuff layers (outlined) swirled and mixed with black argillite containing small fragments derived from originally interbedded layers of chert. Diameter of coin is 2.5 cm. Pacific Rim complex. C: Lenticular fragments of tuff and chert (labeled C) in black mudstone matrix. Diameter of coin is 2.5 cm. Rocks correlative with Pacific Rim complex on southern Vancouver Island.

bedded with lenticular bodies of massive volcaniclastic sandstone, mafic pillow lava, and radiolarian ribbon chert. All of the examples cited below are apparently Jurassic to Early Cretaceous in age. In Alaska, type II mélange occurs in the Uyak Complex on the Kodiak Islands (Connelly, 1978; Moore and Wheeler, 1978); in correlative rocks on the Kenai Peninsula (Cowan and Boss, 1978); in the McHugh Complex in the Chugach Mountains (Clark, 1973); and in rocks mapped as Kelp Bay group on Baranof and Chichagof Islands (Loney and others, 1975; Decker, 1980). In the Pacific Northwest, type II is present in the Pacific Rim complex (Brandon, 1984) and Pandora Peak unit (Rusmore, 1982) on Vancouver Island and in the Constitution formation in the San Juan Islands. Disrupted sequences of mudstone, tuff, and chert are an important component of the lithologically diverse "central belt" of the Franciscan Complex (Aalto, 1981).

Mesoscopic Fabric

The same kinds of structures that typify type I mélanges predominate in type II: pinch-and-swell, necking, and boudinage. A typical exposure or group of exposures of type II mélange displays variably disrupted layering (Fig. 6). In many exposures, zones of incipiently deformed strata alternate with subparallel zones, ranging from tens of centimetres to several metres in thickness, in which strata are more highly disrupted. The boundaries of these "isodeformational" zones are subparallel to original stratigraphic layering, such that most type II mélanges are grossly layered in spite of obvious stratal disruption. The most thoroughly disrupted rocks are polymict and consist of variably shaped fragments of chert, tuff, and sandstone that are scattered through a voluminous matrix of black mudstone. Lenticular fragments typically have a preferred orientation parallel to mesoscopic layering (Fig. 6C). Progressive disruption of stratified sediments, which led in some cases to a "fragment-in-matrix" fabric, was promoted by the ductility contrast between mudstone and beds of chert, tuff, and sandstone. Some tuff layers have irregular, wispy shapes and give an impression of having been swirled or stirred into the associated mudstone (Fig. 6B). The mechanical properties of these disharmonic tuff layers must have been nearly identical to those of the mud matrix. Such evidence for extreme mobility—ductile, cohesive flow accomplished without the development of a slaty cleavage—suggests that at least some of the deformation in type II mélange occurred while the mud and tuff were only partly dewatered and consolidated.

Although layer-parallel extension played the dominant role in stratal disruption, some type II mélanges include not only isolated disharmonic



A B

C

Figure 7. Type III mélanges. A: Elongate, necked inclusion on the left is glaucophane-lawsonite blueschist; block on the right is unmetamorphosed sandstone. Franciscan Complex near San Simeon (see Cowan, 1978). B: Foliated, scaly mudstone (argille scagliose) enveloping an isolated, irregularly necked sandstone inclusion. Southwest Oregon. C: Variably shaped inclusions of sandstone and basalt (labeled V) in black, locally scaly mudstone. Elongate and lenticular inclusions define a foliation approximately parallel to scaly foliation in matrix. Hoh mélange, probably in a mud diapir, Olympic Peninsula, Washington.

folds (Fig. 6B) but also local zones of folding and transposition. Mesoscopic folds, however, are an important fabric element in parts of the Uyak Complex in the Kodiak archipelago. Moore and Wheeler (1978) suggested that much of the disruption in sequences of interbedded chert and argillite there occurred as chert layers were tightly folded and transposed into a penetrative axial planar foliation. Further field studies are required to assess the geometry, structural significance, and relative abundance of fold-dominated zones associated with type II mélanges.

Origin

Few specific hypotheses have been proposed for the origin of type II mélanges. Inasmuch as they share similar deformational styles with type I, they may have formed by the process depicted in Figure 5, in which gravitationally driven downslope stretching led to the development of internally chaotic debris flows and olistostromes containing clasts and olistoliths of chert, sandstone, and tuff. Brandon (1984) viewed the disruption of sand layers by necking and swelling as evidence for earthquake-induced liquifaction. In these two models, deformation occurs prior to and independently of any eventual tectonic imbrication at a convergent plate boundary. Alternatively, the hypothesis that Bachman (1982), Underwood (1984), and Byrne (1985) used to account for stratal disruption in type I mélanges could apply. Connelly (1978) and Moore and Wheeler (1978) ascribed the disruption and folding in the Uyak Complex to progressive strain in tectonic shear zones. Moore and Wheeler (1978) visualized these zones as faults along which ocean-floor and trench sediments were added to a growing accretionary wedge in the hanging wall of a subduction zone.

An important but elusive clue to the actual tectonic setting of deformation (trench, inner trench-slope, continental slope, and so on) probably lies in a correct interpretation of the environment in which the sediments and volcanic materials constituting type II mélanges originally were deposited. Several workers (Cowan and Brandon, 1981; Hein and Karl, 1983; Murchey and others, 1983) have emphasized the unusual and distinctive association of interbedded black mudstone, radiolarian ribbon chert, basaltic tuff, pillow basalt, and volcaniclastic sandstone. Unfortunately, there is as yet no consensus regarding depositional environment, partly because there is no known modern setting in which these materials are presently accumulating together. Several paleogeographic settings have been suggested, including abyssal ocean floor (Connelly, 1978; Moore and Wheeler, 1978), a rifted continental margin akin to the Southern California borderland or Gulf of California (Blake and others, 1982; Hein and Karl, 1983), basins in the vicinity of a ridge-trench triple junction near the continental margin (Cowan and Brandon, 1981), and a rifted continental slope in a forearc setting (Brandon, 1984).

TYPE III: BLOCK-IN-MATRIX MUDSTONE CHAOS

In many ways, the rocks in this category would epitomize mélange for most observers. Certainly, their origin is the most arguable. Hsü (1968) in effect introduced the term mélange to California geology when he applied it to the Franciscan rocks in the vicinity of San Simeon, where type III abounds. Type III mélanges are dominantly polymict; all have a block-in-matrix fabric defined by inclusions of diverse shapes and sizes chaotically disposed (that is, not obviously arranged in stratiform layers) in a fine-grained, pelitic matrix (Fig. 7). Type III differs fundamentally from types I and II because both the origin and ultimate source of most inclusions are obscure or unknown; there is no evidence, for example, that fragments were derived by the progressive *in situ* layer-parallel disruption of bedded sediments. Other Cordilleran examples of type III mélanges are: parts of the central belt of the Franciscan in northern California (Blake and Jones, 1974; McLaughlin, 1978; Aalto, 1981); the upper part of the Coloradito Formation on Cedros Island, Baja California (Boles and Landis, 1984); and the Miocene Hoh mélange on the Olympic Peninsula, Washington (Rau, 1973). World-wide examples probably include the Pliocene Lichi mélange in Taiwan (Page and Suppe, 1981, Plate 5B); parts of the Dunnage mélange in Newfoundland (Hibbard and Williams, 1979); the Tertiary Joes River Formation in Barbados (Pudsey and Reading, 1982); the Bobonaro scaly clay in Timor (Audley-Charles, 1968; Hamilton, 1979); mélange in northern Irian Jaya (Williams and others, 1984); early Tertiary mudstone-rich rocks in the Betic Cordillera of Spain (Hoedemaeker, 1973, Figs. 9–14); and Tertiary allochthonous rocks in the northern Apennines of Italy and in Sicily (Abbate and others, 1970; Page, 1978; Naylor, 1981; and many others). Much of the following summary of important features of type III mélanges is drawn from my work near San Simeon (Cowan, 1978, 1982), where they are particularly well displayed.

Inclusions, Matrix, and Mesoscopic Fabric

The population of inclusions generally includes a variety of rock types, although some domains of a square metre or less in outcrop may be monomict. At San Simeon, inclusions are composed not only of sandstone but of less abundant greenstone (metabasalt) and chert and a small percentage of glaucophane-lawsonite blueschist and other types of foliated metamorphic rocks (Fig. 7A). It is important to emphasize that type III mélange is defined on the basis of its distinctive fabric, rather than the presence or absence of any specific kind of inclusions. In particular, as far as I can tell, the mesoscopic fabrics of blueschist-bearing and non-blueschist-bearing mélanges are identical.

The pelitic matrix ranges from massive (nonfoliated) to weakly fissile to markedly scaly (Fig. 7B). Scaly clay (or *argille scagliose*) can be disaggregated into innumerable polished, lenticular chips. Scaliness defines a weak to strong foliation that is statistically planar in an outcrop but which follows the margins of blocks in detail. It is possible that all type III mélanges are partly scaly, but judging from San Simeon and Piedras Blancas, this fabric is heterogeneously developed, even within outcrops a few metres square.

Clasts range widely in size and have diverse shapes (Fig. 7C). No general rule is applicable, although in some exposures, flattened, oblate ellipsoids, which are grossly lenticular in cross section, are common or predominant. Some inclusions display pinch-and-swell structure, prominent necking, or irregular, drawn-out, wispy terminations. Lenticular inclusions are oriented statistically parallel to the scaly foliation. Some blocks less than a few square metres in size at San Simeon consist of interbedded sandstone and mudstone internally disrupted by ductile, layer-parallel extension.

Taken together, the scaly foliation and irregularly shaped or lenticular inclusions imply that type III mélanges record a heterogeneous bulk deformation, during which some blocks retained their shapes while others were distorted or flattened. In fact, these two fabric elements serve to distinguish type III mélanges from sedimentary pebbly mudstones, which also have, by definition, a block-in-matrix fabric. Moreover, clasts in pebbly mudstones rarely exceed pebble or boulder size (hence the name), whereas a mélange may contain inclusions ranging from a few millimetres to tens of metres and perhaps a kilometre or more in size.

Some additional features of the San Simeon mélange warrant mention here. A more complete description is in Cowan (1978). Variably shaped inclusions indicate that they responded differently during bulk deformation of the mélange. Sandstone blocks range from equant and angular to strongly flattened. Lenticular inclusions of sandstone have shapes similar to necked and flattened blueschists. These mesoscopic changes in shape were accommodated differently on a microscopic scale, however. Many sandstones show scant evidence of broken or comminuted grains, but blueschists and greenstones are thoroughly cataclasized. This difference in behavior may indicate that some sandy inclusions were only partly consolidated during deformation; high fluid pressures promoted intergranular displacements and rotations (Cowan, 1978). The mudstone matrix, which flowed into cracks, fractures, and re-entrants on the surfaces of clasts, conveys an impression of having been extremely mobile.

Some inclusions of sandstone, chert, and blueschist at San Simeon were "frozen" in the process of breaking up into smaller fragments. In small inclusions, extreme necking eventually led to separation. Many inclusions larger than a few metres in diameter have coherent interiors, but their outer few centimetres or so are partly disaggregated where mudstone invaded along a network of fractures. The vast majority of fragments were, nevertheless, originally derived from somewhere other than their immediate surroundings, because they cannot be restored either to nearby inclusions in the same outcrop or to slabs of bedded sandstone and mudstone, tens to hundreds of metres thick, which are in sharp contact with mélange.

Origin of Type III Mélange

The formation of a mudstone chaos is a multistage process. First, fragments of diverse rock types must be broken or plucked from larger, disrupted rock bodies. After initial disruption and fragmentation, the fragments from any one source are widely separated and dispersed through a mobile mud or mudstone host as they are mixed with inclusions from other sources. In some cases, but by no means all, clasts of markedly different ages and metamorphic grades are mixed together. The mélange may experience a bulk deformation, typically expressed by flattened inclusions and scaly matrix, that is somehow connected with the processes of mixing and dispersal or is superimposed on the mélange after its emplacement. Judging from descriptions in the literature (for example, Maxwell, 1974; Page, 1978; Worrall, 1981), all Cordilleran type III mélanges share two fundamental characteristics noted at San Simeon. (1) The origin of most inclusions is obscure because they were derived from neither nearby inclusions nor adjacent rock bodies; and (2) the mélange was ultimately emplaced in a shallow, nonmetamorphic setting. An important conclusion is that each of these chaotic masses of mudstone was emplaced "ready-made," already carrying its complement of dispersed inclusions. In this regard, type III mélange is analogous to ready-made sedimentary pebbly mudstone, but it differs from mélanges of types I and II in which layers of sandstone, chert, and tuff, interbedded with mudstone now forming the matrix of the mélange, were progressively disrupted into isolated fragments *in situ.*

Geologists have proposed several mechanisms to account for the origin of type III mélanges in the western Cordillera. Maxwell (1974) and Page (1978) noted that Franciscan examples are similar in many ways to marine olistostromes. Those at San Simeon have been interpreted as (1) tectonic mixtures resulting from large-scale, gravitational sliding (Hsü, 1967) or imbricate thrusting within an accretionary prism (Hsü, 1973); (2) deformed olistostromes that were deposited in a trench or on a trench-slope at an active subduction zone (Hsü, 1973; Cowan, 1978); and as (3) "flow melanges" formed during subduction-driven flow of unlithified sediments beneath an accretionary prism (Cloos, 1982). Gucwa (1975) and Aalto (1982, Fig. 2) described polymict mudstones in the Franciscan of northern California as variably sheared olistostromes. Rau (1973) and Rau and Grocock (1974) suggested that the scaly Hoh mélange on the Olympic Peninsula formed in a mud diapir; their interpretation is strengthened by offshore seismic reflection profiles showing several such diapirs piercing the sediments in a modern forearc setting (Field and others, 1980). Boles and Landis (1984) found sedimentologic evidence suggesting that parts of the Coloradito Formation in Baja California originated by gravity-induced sliding. Some of the foreign examples cited above also have a controversial origin. Page and Suppe (1981) documented an olistostromal origin for the Lichi mélange in Taiwan. Scaly mudstones in Newfoundland (Horne, 1969; Hibbard and Williams, 1979), the Apennines (Page, 1978; Abbate and others, 1980; and many others), the Betic Cordillera (Hoedemaeker, 1973), and Timor (Audley-Charles, 1968) also have been interpreted as gravity slides or olistostromes. Pudsey and Reading (1982), however, favored the hypothesis that the Joes River Formation in Barbados was emplaced as a mud diapir, and Williams and others (1984) showed that mélange in Irian Jaya has resulted from shale diapirism in a zone of still-active mud volcanism. Hamilton (1979) viewed the inclusion-rich scaly clays on Timor and elsewhere in the Indonesian region as complexly imbricated tectonic mixtures.

Considering all of these mechanisms, two that are certainly compatible with the multistage history outlined above are (1) the emplacement of mud-rich, submarine debris flows or olistostromes and (2) mud diapirism or similar processes involving the migration and intrusion of mobile, mud-rich masses. Both mechanisms allow fragments from diverse sources to be mixed together and dispersed through a mobile matrix of mud prior to the complete lithification of both the mud and some of its inclusions. More important, inasmuch as the masses of chaotic mud themselves are bodily displaced, the fragments they contain can be transported away from their source terranes. The best field criteria for determining whether a particular chaos was emplaced as an olistostrome or a diapir are its over-all geometric form and the nature of its contacts (depositional or intrusive) with adjacent rocks. Unfortunately, the over-all geometry of most type III mélanges in the Franciscan and elsewhere in the western Cordillera is obscure partly because they are prone to excessive landsliding and surficial flowage. Even though some strongly resemble olistostromes in Italy (Maxwell, 1974; Page, 1978) and Taiwan (Page, 1978), their critical contacts are typically unexposed, equivocal, or have obviously been modified by later deformation.

The ultimate source of both matrix and inclusions in diapiric and olistostromal mélanges is speculative. Cloos (1983a) presented mineralogical evidence that the matrix of some blueschist-bearing Franciscan mélanges is sedimentary mudstone that was metamorphosed at depths of 10–20 km. Perhaps, as Cloos (1982) proposed, muds on the ocean floor are first carried deep within an accretionary wedge (Cowan and Silling, 1978) where they can sample (pluck off) fragments of high-grade metamorphic rocks before flowing back toward the surface, rising diapirically, or otherwise intruding (Cloos, 1983b) shallow levels of the wedge. In contrast, unmetamorphosed matrix in ancient mélanges and in active diapirs, such as those offshore of Washington and northern California, may have been derived from rapidly buried, overpressured, unconsolidated slope muds that rose through and sampled partly to completely lithified, overlying strata. The matrix of olistostromal mélanges is presumably shelf or slope mud, but diapirs exposed on the sea floor could also have contributed debris.

What about the hypothesis that type III mélanges are simply tectonic breccias or fault rocks? As Worrall (1981) noted and as I discussed above, these mélanges typically contain inclusions that are foreign to presently adjacent rock units. This important observation seems to require that, even if a type III mélange formed *in situ* as a fault-related tectonic mixture, it has since been mobilized and displaced from its original setting within a brittle shear zone.

A Possible Analogue: Scaly Serpentinite

All pelitic type III mélanges attest to the extreme mobility of mudstone on both outcrop and larger scales. This property alone might explain why the contacts of so many bodies are described as tectonic or "sheared." I think we can get a clearer picture of how these problematical mélanges might have been mobilized and eventually emplaced if we compare them with "sheared serpentinites," which they strongly resemble in many respects.

Sheared serpentinites consist of a weakly to strongly foliated, scaly matrix of generally friable serpentinite containing rounded to lenticular blocks of partly to wholly serpentinized ultramafic rocks, mafic igneous rocks, and, in some cases, a wide variety of sedimentary-rock types. The matrix can be disaggregated into polished lenticular chips or scales. The over-all fabrics of sheared serpentinites and scaly parts of type III mélanges, both of which consist of blocks in a locally scaly matrix, are very similar, although inclusions in mélange display a wider variety of irregular shapes. Scaly serpentinite and mudstone are macroscopically ductile, but their deformation is accomplished by distributed cataclastic flow. Scaly foliation is a fabric element that records the movement picture within a cataclastically flowing body of mobile mudstone or serpentinite. Cowan and Mansfield (1970) estimated that strongly sheared, scaly serpentinite has a shear strength on the order of one bar, orders of magnitude lower than the strength of massive serpentinite. By analogy, scaly mudstone is a comparably weak, readily deformable material. One obvious difference between the analogues is that the matrix of type III mélange is sedimentary (Cloos, 1982), whereas scaly serpentinite forms initially by frictional abrasion within fault zones that cut massive, serpentinized ultramafic rock.

Once generated, however, the matrix is exceedingly mobile (Saleeby, 1985). In some instances, it flowed away from its ultramafic or ophiolitic host into shallow-level, high-angle faults (for example, McLaughlin, 1978). It occurs in a 22-km-long diapir rising through Franciscan rocks in the southern Diablo Range, California (Eckel and Myers, 1946). Scaly serpentinite occurs in ancient and modern debris flows (Cowan and Mansfield, 1970; Lockwood, 1971; Casey and Dickinson, 1976). Some fault zones containing tectonic inclusions set in serpentinite matrix are tens of kilometres long and several kilometres wide (for example, parts of the Ingalls Complex in Washington, Cowan and Miller, 1981; and serpentinite or ophiolite mélanges in general) (Gansser, 1974; Saleeby, 1982). These wide zones of tectonic dislocation present the same perplexing

A

B

C

Figure 8. Examples of type IV mélange. A: Planar fabric, dipping parallel to hammer handle, defined by elongate inclusions of Franciscan sandstone bounded by an anastomosing network of faults (from Cowan, 1974). B: Interbedded white ribbon chert and black mudstone sliced into lenses by anastomosing faults and mudstone-rich fault zones subparallel to hammer head. San Juan Islands, Washington. C: Two approximately lenticular inclusions of sandstone enveloped in a matrix of mudstone and smaller sandstone fragments. Both matrix and inclusions were derived from a rock unit adjacent to the fault zone. The matrix is pervaded by myriad subparallel slip surfaces which impart a crude "shear-fracture foliation." Kenai Peninsula, Alaska.

problem as do type III mélanges: some of the inclusions are exotic in that they apparently were not derived from rocks bordering the sheared serpentinite. Large-scale diapiric movement, or complex heterogeneous flow in response to tectonic stresses, is probably responsible for the considerable tectonic mixing within these serpentinite mélanges (Cowan and Miller, 1981; Saleeby, in press).

I draw this analogy to emphasize that type III mélange is a fundamentally mobile material. Many mélanges that were originally emplaced as olistostromes or diapiric masses have probably been remobilized tectonically and squeezed or intruded into shallow-level faults and fault zones, some of which could be Cenozoic in age. It is not surprising that type III mélanges have proven so difficult to interpret.

TYPE IV: MUDSTONE-DOMINATED BRITTLE FAULT ZONES

Some of the mudstone-rich mélanges with a block-in-matrix fabric in the western Cordillera contain elongate inclusions bounded by a system of subparallel, anastomosing faults. Although very few descriptions of the fabric in type IV mélanges have been published, these tectonites warrant a separate category because they are probably a widespread but largely unrecognized component of Cordilleran terranes like the Franciscan Complex. Moreover, kinematic interpretations (thrust versus transcurrent faulting) are typically ambiguous. Mesoscopic fault-zone fabrics have been emphasized in parts of the Franciscan by Suppe (1973), Cowan (1974),[2] and Korsch (1982). Outside the Cordillera, fault-zone tectonites identified as mélange occur: in the East Coast Deformed Belt of New Zealand, where Pettinga (1982) attributed them to imbricate thrusting in an accretionary wedge; beneath Taconic allochthons in New York (Bosworth, 1984) and

[2]It may be of nomenclatorial interest to note that Cowan (1974) coined the term "tectonic melange" for mappable units which have an "internal fabric dominated by penetrative mesoscopic shear fractures" and which "contain tectonic inclusions of all sizes" (p. 1631). He specifically ascribed the fabric to faulting and interpreted tectonic mélanges as being rock bodies formed in fault zones. Raymond (1975) defined rocks with this fabric as "SF-tectonites."

western Newfoundland (Williams and Smyth, 1983); and in the Gundahl Complex of eastern Australia, which Fergusson (1984) interpreted as having formed largely by tectonic imbrication at the toe of an accretionary prism.

Mesoscopic and Macroscopic Fabric

The principal mesoscopic fabric element is a semipenetrative foliation defined by myriad anastomosing subparallel surfaces of slip (faults, shear fractures) that envelop statistically lenticular tectonic inclusions (Fig. 8). Skempton (1966), Tchalenko (1970), and others have shown that these "shear lenses" and slip surfaces are characteristic of natural and experimental, small- and large-scale brittle fault zones. In type IV mélanges, the dominant deformation mechanism was cataclasis; fault surfaces are generally polished and striated and microfracturing is obvious in thin sections. Lenses are progressively sliced off of either existing lenses, larger slabs, or wall rocks along subparallel faults. Bosworth (1984) defined progressive disruption of this kind as "structural slicing" and distinguishes it from necking and boudinage (of the types prevalent in types I and II), which are manifestations of mesoscopically ductile deformation and ductility contrasts. In type IV mélange, slicing can isolate inclusions consisting of either a single rock type such as sandstone, chert, or basalt; mudstone interbedded with sandstone or chert; or fine-grained cataclastic matrix. Layering in mudstone-rich slices is typically folded or disrupted (Fig. 8B).

It should be stressed that there is a wide range in the amount of mudstone in brittle fault zones and a corresponding range in the strength of their planar fabric (Fig. 8). In general, inclusions are most sharply defined and strongly oriented where mudstone is subordinate to other rock types (Fig. 8A). Where mudstone is more abundant, it occupies wider individual fault zones and thus serves as a typically scaly matrix enveloping inclusions (Figs. 8B, 8C). Locally, inclusions of sandstone, greenstone, and other more competent rock types are variably shaped rather than predominantly lenticular, and many have irregular re-entrants and fractures that were filled or intruded by mudstone.

Pettinga (1982), Williams and Smyth (1983), and Fergusson (1984) were able to document the relation of outcrop-scale fault-zone mélanges to map-scale structure. In each case, variably deformed, but relatively intact, slabs ranging from hundreds of metres to several kilometres long are separated by an anastomosing network of subparallel faults and genetically related zones of mélange. Figure 9, which diagrammatically illustrates the scale-independence of fault-related fabrics, is compatible with their detailed studies. It could represent an outcrop or an area encompassed by a 15-min quadrangle. Note the wide range in the ratio of slabs to matrix. Elongate, subparallel slices predominate where the proportion of matrix is low (compare Figs. 4 and 9 in Pettinga, 1982); irregularly shaped inclusions typify matrix-rich fault-zone tectonite. The over-all sense of displacement is unspecified but could involve large components of either reverse-slip or strike-slip. The mélanges studied by Pettinga (1982), Williams and Smyth (1983), and Fergusson (1984) are associated with imbricate thrusts, but van de Fliert and others (1980) described the map-scale fabric of Figure 9 in high-angle transcurrent fault zones.

It is not yet known how many Cordilleran rock units described as mélange on the basis of simple criteria such as "stratal disruption," "lenticular fabric," "blocks-in-matrix," or "pervasive shearing" owe part or all of their mesoscopic fabric to deformation along faults or within brittle fault zones. Fault-zone tectonites, identified using the fabrics described in this section, might be prevalent where detailed mapping (for example, by McLaughlin, 1978, in the Franciscan Complex) has delineated units of undifferentiated mélange bounded by numerous high-angle faults and thrusts.

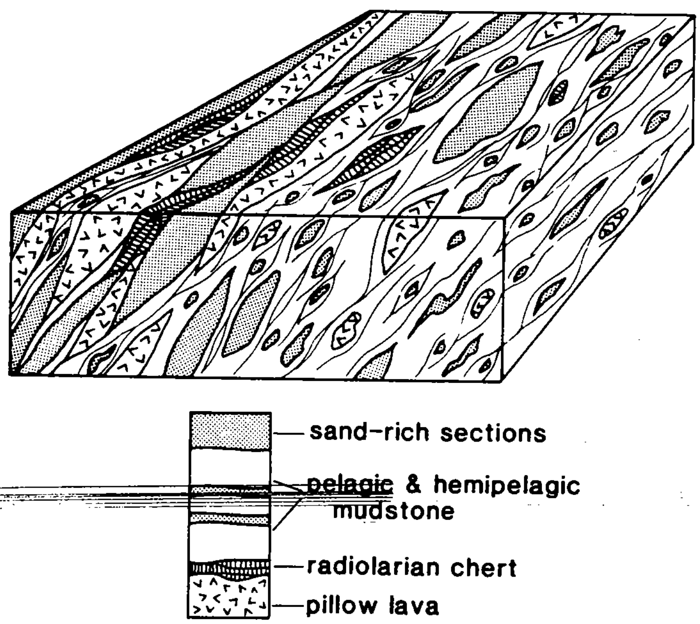


Figure 9. Three-dimensional structure of a brittle fault zone schematically illustrating the fabric characteristic of type IV mélanges at outcrop- to map-scales. In this model, comparable to an actual mélange described by Fergusson (1984), slices are derived from the stratigraphic sequence in the column at the right. Anastomosing fine lines represent faults or scaly fabrics in mudstone-rich matrix. Modified from Cowan and Miller (1981).

MÉLANGES AND SUBDUCTION

Mélanges and plate convergence, or subduction, are closely linked in the minds of many geologists, partly because the first eugeosynclinal assemblage in the North American Cordillera to be described as mélange, the Franciscan Complex, was soon afterward generally interpreted as having formed in a subduction zone. Subsequently, other Cordilleran mélanges, however vaguely or incompletely described, have been used as primary evidence for ancient convergent plate boundaries and sutures. It is fair to say that "subduction melange" is popularly conceived as having formed wherever trench sediments were scraped off of a descending plate of oceanic lithosphere. This virtual equation of mélanges with subduction needs to be reevaluated. For example, four different kinds of mélange are described in this paper; can one or more be identified as not only diagnostic of subduction but also unique to subduction zones?

One approach to this problem is to consider a very simple case: the origin of the four common types of mélange in the context of an idealized accretionary wedge at an active convergent margin. Figure 10, adapted from a more detailed analysis by Cowan (1985), simply illustrates *possible* environments where mélanges could form. High-quality seismic-reflection profiles and deep-ocean drilling during the past decade define several settings in which mélanges, defined as broadly as possible to include stratally disrupted and chaotic block-in-matrix units, could theoretically evolve. Imbricate faulting in the lower trench-slope is known to be a significant deformational process (for example Karig, 1983), and, as mentioned above in this paper, certain type I mélanges are interpreted as having formed in this setting. As Karig (1983) and Moore and others (1981) pointed out, however, ocean-plate materials are almost certainly carried beneath the wedge and underplated, and even though the style of deformation attending this phenomenon is conjectural, examples of types

I, II, and III are envisioned by some workers to have formed in this way. Maxwell (1974), Page (1978), and others have emphasized the possible role of gravity-driven processes on trench-slopes and even in forearc basins, and Suppe (1973) was one of the first to suggest that some Franciscan mélanges may be the product of submarine mud volcanism (diapirs and mudflows) rather than "churning" deep within a wedge. Figure 10 suggests that each of the four types of mélange could have formed in a variety of settings at a simple convergent margin. Even more complicated models are possible because Figure 10 ignores such effects as deformation distributed across the prism, telescoping due to collision, or internal slicing promoted by oblique convergence. In fact, some of the processes invoked to explain the fabrics of mélanges (mud diapirism for the chaotic fabric of type III or brittle faults for type IV, for example) are not restricted to convergent margins at all.

A well-controlled genetic interpretation of a particular mélange requires, in addition to a complete description and kinematic interpretation of its fabric, independent evidence concerning its original, large-scale paleogeographic and paleotectonic setting. For nearly every specific Cordilleran mélange cited in this paper, these independent criteria are lacking, in part because mélanges typically occur in fault-bounded terranes that have been displaced from their original paleogeographic setting. There is, nevertheless, good evidence that most of these mélanges are broadly related to convergence, even if their specific setting within a convergent margin cannot be documented. For example, many occur in structurally thickened terranes comprising landward-dipping, fault-bounded panels that progressively young oceanward, and some are either intimately associated with blueschist inclusions or have themselves experienced high pressure/low temperature metamorphism.

CONCLUSIONS

This review focuses on the mesoscopic features of rocks described as mélange in the western Cordillera. In practice, the term is used for several types of rock bodies which can be differentiated on the basis of structural style and lithologic composition. With regard to the origin of each type of mélange, two questions need to be addressed. The first concerns the deformational and depositional processes that operated locally to produce the characteristic outcrop-scale stratal disruption or block-in-matrix fabrics. Although a variety of processes have been hypothesized, a common theme is the great mobility and deformability of mud or mudstone, which not only influenced mesoscopic fabrics but also determined the geometry and contact relations of type III mélanges. The second question concerns the larger-scale geotectonic environments in which mélanges evolve. I suggest that because we have yet to identify a singular subduction melange, it is inappropriate to conclude, without additional corroborating evidence, that a unit described in the literature simply as mélange necessarily formed

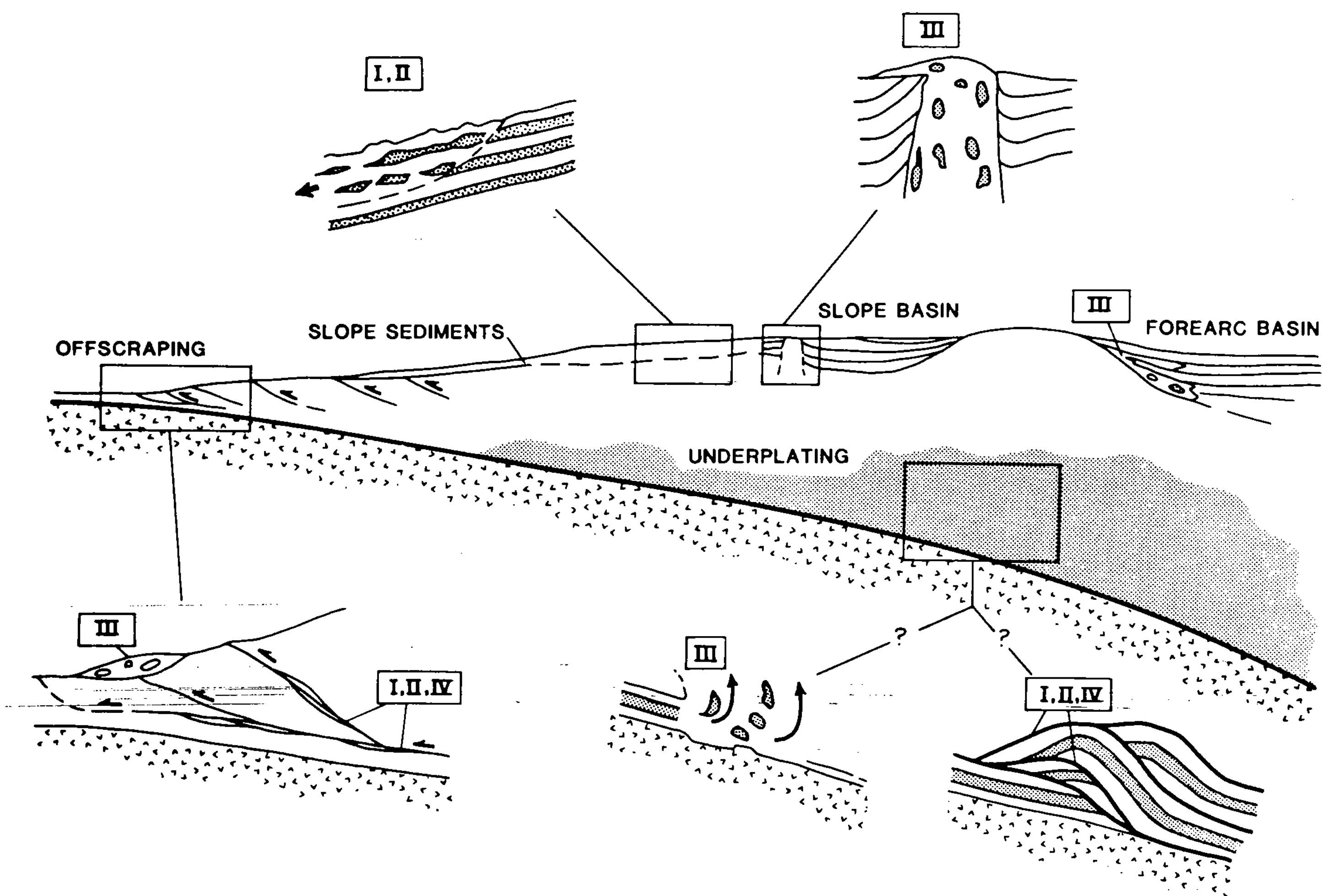


Figure 10. Schematic cross section through an idealized accretionary wedge at an active convergent margin. Diagram illustrates processes that are known or inferred to predominate on or within a wedge and which workers cited in the text have suggested were responsible for the four types of mélange. On the basis of mesoscopic fabric alone, each type of mélange could have evolved in more than one setting. Structural styles in the zone of underplating are hypothetical; imbricate thrust model suggested by Brandon (1984). Adapted from Cowan (1985).

in an accretionary wedge, let alone by offscraping along imbricate thrusts at a trench.

In view of the fact that mélanges in the western Cordillera, and undoubtedly in other orogens, are plural, the term mélange itself has limited utility as it cannot discriminate among different types of disrupted or chaotic rocks. The term should be supplemented or superceded by comprehensive, detailed descriptions whenever possible.

ACKNOWLEDGMENTS

Many people have willingly or unknowingly influenced the evolution of my ideas on mélanges. I am particularly indebted to Mark Brandon, Tim Byrne, and Ben Page for their invaluable contributions and criticism. Some of the material in this paper germinated at the Penrose Conference on Mélanges in 1978, on a field trip sponsored by the Geological Society of America to Baja California in 1979, on a U.S. Geological Survey sponsored field trip in southeast Alaska in 1980, and during recent trips in the Shimanto belt of Japan organized by Yujiro Ogawa and Asahiko Taira. Greg Davis and Clark Blake made important suggestions on an earlier version of the manuscript.

Field work in the San Juan Islands and on Vancouver Island was supported by the National Science Foundation.

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MANUSCRIPT RECEIVED BY THE SOCIETY MARCH 26, 1984
REVISED MANUSCRIPT RECEIVED AUGUST 28, 1984
MANUSCRIPT ACCEPTED SEPTEMBER 16, 1984