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Flow melanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California

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ABSTRACT

In northern California, the central belt of the Franciscan subduction complex of late Mesozoic to early Tertiary age is largely a zone of chaotically mixed pelitic-matrix melange. The melange contains a diverse assemblage of rocks of various sizes and degrees of metamorphism. The most abundant rock types are graywacke and greenstone, but the exotics such as blueschist and eclogite are the most distinctive rocks in the belt. The melange belt is traceable for hundreds of kilometres along strike and is up to tens of kilometres wide. Elongate fragments of most rock types show pinch and swell structure that grades into boudinage. This suggests they behaved as relatively rigid bodies in a ductilely deforming matrix. The general planar preferred orientation of elongate blocks, development of foliation in the matrix, wide separation of blocks, and chaotic mixing indicate that large amounts of flow occurred during melange formation.

The major mineralogy of the matrix is quartz + albite + chlorite + white mica and rarely kaolinite. Minor amounts of pumpellyite and lawsonite are present. Comparison with burial metamorphic sequences and other blueschist terranes indicates that most of the blocks and matrix are compatible with conditions of metamorphism in the range of $100 < T < 250$ °C and $2 < P < 8$ kb.

A model is proposed in which the pelitic matrix melanges of the Franciscan represent zones where flow, driven by the movement of the descending plate, occurred in the accreted sediment pile. When flow occurs in a low-angle corner, a forced convection drives material back to the surface and transports blocks of blueschist and eclogite upward. A varied assemblage develops because fragments of various lithologies and grades of metamorphism are plucked from many points along the walls of the melange wedge and added to subducted material. Laminar flow causes particles to be dispersed. Most large clasts are broken into smaller, rounded fragments by boudinaging as the melange turns the corner to flow back towards the surface. Mixing is enhanced because differences in block size and density cause differential settling of large blocks within the nonuniform velocity field. Oblique convergence causes blocks to take helical paths and may explain the dispersal of blocks such as eclogite along the length of the Franciscan from a few localized sources. The thermal regime in a mature flow melange is such that the downward and upward P-T paths of contained material almost coincide. This accounts for the retrograde blueschist facies metamorphism of the high-grade blocks such as eclogite.

The Franciscan melange belt was probably initially produced by the subduction and deformation of a thick continental margin sequence with a high shale/sandstone ratio (the "Knoxville"). Similar chaotic zones that do not contain exotic blocks in other subduction complexes may have originated as small flow melanges that developed in wide-angle wedges that did not go to great depth.

INTRODUCTION

Many active and fossil subduction complexes around the world contain bodies of rock that have been characterized as melanges. Melanges are mappable bodies of fragmented and mixed blocks in a matrix (Silver and Beutner, 1980). The Franciscan Complex of California and Oregon contains one of the most extensive terranes of melange with a pelitic matrix. In northern California the Franciscan has been divided into the coastal, central, and eastern belts (Blake and others, 1967; Blake and Jones, 1974). The central belt is largely a melange terrane. It is distinguished from the other two belts by a relative lack of coherent structures and the presence of "exotic" blocks of eclogite, blueschist, and amphibolite. These blocks have no readily identifiable source and were originally metamorphosed at higher temperatures than the matrix of the melange in which they now reside. The melange belt is up to 30 km across, and it can be traced more or less continuously from San Francisco into southern Oregon (Blake and Jones, 1974; Koch, 1966). Exposures of similar melange are also present south of San Francisco in the Diablo Range (Ernst, 1965; Cotton, 1972; Cowan, 1974) and even farther south in a narrow strip of discontinuous exposures of Franciscan material along the San Andreas fault zone. Because the melange belt is hundreds of kilometres long, whatever processes are responsible for the formation of the belt must be fundamental to the development of the entire Franciscan subduction complex.

Over the past ten years, most geologists have explained the Franciscan melanges as the product of subduction of the Kula, Farallon, or other plates beneath the North American plate during late Mesozoic time (Hamilton, 1969; Ernst, 1970; Page, 1970). However, the processes involved in melange formation at a convergent plate margin are poorly understood. Previous mechanisms proposed to explain the origin of melange can be characterized as sedimentary, tectonic, or both. However, no single process accounts for the thorough mixing of rock types found in the melanges, as well as the uplift, emplacement, and preservation of once deeply buried blocks of blueschist and eclogite (Jones and others, 1978; Silver and Beutner, 1980). Because both sedimentary and tectonic processes occur at a convergent plate margin, a comprehensive

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study of melange formation must consider their relative significance and interplay.

Sedimentary Models

A dominantly sedimentary origin for melange has been suggested by several workers on the premise that melanges are large accumulations of submarine slides (olistostromes) that moved down the trench wall (Hsü and Ohrbom, 1969; Maxwell, 1974; Cowan, 1978; Page, 1978). Gravity slides or flows are efficient mixers of all rock types exposed in the source area. Because slopes of present trench walls are relatively steep, it is difficult to dispute landsliding as a possible mechanism. Although undisputed slide deposits have not been recognized in the Franciscan, it can be argued that olistostromes are common but are so highly deformed that they are now unrecognizable (Cowan, 1978; Page, 1978). It is still unclear how important landsliding is in trench environments because few olistostromes have been identified in seismic studies of active trench systems (Hamilton, 1978; Karig, 1980). In addition, high pressure rocks such as eclogite have not been found on the walls of trenches. However, the lack of olistostromes in the axis of trenches may just reflect the continual sweeping of trench sediments by subduction. In any case, the olistostrome model does not account for the uplift of blueschists into the source terrane during a continuous period of subduction. The fact that only minor amounts of blueschist detritus have been found in Franciscan sandstones and conglomerates (O'Day and Kramer, 1972; Cowan and Page, 1975; Smith and others, 1979; Moore and Liou, 1980) suggests that a widespread blueschist terrane was never exposed to erosion while the Franciscan accumulated. Lastly, even if the melanges were olistostromes, significant tectonism is still required to account for the ellipsoidal shapes of large high-grade blocks.

Tectonic models

A dominantly tectonic origin of melange has been suggested by several workers. One model postulates that melanges represent chaotic deposits formed at the base of an imbricate thrust system (Hsü, 1973; Hamilton, 1977). A thrust plate would slowly become incorporated in the melange because of gravitationally driven, downslope flow or creep of the trench wall. Usually, many thrusts would operate simultaneously and an approximately steady state could be reached between the rates of underthrusting and downslope flow. Material could be underthrust and elevated many times (Hamilton, 1977). This model is appealing, but the amount of uplift that can be obtained by underthrusting as well as the degree of mixing are uncertain. Ernst (1975) suggested that large imbricate slices that are decoupled from the down-going plate at depth may rise buoyantly towards the surface owing to erosion of the top of the slice. Thorough mixing occurs as the eroded ends of thrust slices are redeposited as olistostromes. However, the lack of evidence of significant exposure and erosion of blueschists at the surface of the Franciscan trench slope argues against this model.

Another model proposes that the melanges develop as broad fault zones that extend to great depth and possibly widen with time as more material is accreted (Hsü, 1971, 1973; Suppe, 1973; Cowan, 1974; Moore and Karig, 1980). Displacement occurs along innumerable anastomosing faults that change position with time and effectively dismember, mix, and round any rock type that becomes incorporated in the zone. Again, it is difficult to envision how high-pressure rocks are uplifted.

A third tectonic model is based on the linear nature of the Franciscan melange belt. Some workers suggest that the melanges developed as broad strike-slip fault zones or shear zones that were related to the San Andreas or ancestral faults (Bailey and others, 1964; Dott, 1965; Koch, 1966). Recently, Saleeby (1979) described the Kaweah serpentinite-matrix ophiolitic melange in California and inferred that mixing developed along an oceanic fracture zone. However, this serpentinite melange, unlike the Franciscan melange, does not contain exotic blocks. Some parts of the Franciscan melange belt are presently being deformed by strike-slip displacement related to the San Andreas fault (Fox, 1976; Herd, 1978) as part of the change in plate motion during the Tertiary (Atwater, 1970). This motion may locally contribute to mixing, but the mechanism of uplift and emplacement of exotic blocks is still unanswered.

In a modification of the strike-slip model, Karig (1980) proposed that high-pressure metamorphic rocks could be exposed on, or near, the trench slope by the removal (tectonic erosion) of part of the accretionary prism closer to the trench axis (Karig and others, 1978). Once exposed, the metamorphics could be emplaced at the base of the slope by sedimentary transport or thrust faulting. Continued or renewed subduction would form melange containing blocks that were once deeply buried. Karig's model may be applicable to some complexes, particularly those with complicated histories of plate convergence. Vertical displacements of at least 4 km are well documented along the San Andreas fault (Crowell, 1974), and uplift resulting from the combined effects of isostatic adjustment and folding associated with wrench tectonics might be greater (Karig, 1980). However, blocks of eclogite and high-grade blueschist must have been uplifted 20 to 30 km or more and from locations that were probably beneath the fore-arc basin. Thus, a major problem in applying this model to the Franciscan is that the required amount of uplift for the high-grade blocks appears to be considerably larger than that observed along a major strike-slip fault such as the San Andreas. Also, it is assumed in this model that melange formation must occur near the trench axis because of the unwarranted assumption that the shale matrix of the melange was never deeply buried.

As mentioned, one of the major problems that must be considered in explaining the origin of the Franciscan melanges is the mechanism of uplift of the high-grade blocks such as eclogite. One mechanism that has been suggested is that the blocks were uplifted in serpentinite diapirs (Coleman, 1961; Ernst, 1965) and subsequently dispersed by sedimentary processes (Lockwood, 1971). The fact that many of the blocks have remnants of an actinolite rind demonstrates former association with serpentinite (Coleman and Lanphere, 1971; Moore, 1980). Uplift of eclogitic rocks in serpentinite diapirs appears to have occurred in several former subduction complexes such as the Alps (Ernst, 1976) and Ecuador (Feininger, 1980). However, serpentinite diapirs that came from sufficient depth to carry blocks of eclogite should have emerged in the Great Valley fore-arc basin. Some blueschists may have been uplifted in this manner because a blueschist clast was reported in a sedimentary serpentinite near Wilbur Springs (Carlson, 1981). Also, the blueschist bearing New Idria serpentinite rose in the Tertiary after subduction stopped (Coleman, 1961). But many, if not most, of the high-grade blocks have no present relationship to serpentinite (Bailey and others, 1964, p. 105). Furthermore, the serpentinite diapir model requires many stages. The first would be emplacing the blocks in the serpentinite, followed by their rise towards the surface, subsequent removal from the serpentinite (but without exposing the blocks to much sedimentary reworking at the surface), and finally emplacing them in the pelitic matrix melanges and tectonizing them to develop their ellipsoidal shape. While possible, even such a complicated history does not begin to address the metamorphic history of the blocks (discussed later) and their wide dispersal down strike in the Franciscan.

While all of the previously mentioned processes could create a chaotic package of rocks that could be called a melange, none of them adequately explains all of the features of the Franciscan melange belt. The main purpose of this paper is to present a tectonic model that can account for the mixing of the pelitic matrix melanges of the central belt of the Franciscan as well as the incorporation, uplift, and retrograde metamorphism of the high-grade blocks. But first, a review of the structure and metamorphism of the Franciscan melange belt is warranted in order to summarize some of the tetonic and petrological constraints on its origin.

FRANCISCAN MELANGES

The pelitic matrix melanges of the Franciscan were first studied in detail in the mid-1960s by Hsü (1965, 1969) who stressed the problems of working in such a chaotic terrane. Hsü investigated melange terranes just south of San Francisco and in the Santa Lucia Range. He recognized that the stratigraphic laws of superposition and lateral continuity do not hold for melanges and that included fossils do not date the time of formation (Hsü, 1968, 1974). Hsü described many structural aspects of the melanges and proposed several mechanisms to account for their origin. More recently Cowan (1974, 1978) has investigated the Franciscan melanges in the Diablo Range and near the town of San Simeon. The present report is based on field studies of Franciscan melanges in the above areas and in northern California, principally near Covelo and Garberville. The following general description of the structure of the pelitic matrix Franciscan melanges is modified in part from the studies of Cowan and Hsü.

Field Relations

The melange terrane is characterized by hummocky, grass-covered hillsides dotted by protruding blocks ("knockers") that are relatively resistant to erosion. These blocks consist of chert, graywacke, conglomerate, greenstone, blueschist, serpentinite, and rarely eclogite and amphibolite. Typically, their diameters range from more than 20 m to less than a few centimetres. In several areas, slabs of bedded graywacke, each several kilometres long, have been recognized as well as large bodies of serpentinite (Hsü, 1969; ~~Maxwell, 1974; Cowan, 1974~~; McLaughlin, 1978; Page and others, 1979). Usually, the matrix is poorly exposed because it is erodable and unusually susceptible to surficial mass movement. Because preferential erosion of the matrix tends to concentrate the high-grade metamorphic blocks on the surface or in stream bottoms, it is often difficult to demonstrate that the blocks dispersed around the countryside are, or were, immersed in the melange. This makes it difficult to subdivide large tracts of melange into different units on the basis of type and abundance of various blocks and the type of matrix.

Structure

Observation of the structural relations between the blocks and the matrix is usually inhibited or prevented by poor exposure. Outcrops in roadcuts and stream bottoms are usually small and discontinuous. The best place to see structure in the melange is in the seacliffs near San Simeon. These cliffs are 5 m or more in height, and they are nearly continuous for several kilometres. In the seacliffs, elongate fragments of all rock types have a rough preferred orientation, with their long axes parallel to a crude spaced cleavage in the matrix. The cleavage plane, which is most obvious on weathered exposures, tends to dip steeply landward, but it curves to parallel the edges of blocks. Locally, the cleavage surfaces appear polished and, more rarely, slickensided.

Near San Simeon, the largest blocks that can be seen surrounded by matrix are about 10 m across. The shale matrix/block ratio is about 1. This ratio is probably typical for the poorly exposed parts of the melange belt. On the outcrop, the relative numbers of blocks of graywacke and greenstone are, in a crude way, inversely proportional to their area. Blocks less than about 10 m across are usually approximately ellipsoidal in shape but, where a good three-dimensional view of the melange is available, small inclusions, commonly of greenstone or graywacke, can be found as highly flattened, often elongated "pancakes," which are oriented roughly parallel to the cleavage. The aspect ratios of different blocks can show considerable variation within a single outcrop, but the true shape of blocks larger than a few metres across is difficult to determine in two-dimensional exposures. Rock types such as chert, greenstone, graywacke, and even low-grade blueschist locally have developed pinch-and-swell structures that in places grade into boudinage (Cowan, 1978). Evidence of rotation of blocks is scarce. Typically, on each individual outcrop, less than 5% of the blocks show clear evidence of having been generated by the boudinaging of larger blocks. However, when boudins are separated by more than a few metres, it is difficult to "rejoin" them with certainty because other rock fragments of different lithology would have been interspersed when the matrix flowed into the gaps. Blocks which can be identified as once probably having been boudins, range in size from about 10 m across to the smallest structures resolvable in thin section. Some elongate blocks or bedded units of graywacke are cut by extension or shear fractures (as defined by Handin, 1967). Usually these faults cannot be traced very far into the enveloping shale.

The matrix has *not* been derived from the "milling down" of blocks. The estimated proportions of phases from X-ray diffraction study indicate that the matrix is of pelitic bulk composition. Thin section study of matrix samples shows mica grains are micron sized. This indicates only minor enlargement of grains during recrystallization. During deformation, grain boundary sliding may have been important as the deformation mechanism (Borradaile, 1981) and high fluid pressures (discussed below) probably supported some or most of the load, thereby enhancing rotation of grains.

As discussed before, an important question is whether deformation of clasts in the melange is dominantly the result of processes near the sediment-water interface or deeper (that is, tectonic). The cause of mixing is a more fundamental problem. During early stages of deformation, the shale matrix and clasts of siltstone, graywacke, chert, and tuffaceous greenstone may have been unlithified. Clasts of graywacke rarely show any evidence of brecciation, and intricate re-entrant boundaries and tails may be similar to those expected to develop in weakly lithified sediment incorporated within submarine slides or debris flows (Kleist, 1974; Gucwa, 1975). On the macroscopic scale, many clasts of chert and greenstone appear to have a ductility similar to that of graywacke, but they frequently show evidence of brecciation along their margins and in the necked region between boudins (Cowan, 1978), indicating they were lithified during deformation. Furthermore, mafic blueschists, which certainly were completely lithified during deformation, have developed pinch-and-swell or boudinage structure on the macroscopic level and have brecciated on the microscopic scale. The tectonism that is required to contort lithified clasts of blueschist, greenstone, and chert into complex shapes certainly would be sufficient to cause similar (if not more dramatic) effects in partly or completely lithified graywacke. Therefore, even though many clasts may once have been unlithified and initially deformed by surficial processes, it seems that their shapes can equally well be explained as *solely* resulting from tectonic deformation.

As mentioned before, rock is *not* milled, ground up, or crushed to form the matrix. For the most part, large blocks are transformed into smaller fragments by boudinaging or fracturing. Large equant blocks of graywacke sometimes fracture into several elongate fragments that become separated by the intrusion of shale matrix. These elongate fragments develop pinch-and-swell structure or boudinage to form even smaller pieces. By such processes, big blocks of graywacke and other rock types are disaggregated. Considerable variation can be seen in the behavior of certain rock types. Some blocks of graywacke, for example, have boudinaged, whereas others in the same outcrop have fractured. Some chlorite-rich greenstones (possibly originally tuffaceous or altered serpentine) are streaked out into thin wisps and stringers, indicating that the ductility contrast between them and shale can be quite small. Differences in ductility of clasts are probably due to variations in grade of metamorphism, degree of recrystallization, and grain size. Local variations in strain rate and changes in P, P_{H_2O}, and T during deformation may also have been important.

It is difficult to estimate the magnitude of strain in the melange. Bedding is rare in small blocks of graywacke incorporated within the melange (Cowan, 1978). Slabs of bedded graywacke which are kilometres long and surrounded by melange are often boudinaged or fractured and have been called "broken formations" (Hsü, 1969; Cowan, 1974; Smith and others, 1979). Many of these slabs appear coherent in their interiors, but they are almost always surrounded by subsidiary blocks derived from them. In this way, they tend to grade into the enveloping melange (Cowan, 1974; Smith and others, 1979). Greenstones rarely exhibit much relict structure, but the more thoroughly recrystallized blueschist blocks often have a layering that developed before incorporation in the melange. Blocks of both deformed and undeformed conglomerates are present (Platt and others, 1976). Commonly, chert fragments have preserved bedding, but locally they are highly contorted. For the most part, clasts of various lithologies have behaved as relatively rigid blocks and their shape does not record total strain in the ductile matrix. The fact that many boudins appear to be stretched out and separated suggests substantial strains. The lack of bedding or lamination in most fragments of graywacke suggest the deformation was of sufficient magnitude to cause fragmentation of such sediments along all planes of weakness or discontinuity. In addition, the over-all preferred orientation of elongate clasts suggest that total strain is considerable. Field relationships described above indicate that most, if not all, of the deformation of the melanges is of tectonic origin as opposed to being related to olistostrome formation. The deformation can be best characterized as ductile flow of a large magnitude in the shale matrix and smaller amounts in most clasts.

METAMORPHISM

Information on the metamorphic history of the blocks before and after their incorporation into the melanges puts valuable constraints on models for the origin of melanges. A study of the metamorphism of both the blocks and matrix will be presented elsewhere (Cloos, 1981, and in prep.), and the account below is a preliminary summary of some of the results of that study and of earlier investigations by other workers. Because the Franciscan melanges contain blocks of blueschists, the development of melanges has become, to some workers, synonymous with subduction, even though many other melanges do not contain "exotic" blueschist blocks. This perspective on the relationship of melanges to subduction has developed, in part, because a subduction zone is the only tectonic regime with suitable P-T conditions for blueschist-facies metamorphism (Ernst, 1971a).

By far the most abundant type of mafic block in the Franciscan melanges is greenstone (a general field term for any green-colored mafic rock). The color of Franciscan greenstones is due to abundant chlorite. Other major constituents include albite ± pumpellyite ± lawsonite ± Na-pyroxene ± quartz ± sphene. Some samples contain relict igneous pyroxene and plagioclase. In places, greenstone can be found intimately intermixed with low-grade blueschist (glaucophane + lawsonite + chlorite + sphene). In many cases, the textural relations are equivocal and the greenstones may have been replacing blueschist, blueschist replacing greenstone, or the two assemblages may have been coexisting.

Blocks of high-grade blueschist (glaucophane + epidote + rutile or sphene ± Na-pyroxene ± garnet ± white mica) and eclogite (garnet + Na-pyroxene + rutile ± epidote ± white mica) are among the most enigmatic features of the Franciscan melanges because they must have been metamorphosed at great depth and then uplifted. Although they are a volumetrically minor constituent of the Franciscan, they have a wide distribution (Bailey and others, 1964; Coleman and Lanphere, 1971). The large grain size of minerals in these blocks makes them more amenable to study than the fine-grained, low-grade blocks. Many studies have concluded that these blocks were originally metamorphosed at temperatures of 400 °C to over 500 °C and at pressures of 7 kb or more (Coleman and Lee, 1964; Taylor and Coleman, 1968; Ernst and others, 1970; Ghent and Coleman, 1973; Brown and Bradshaw, 1979). These exotic blocks are clearly out of metamorphic equilibrium with the rest of the melange, and commonly show alteration along their margins to low-grade blueschist assemblages. Ernst (1977) pointed out that during retrograde metamorphism they must have traversed the same P-T path as did the other Franciscan rocks during prograde metamorphism, but in the opposite direction. Thus their presence is compelling evidence that subduction zones can be "two-way streets" (Suppe, 1972; Coleman, 1972a).

Graywacke is by far the most abundant type of block, but field inspection of hand specimens and outcrops generally does not reveal obvious indications of high-pressure metamorphism. Detrital minerals and textures are often well preserved, and thin-section study is required to see evidence of incipient recrystallization even in the blueschist facies. Because of disruption, the sequence of mineralogic changes from unmetamorphosed graywacke to high-grade metagraywacke can only be inferred (Blake and others, 1967; Ernst and others, 1970; Ernst, 1971b). Major metamorphic changes include the replacement of laumontite by pumpellyite or lawsonite. Aragonite, Na-amphibole, or, commonly in parts of the Franciscan, jadeitic pyroxene grew at the highest pressures. Most of these phase changes reflect increasing amounts of pressure rather than temperature. Graywackes containing some or all of these diagnostic phases can be found as small fragments a few centimetres across up to slabs several kilometres long totally surrounded by melange (Maxwell, 1974; Cowan, 1975; McLaughlin, 1978; Ernst, 1980).

The shale matrix has received inadequate study by past workers, probably because of its fine grain size. Bulk X-ray diffraction studies of 25 samples of the pelitic matrix of Franciscan melanges from northern California and near San Simeon show that it consists of an assemblage of quartz + albite + chlorite + phengitic white mica and rarely kaolinite. Small amounts of pumpellyite and lawsonite have been recovered following disaggregation and heavy liquid separations of the matrix. These phases have also been reported in "matrix" samples by Jones and others (1978). The relatively coarse grain size of the separates, their association with phengitic mica and the lack of accompanying glaucophane, pyroxene, garnet, and epidote indicate that these high-pressure–low-temperature phases were growing *in situ* and are not detrital.

METAMORPHIC CONDITIONS AND CONSTRAINTS FOR MELANGE FORMATION

A fundamental concern in studying melange formation is the magnitude of metamorphism of the shale matrix because this indicates the depth of burial and thermal regime of the melange during deformation. The mineralogy of the matrix samples is identical to the essential mineralogy of high-pressure metashale at Pacheco Pass, California. This shale was subjected to pressures of at least 5 kb because it is interbedded with jadeite-bearing metagraywacke (Ernst and others, 1970). Shales remain fine grained during low-temperature blueschist-facies conditions, and few phase changes occur in them. One reason for the lack of such phase changes is their low calcium content. The Ca-silicates and carbonates undergo many of the mineralogic changes that are diagnostic of grade in blueschist facies metamorphism of graywacke and basalt. Because of these complications, field inspection of shale is inadequate for evaluating the pressure conditions to which the shales were subjected. In fact, many supposedly "unmetamorphosed" bodies of Franciscan shale may well have been subjected to pressures in excess of 5 kb.

The absence of montmorillonite group minerals in unweathered matrix and the presence of chlorite and secondary white mica indicate minimum temperatures on the order of 100 to 150 °C by comparison with burial metamorphic zones (Burst, 1969; Zen, 1974; Hower and others, 1976; Ghent, 1979). The presence of pumpellyite and rarely kaolinite and the lack of pyrophyllite, glaucophane, spessartine, stilpnomelane, paragonite, chloritoid, and epidote provide upper temperature limits of 200 to 300 °C by comparison both with burial sequences and other blueschist facies terranes such as New Caledonia (Black, 1974, 1977; Diessel and others, 1978). Independent confirmations of this temperature range include vitrinite reflectance studies of graywackes near Pacheco Pass where, as mentioned, the shale has the same basic mineralogy as most matrix samples. The reflectance studies give temperature estimates that range from 110 to 150 °C (Bostick, 1974). The color alteration of conodonts in chert cobbles within conglomerate blocks near San Simeon indicate those melange blocks could not have been subjected to temperatures greater than 60 °C for many tens of millions of years or temperatures as high as 150 °C for more than a few million years (Seiders and others, 1979).

Oxygen isotope geothermometry of glaucophane-bearing metabasalt at Ward Creek (Taylor and Coleman, 1968) gives temperature estimates for the *in situ* low-grade blueschists (Type III of Coleman and Lee, 1963) of 170 to 220 °C using recalibrated quartz-carbonate and quartz-mica fractionations (O'Neil and others, 1969; Clayton and others, 1972). The fact that most of the mafic blocks in the melanges are greenstones instead of blueschists indicates that the melanges were metamorphosed at lower temperatures (Brown and Bradshaw, 1979) or lower pressures (or both) than was the Ward Creek blueschist. Another independent confirmation of very low temperatures is the widespread occurrence of aragonite in the Franciscan (Coleman and Lee, 1962; Brown and others, 1962). Aragonite most often occurs as fracture fillings or linings in blocks or slabs in the melanges. The recrystallization rate of aragonite is fast enough that none should be preserved during uplift of the blocks if temperatures were above 200 °C for pressures below that of the aragonite-calcite transition (Carlson and Rosenfeld, 1981).

Pressure is a more difficult variable to determine, but it is very important in that it allows a depth of burial to be estimated. The presence of lawsonite in some samples of matrix suggests minimum pressures of 3 kb for some samples (Thompson, 1971; Liou, 1971). Unlike many subduction complexes such as the Alpine Belt of New Zealand (Coombs, 1960) and the Uyak Complex of Alaska (Connelly, 1978), which have well-developed zones in the prehnite-pumpellyite facies, prehnite is scarce in the Franciscan melange belt. Because of the lack of prehnite, pumpellyite-bearing greenstone and graywacke of the Franciscan can be characterized simply as pumpellyite facies. The lower pressure limit of the pumpellyite facies is unknown but must be at least 3 to 4 kb (Seki, 1969; *compare* Perkins and others, 1980). Upper pressure limits are more difficult to constrain. The presence of albite instead of jadeite and quartz indicates a maximum pressure of metamorphism of the matrix of 8 to 10 kb in the temperature range of 100 to 250 °C (Newton and Smith, 1967).

The study of the metamorphism of the Franciscan melanges is still far from complete, but the comparison of the present data with other metamorphic belts strongly suggests that the melanges in northern California, the Diablo Range, and near San Simeon were metamorphosed at very low temperatures and relatively high pressures. With the notable exception of the high-grade blueschists, amphibolites, and eclogites, the metamorphic grade of all rock types and matrix is compatible with the range in conditions of $100 < T < 250$ °C and $2 < P < 8$ kb. A depth of burial of at least 6 km and probably much more is required for the melanges. If the melanges were the only medium in which blocks of eclogite were transported to near the surface, then parts of the melange belt must have been buried to depths of at least 25 km.

LARGE-SCALE FLOW OF SHALE

Most models of subduction zone deformation show sediments being detached from the downgoing plate along discrete thrust faults (for example, Karig and Sharman, 1975; Hamilton, 1979). These models have been constructed from limited marine geophysical studies and even fewer field and drill core studies, all of which are restricted to the top few kilometres of the accreted wedge. The extrapolation of these observations to greater depths is difficult because of the poor understanding of the changes in the material properties of sediments with burial. In particular, the Franciscan melange belt has defied subdivision into a series of imbricate thrusts. Instead, the field descriptions suggest that the Franciscan melanges underwent ductile flow of unknown but possibly large magnitude. This indicates that major changes occur in the mechanical behavior of sediment as it is subducted. Even though it is difficult to correctly scale models of subduction zones, the clay cake experiments of Seeley (1977) and Cowan and Silling (1978) are instructive. At the beginning of both experiments, imbricate thrust faults developed. However, Cowan and Silling noted that flow rather than faulting occurred in clays that became "deeply" buried in their growing accretionary wedge. This led them to propose that flow can occur deep within a subduction complex while thrusting occurs near the trench axis. In addition, they observed that material rose upward along the vertical wall that formed a right angle corner with the underthrust slab. They proposed that such flow could uplift blueschists.

There is reason to believe that significant viscous flow is to be expected in a subduction complex, particularly if abundant shale is being accreted. This is because shale can flow viscously. Examples of this behavior include the development of growth faults due to the diapiric rise of low density shales in the Gulf Coast region of Texas (Bruce, 1973; Harding and Lowell, 1979). Diapirs or shale-cored anticlines of oceanic pelagics have also been recorded in the deep ocean in areas where shales have been loaded by the deposition of terrigenous sediment (Tiffen and others, 1972; Lancelot and Embley, 1977; Hamilton, 1977). Similar shale diapirs crop out along the coast of Washington (Rau and Grocok, 1974) and offshore of California (Field and Gardner, 1980). Mudlump islands in the deltas at the mouth of the Mississippi (Morgan and others, 1968) and Magdalena Rivers (Shepard and others, 1968) are further evidence of the flow of shale or clay masses after only moderate loading. Yet another example of flow in mudstone is the common engineering problem of "Squeezes" in coal mines, tunnels, or excavations (White, 1956; Harper and others, 1979). A squeeze occurs when the loaded underclays or shales flow up from the floors or in from the walls to fill the mined-out room or excavation. It is important to note that all of these examples of flow in shale are from relatively shallow depths of burial.

In a subduction complex, near-surface fracturing may facilitate dewatering (Arthur and others, 1980). However, at depth, abnormally high fluid pressures should be produced by the combined effects of gravitational and tectonic compaction (Bredehoeft and Hanshaw, 1968; Berry, 1973) because the low permeability of shale prevents the rapid dissipation of high fluid pressures (Hubbert and Rubey, 1959). Temperature- and pressure-induced dehydration reactions in clays and mixed-layer micas would also keep the fluid pressures high, possibly near lithostatic values (Burst, 1969; Barker, 1972). Overpressured and undercompacted shales deform like a viscous fluid once cohesion is overcome (Hedberg, 1974; Seeley, 1977). Ductile flow is enhanced because the high fluid pressures support part of the load and allow grains to rotate (Handin and others, 1963; Borradaile, 1981).

Many examples demonstrate that shale can flow at relatively low confining pressures. In a subduction zone, overpressuring of shale should enhance flow. Hence, the idea that Franciscan melanges were zones of tectonically driven flow deep within the accreted sediment pile is reasonable. In fact, it seems probable that flow should be expected whenever abundant shale is subducted.

THE MODEL

The Franciscan Complex appears to have accumulated at the junction of convergent plates, and the melange belt is a large part of this accumulation. Metamorphism of both the matrix and included blocks indicates that the belt was buried to depths considerably greater than the thickness of the sediment pile at the fore-arc high of presently active subduction complexes (about 10 km = 3 kb; Hamilton, 1979). Many of the blocks included in the melanges must have been buried at mantle depths beneath the hanging wall of the overriding plate. The simplest geometry for these offscraped and metamorphosed sediments is that they were accreted into a low-angle wedge formed between the overriding and descending plates (compare with Ernst, 1970). It is proposed that the Franciscan melanges that contain exotic blocks in a pelitic matrix are zones in which a forced convection or reversed flow occurred in sediment accreted into the wedge. Blocks carried down in the melange or detached from the hanging wall were transported to near the surface in the upwelling melange (Cloos, 1980). The circulation of clay modeled in the laboratory experiment of Cowan and Silling (1978) has many similarities to the analysis in this paper.

Figure 1 illustrates an idealized subduction zone and shows the circulation pattern envisioned within the melange zone. This geometry is identical to the fluid mechanics problem involving flow of a viscous fluid in a corner with a moving boundary. A similar corner-flow problem has been treated by geophysicists in modeling induced convection of the mantle above the subducting slab (McKenzie, 1969; Tovish and others, 1979). One purpose of this analysis is to show how the proposed circulation could produce not only the required uplift of blueschists but also the mixing of blocks in melanges.

For modeling purposes, simplifying assumptions must be made. These assumptions are discussed in the following section. The melange is assumed to be incompressible and to have uniform newtonian viscosity; the walls of the wedge are rigid; the wedge angle, θ^0 is 10°; the plate dip, α, is 25°; and the wedge length, L, is 100 km. The subduction rate, U, was varied in different calculations from 2.5 to 10 cm/yr. The idealized problem (Fig. 2) is two-dimensional because the geometry of the melange wedge is assumed

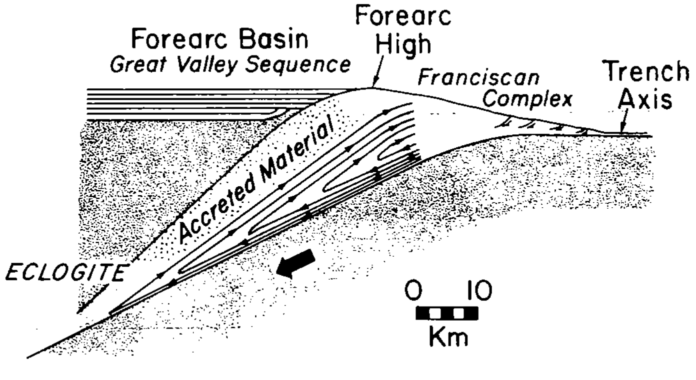

Figure 1. Schematic cross section illustrating the circulation pattern of the Franciscan flow melange during late Mesozoic convergence. (Compare with Fig. 7 of Cowan and Silling, 1978.)

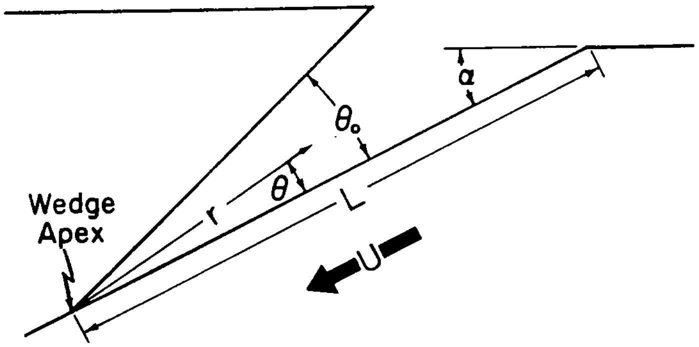

Figure 2. Diagram showing parameters that were varied in the modeling. Particle location in polar coordinates, r, θ : wedge angle, θ_0; plate dip, α; wedge length, L; and subduction rate, U.

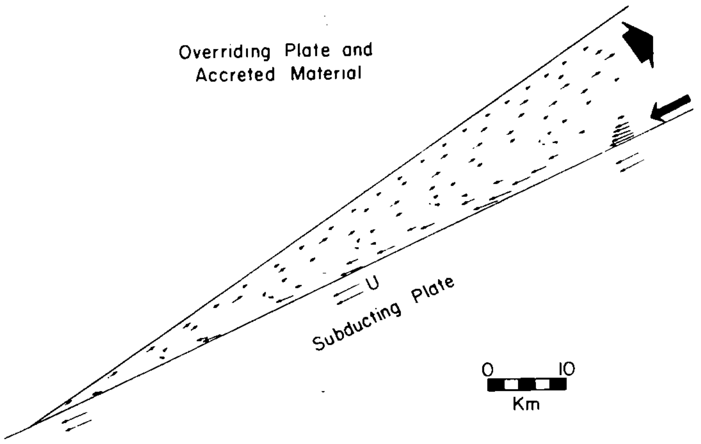

Figure 3. Velocity field calculated in the flow melange. Vectors are proportional to the subduction rate U. The wedge angle $\theta_0 = 10°$. Note the narrow zone going downward fast with large velocity gradients and the broad zone going upward more slowly.

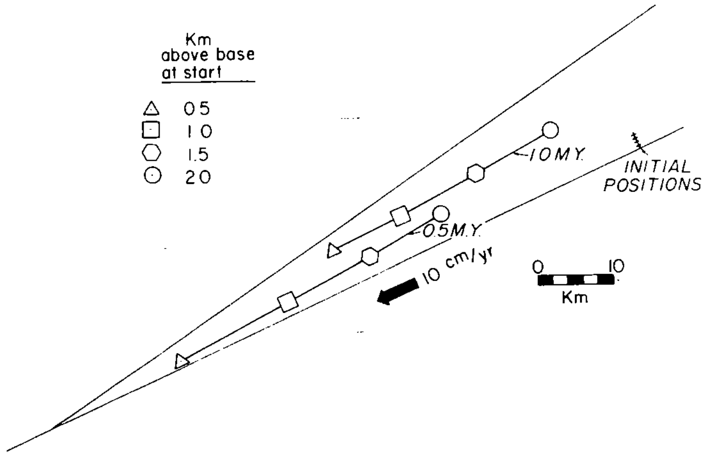

Figure 4. The dispersal of particles due to nonuniform laminar flow. Particles initially separated by 0.5 km become separated by 15 km after 500,000 yr at a 10 cm/yr subduction rate. During upward flow, the particles tend to come together but have a separation of 10 km upon reaching the original depth of burial.

not to vary along strike of the complex. Because the problem is two-dimensional and mass is conserved, use of the stream function, ψ, simplifies the problem. In polar coordinates the derivatives of ψ (Batchelor, 1967, p. 77) give the velocity, v, in the r and θ directions:

$$V_r = \frac{1}{r}\frac{\partial\psi}{\partial\theta}$$

$$V_\theta = -\frac{\partial\psi}{\partial r}$$

The boundary conditions for this geometry are:

$$\frac{\partial\psi}{\partial r} = 0,\ \frac{1}{r}\frac{\partial\psi}{\partial\theta} = -U \text{ at } \theta = 0$$

$$\frac{\partial\psi}{\partial r} = 0,\ \frac{1}{r}\frac{\partial\psi}{\partial\theta} = 0 \text{ at } \theta = \theta_o$$

The general solution of the equations of motion for the given boundary conditions is (Batchelor, 1967, p. 225):

$$\psi = \frac{rU}{\theta_0^2 - \sin^2\theta_0} - [\theta_0^2 \sin\theta + (\theta_0 - \sin\theta_0\cos\theta_0)(\theta\sin\theta) + \sin^2\theta_0(\theta\cos\theta)]$$

Standard Runge-Kutta methods (Boyce and DiPrima, 1970) were used to calculate the position and velocity of particles with time as they circulated within the wedge.

Uplift and Dispersal Due to Laminar Flow

Material is uplifted in a flow melange because of the reversal of flow within the wedge. The streamlines in Figure 1 show the paths that particles would take within the flow melange if they did not sink or rise. Figure 3 shows the wedge with enough calculated velocity vectors to illustrate the nature of the velocity field within the wedge. Note that a relatively narrow zone in the lower part of the wedge moves downward and a much broader zone in the upper part of the wedge moves more slowly upward. The velocity gradients in the downward-moving part of the wedge are greater than in the upward-moving part so material in the lower part of the wedge is being sheared more during any given amount of displacement than material in the upper part. Figure 4 illustrates the separation that could occur for particles immersed in a flow melange wedge with a 10 cm/yr subduction rate. In this case, particles at 0.5, 1.0, 1.5, and 2.0 km above the lower plate become separated from each other by 15 km after flowing for 500,000 yr, at which time they begin their return to the surface. Because of the nature of the velocity field in the upper part of the wedge (Fig. 3), the separation decreases during upward flow, but when the melange has reached the original depth of burial the blocks still have a separation of 10 km (a distance between blocks that is 20 times the original separation!). This dispersal of particles occurs simply by laminar flow. Melange that flows to near the surface may become recoupled to the descending plate. When this happens, the cycle starts over again and contributes to further dispersal. For the given conditions (length of wedge = 100 km, a 10° wedge angle, plate dip = 25°, and a 10 cm/yr subduction rate), the "turnaround time" would be about 2 m.y. Slower subduction rates would cause proportionally longer transit times.

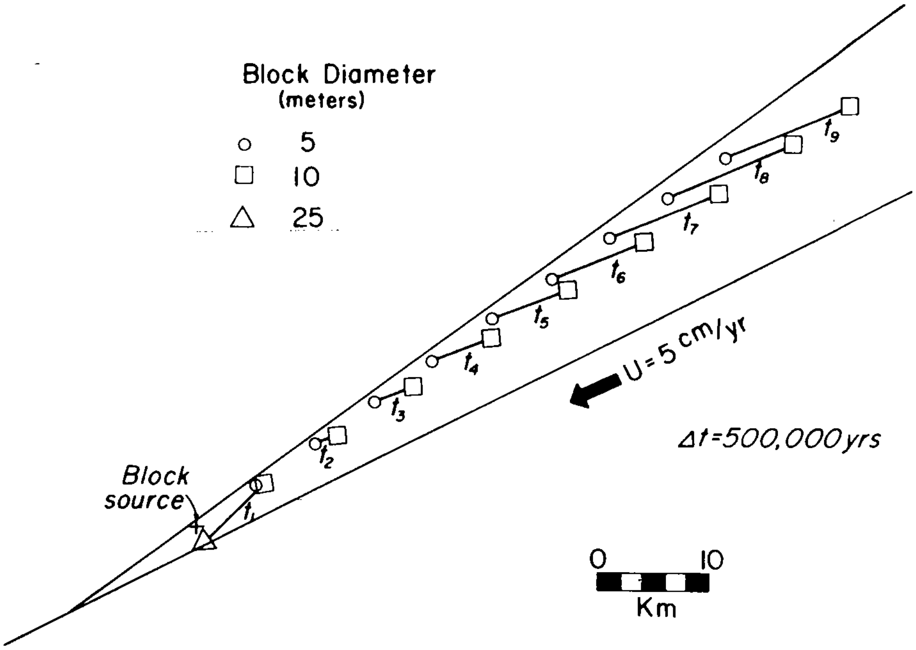

Figure 5. The effect of settling of different sized blocks, such as eclogite, that were plucked from the walls of the melange near its apex. The rate of settling follows Stokes' Law. Note that even though large blocks sink faster than the smaller ones, the 10-m block approaches the surface before the 5-m one because it sinks into the more rapidly upwelling part of the melange sooner. However, blocks that are too large, such as the 25-m one, sink to the bottom and are not uplifted. The density contrast between blocks and matrix is 0.6 gm/cm^3; plate dip, α = 25°; wedge angle, θ_0 = 10°; matrix viscosity is 10^{16} poise; and the subduction rate, U = 5 cm/yr.

Mixing Due to the Settling of Blocks

It is likely that large blocks either sank or rose depending on the density contrast while the flow melange was circulating. One reason to expect this behavior is because bodies such as the New Idria serpentinite have risen diapirically through the Franciscan (Coleman, 1961; Bailey and others, 1964; Ernst, 1965; Oakeshott, 1968). The density contrast between serpentinite and the melange matrix through which it passed is equal to or less than the contrast between eclogite or blueschist and matrix, suggesting dense blocks should sink. The effect of settling or floating can easily be included in the modeling if the rate of sinking or rising of blocks is assumed to follow Stokes Law. The velocity, V_s, of a sphere settling (or rising) through a viscous fluid according to Stokes Law is:

$$V_s = \frac{(\Delta\rho)\, g\, d^2}{18\eta}$$

where $\Delta\rho$ is the density contrast between te blocks and the matrix, g = 9.8 m/s^2, d is the diameter of the block, and η is the viscosity of the matrix. For convenience in the settling calculations, the velocities, V_r, V_θ, in polar coordinates were converted to V_X, V_Y, in Cartesian coordinates defined with the origin at the apex, Y-axis pointing upward and X-axis parallel to the top of the descending plate. The settling velocities, V_{SX} and V_{SY}, in the X and Y directions are therefore:

$$V_{SX} = V_X - V_S \sin\alpha$$

$$V_{SY} = V_Y - V_S \cos\alpha$$

Figure 5 shows the effect of settling for dense blocks shed into the melange from a point near the apex of the wedge. Large blocks sink faster than small ones and thereby cross streamlines faster in the nonuniform velocity field. In Figure 5, a 5 cm/yr subduction rate and a density contrast between blocks and matrix of 0.6 g/cm^3 were used. This density contrast would be equivalent to the incorporation of eclogite (ρ = 3.2 g/cm^3) in the melange matrix (ρ = 2.6 g/cm^3). The matrix viscosity was assumed to be 10^{17} poise. Under these conditions, eclogite blocks 5 m in diameter would have sunk through the melange less than 10-m blocks would have, but both would have been transported to a level near the surface. At the same time, the large, 25-m blocks would have sunk much faster than the rate at which the melange was flowing upward so that they would not have been carried to the surface. An interesting, perhaps surprising, result of the calculation is that the 10-m blocks would have approached the surface faster than the 5-m blocks, because as the large block sinks faster, it passes more quickly into melange with a greater upward rate of flow (Fig. 3). Modeling under somewhat different conditions (Fig. 6) shows that a block sinking at a rate similar to that of upward flow would take a looping path. This shows that complex trajectories are possible, particularly if subduction rates vary.

While discrete blocks of accreted material may be plucked or fall from the hanging wall, some material may be incorporated into the melange as large slabs. A slab would sink at a rate slower than that predicted by Stokes Law because of the large surface-to-volume ratio. During flow the slab would tend to break into smaller fragments as it rotates, but the amount of rotation of a slowly sinking particle is dependent not only upon total strain and strain rate, but also its shape (Willis, 1977). If the velocity gradients in the rising part of the melange are relatively small (Fig. 3), the dominant effect of flow on flat slabs may simply be to "raft" them toward the surface. This rafting process may explain the occurrence of slabs of jadeite-bearing metagraywacke that are engulfed in melange that were described by Cowan (1974) in the Diablo Range and the sheets of blueschist that were mapped by McLaughlin (1978) in the Geysers area.

The mixing process described above is purely tectonic. Laminar flow causes particles to be dispersed. A varied assemblage develops because rocks with differing degrees of metamorphism are

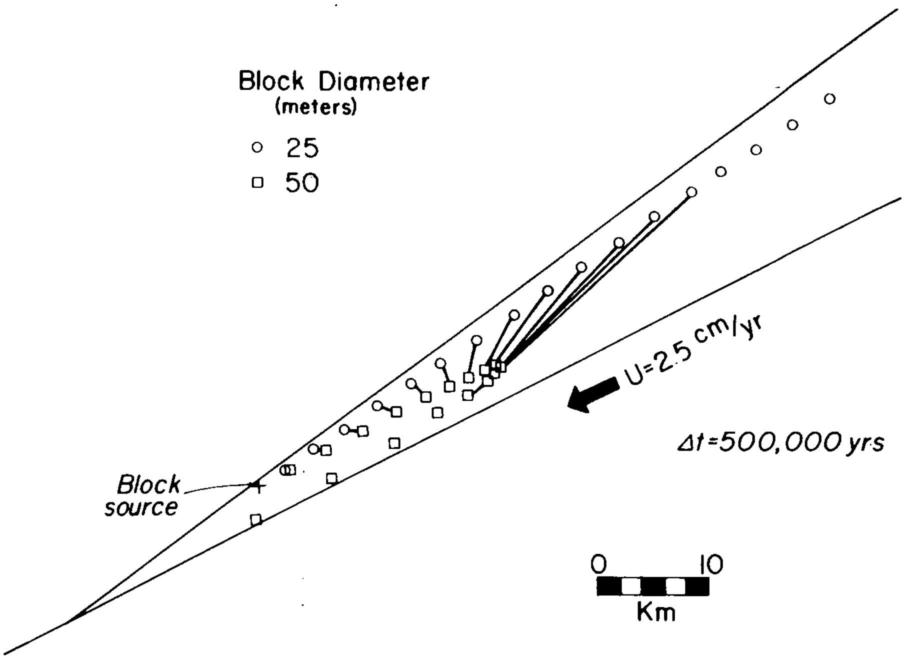

Figure 6. A block settling at approximately the same rate of upward flow follows a looping path. Complex trajectories are possible in a flow melange. Here, the density contrast between blocks and matrix is 0.3 gm/cm^3; plate dip, α = 25°; wedge angle, θ_0 = 10°; matrix viscosity is 10^{17} poise; and the subduction rate, U = 2.5 cm/yr.

plucked from anywhere along the walls of the wedge and added to newly subducted material. Mixing is enhanced because blocks would take many different trajectories owing to different rates of settling as a result of size and density contrasts. While blocks settle they would tend to break into different sized fragments that would be dispersed at different levels of the flow system. Furthermore, even though small blocks may not undergo any appreciable sinking over the time period of flow, they can change position within the flow field by being entrained in the distorted flow field near rapidly sinking blocks. It is important to note that most of the break-up of large clasts into smaller blocks probably occurs near the apex of the wedge. That occurs because there are large velocity gradients in the region where the melange turns the corner and flows back toward the surface. Near the apex, the high confining pressures would enhance the development of rounded particles by boudinaging larger fragments. As a result, there is relatively little evidence for wholesale boudinaging of blocks in outcrop, because during flow back to the surface the particles were mostly just being dispersed by laminar flow. The preferred orientation of elongate blocks in the melanges results from the rotation of the long axes of blocks into the plane of flow (*compare* Ramsay, 1967, p. 225).

The flow melange process has remarkable similarities to the flow of ice in glaciers. The magnitude of mixing of blocks in a glacial till is similar to that of the melanges (Hsü, 1965), elongate rocks have a planar preferred orientation in some flowing glaciers (Lawson, 1979), and even boudinage of coarse or silty ice has been reported in active glaciers (Hambrey and Milnes, 1975). The similarity between melanges and glacial deposits is not surprising because the mixing process in both is actually quite similar. Both flow melanges and glaciers may pluck any type of rock that forms the walls that bound the flow. Similar rocks may be plucked at many different times from the same point along the wall and then be dispersed.

ASSUMPTIONS

In this section, the major assumptions will be considered. The melange is assumed to be incompressible; this assumption is usually justified, because volume changes due to deformation are generally small. However, many of the sedimentary rocks incorporated in the melange at shallow levels could be expected to become denser because they dewater due to compaction and dehydrate due to pressure- and temperature-induced reactions. The total volume changes expected may be significant, but the effect of the volume change is probably minor compared to changes in material properties such as strength and viscosity of the melange matrix (Moore and Karig, 1976). Moreover, most of the compaction and dewatering probably occurs in the first few kilometres of burial (Moore, 1973; Carson, 1977), and the modeling is applied to greater depths of burial.

For the purposes of calculation, the flow melange was assumed to behave as a newtonian fluid. The melange matrix must have a strain-rate–dependent yield strength and viscosity. This would control the velocity of sinking (or floating) of blocks. Often geologic materials are more realistically modeled as non-newtonian fluids (Carter, 1976). Numerical studies of nonlinear corner flows by Tovish and others (1979) show that the main difference between the flow fields calculated using a power law instead of a newtonian rheology is that the flow rate is slower. In any event, the qualitative results of the modeling will not be changed by non-newtonian behavior, although the calculations can be refined if a flow law is determined for material similar to melange matrix.

The assumption of constant viscosity used in the calculation of settling is undoubtedly a poor one. The viscosity of melange is a function of many variables such as P, T, P_{H_2O}, and strain rate, which would vary during circulation. Specific values for viscosity do not enter into the initial calculation of the velocity field because the melange is assumed to be homogeneous and of constant newtonian viscosity. However, if the Stokes' Law approximation is used to account for the settling (or rising) of blocks, a viscosity must be assumed. For reasonable subduction rates (1 to 10 cm/yr), calculations indicate that no blueschist blocks larger than a few metres across could reach the surface if the melange has a viscosity less than 10^{15} poise. Under similar conditions, if the viscosity were higher than 10^{17} poise, blueschist blocks many hundreds of metres across should be present in the melanges if they were not broken into small fragments during upward transit. Unfortunately, there are few estimates of the viscosity of shale. Kehle (1970, p. 1660) estimated that the gumbo shales of the Gulf Coast have a viscosity of 10^{14} poise for low temperatures and less than 2 km of burial. He also estimated a viscosity of 10^{20} poise for deeply buried, siliceous shales of lower Paleozoic age. This range of 10^{14} to 10^{20} poise is quite large, and until the relevant deformation experiments are done, it is reasonable to assume for these calculations that the melanges have viscosities on the order of 10^{15} to 10^{17} poise.

The assumption of rigid boundaries for the melange wedge is justified because of the large viscosity contrast between the melange and its walls. Mantle viscosities typically are estimated to be on the order of 10^{21} to 10^{23} poise at normal mantle temperatures and strain rates estimated for plate-tectonic processes (Carter, 1976, p. 346). At temperatures appropriate for blueschist-facies conditions, the oceanic crust underlying the wedge and the mantle material overlying it would have viscosities on the order of 10^{26} and 10^{28} poise (Carter, 1976). As discussed, the viscosity of the melange is probably on the order of 10^{15} to 10^{17} poise. This viscosity contrast of at least nine orders of magnitude indicates that the mantle hanging wall and the top of the descending oceanic plate that bound the flow melange would be effectively rigid (*compare with* Kehle, 1970). However, because of the density inversion created by subducting sediment, the mantle hanging wall will tend to settle and squeeze out the sediment. For sediment subduction to occur, the viscous forces that are induced by flow of the sediment must be sufficient to support the hanging wall. Because the stresses in the fluid at the apex of the wedge become very large (Batchelor, 1967, p. 226), the apex is probably never closed and some sediment is always subducted. As long as the opening at the apex is less than the thickness of the layer of melange coupled to the descending plate, the circulation pattern envisioned in this model should still occur.

The initial geometry has a major effect on the degree of mixing attained during one cycle. A plate dip of 25°, wedge angle of 10°, and wedge length of 100 km appear to be a reasonable geometry by comparison with the depth from which metamorphic blocks have been recovered, the degree of metamorphism of the matrix, and the observed dips of Benioff zones. Furthermore, the length of the wedge, position of the apex, and wedge angle must interact in some poorly understood feedback system with changes in plate dip, subduction rate, and the type and volume of accreted sediment. The latter parameters are controlled by factors external to the region considered in the flow melange model and may vary with time (Karig and others, 1976). If the wedge is narrower, there will be greater dispersal of particles upon one cycle of circulation.

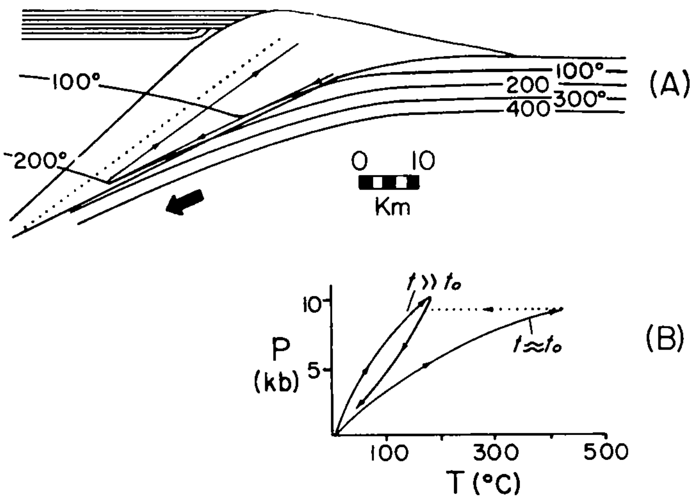

Figure 7. (A) Schematic diagram showing the nature of the isotherms expected in a mature flow melange. The mantle hanging wall has cooled because the conduction of heat from below is greatly diminished, and heat has been conducted into the cold accreted sediments.

(B) Hypothetical P-T trajectory for material in a mature flow melange ($t \gg t_0$). The downward and upward paths are nearly identical. Because of the hot hanging wall, material that is subducted and accreted early ($t \approx t_0$) will follow a P-T trajectory at a higher temperature for a given pressure than later on. If early subducted material is accreted, stored at depth, and uplifted after cooling of the hanging wall, it can then follow a P-T trajectory at a *lower* temperature for a given pressure than on the original downward path.

THERMAL STRUCTURE AND P-T PATHS

Many attempts have been made to model thermal regimes in the vicinity of convergent plate margins. Various methods using different boundary conditions give somewhat different results, but all approaches show a remarkable downbowing of isotherms in the region of the subduction zone because heat transfer due to convection in the mantle dominates that due to conduction (Turcotte and Oxburgh, 1972). Because the kinematics of accretion are poorly known, the pattern of isotherms within the accretionary wedge has not been modeled. Another major unknown concerns the direction and magnitude of heat transfer by migration of water derived from the subducted sediments. In general, the hanging wall must cool if subduction rates are constant or increase, because upward heat flow is greatly reduced by the underflow of the cold oceanic plate, and because heat is conducted into the descending plate and the cold wedge of underthrust sediment (Oxburgh and Turcotte, 1974; Platt, 1974; Hsui and Toksoz, 1979). A heat source of unknown but probably small magnitude is viscous or shear heating in the melange (Turcotte and Schubert, 1973; Graham and England, 1976; Bird, 1978). Excepting the last mentioned effect, all of the proposed conditions predict a downbowing of the isotherms, which would be expected to increase with constant or increasing rates of subduction. A steady state may never be attained, however, if subduction rates vary.

Because the rate of upward motion in a flow melange is slow relative to the rate of downward movement, the rising material would be closer to thermal equilibrium with its boundaries than would the underlying material moving downward in the wedge. In fact, the lower thermal boundary for the upward-flowing melange is the relatively cold, downward-flowing melange. The upper thermal boundary consists of material previously accreted, and the mantle hanging wall, which may cool with time as discussed above. Therefore, the pattern of the isotherms would resemble that shown schematically in Figure 7A. As a result, material moving in a mature flow melange will follow P-T paths (Fig. 7B, $t \gg t_0$) during both downward and upward transit, which are very similar. Thus, both the prograde (downward) and retrograde (upward) metamorphic histories of included blocks are similar but reversed.

Because increased depression of the isotherms will occur with constant or increased rates of convergence, the P-T paths taken by rocks during the initial stages of subduction ($t \approx t_0$, Fig. 7B) will be different than paths of rocks during the latter times ($t \gg t_0$, Fig.

7B). Rocks metamorphosed and accreted at relatively high temperatures during the early stages of subduction may be "stored" at depth. Later, after cooling, the rocks may be plucked off of the hanging wall and transported upward. What in effect has happened is that material stored at depth is "quenched" without a decrease in pressure. The return P-T path of early accreted material, such as old blocks of eclogite, could be at *lower* temperatures for a given pressure than the downward path. The types of P-T paths possible in a flow melange are in striking contrast to most P-T paths predicted for rocks exposed at the surface only by erosion of the overlying rock. P-T trajectories calculated from models in which uplift occurs by post-subduction erosion necessitate the return path to the surface to be at a *higher* temperature for a given pressure (England and Richardson, 1977).

Thus, the flow model can account not only for uplift and mixing of high-grade blocks, but at the same time, it can explain the retrograde blueschist facies metamorphism of the older blocks of eclogite and amphibolite. In addition, the model explains the wide distribution of blocks and slabs of lower-grade blueschists in the Franciscan, which show no evidence of a retrograde greenschist facies metamorphism that would be expected if they were slowly elevated only by erosion (England and Richardson, 1977; Ernst, 1977). Furthermore, uplift after a high-pressure quench provides an explanation for the preservation of aragonite in blocks in the melanges (Carlson and Rosenfeld, 1981). Complex P-T-time paths can easily be envisioned for blocks that are circulating in the melange (Fig. 5). This may help explain some of the complicated phase relations found in some Franciscan high-grade blocks, such as the one in the Laytonville Quarry that was studied by Wood (1979a, 1979b).

FLOW MELANGES AND THE TECTONIC EVOLUTION OF THE FRANCISCAN COMPLEX

Source and Development of the Melange Belt

One prerequisite for the development of a flow-melange system is the subduction of sediment with a high proportion of shale. In the Franciscan, the original source of the shale probably was the oceanward continuation of the basal Great Valley sequence ("Knoxville Formation") which was deposited on oceanic crust in the latest Jurassic and earliest Cretaceous time just before subduction began (Hamilton, 1969; Ernst, 1970). This now subducted sediment blanket should have been at least as rich in shale as the Knoxville. These sediments have a shale-to-sandstone ratio commonly of 2 or 3 or more (Blake and Jones, 1974; Ingersoll, 1978). This agrees with the suggestion by Blake and Jones (1974) that the melanges were initially generated from the subduction of Knoxville sediments because of the similarity of lithology and the type and ages of included fossils.

While the Knoxville seems to be a likely source for the melange belt, it also seems likely that the processes occurring during the initial stages of subduction may be different from those later on because of possible changes in such things as the type and volume of subducted sediment, the rate of subduction, and the thermal structure of the complex. Good evidence of a fundamental change in subduction processes in the Franciscan is found in the South Fork Mountain Schist of the eastern belt (Blake and others, 1967) in northern California. This long and narrow belt of coarsely recrystallized and foliated blueschist is, for the most part, directly below the Coast Range thrust. Bishop (1977) suggested that the schist formed by metamorphism and deformation of the Knoxville during the initial stages of subduction. His suggestion is based on the Early Cretaceous age of metamorphism of the schist (Lanphere and others, 1978) and its similarity to the Knoxville in both general lithology and ages of fossils found within less deformed parts of the schist belt. The schist and related rocks in Oregon (Coleman, 1972b) are transitional blueschist-greenschist facies metamorphics (Ghent, 1965) and are characterized by isoclinal folding (Wood, 1971; Bishop, 1977). Apparently there is an inverted textural zonation in which the most foliated and thoroughly recrystallized rocks are closest to the Coast Range thrust (Blake and others, 1967), although these textural gradations are probably nowhere continuous or totally systematic (Wood, 1971; Suppe, 1973; Worral, 1978).

If both the South Fork Mountain Schist and the melange belt were derived from the subduction of the Knoxville, why are they so different? The primary cause of the transition from recrystallization (to form a coarse-grained schist accompanied by isoclinal folding) to large-scale flow (and little, if any, coarsening of grain size) is probably the cooling of the hanging wall of the subduction complex. Heat-flow calculations (Zen, 1974) show that if thrusting occurs at a rate of centimetres per year, the local geotherm will become highly depressed and kinked, and rocks buried to depths of at least 9 km will be in the lawsonite + quartz stability field. If the thrust movement stops, lawsonite becomes unstable when the kink in the geotherm disappears after a few million years due to the conduction of heat from below (Oxburgh and Turcotte, 1974). In a subduction zone, however, the continued underflow of the descending plate and the accretion of cold sediment cause the hanging wall to cool off with time. Thus, during the early stages of subduction, the higher temperatures (although still in the range of the blueschist facies) near the fault plane would cause the sediments of the Knoxville to recrystallize and become coarse grained. The upside-down textural zonation reflects the original temperature gradient, but later faulting and folding cause complications. Near the base of the thrust, the early isoclinal folds are still recognizable because the coarse grain size of the schist inhibited the exceedingly ductile flow that occurred in the fine-grained shale of the melange belt. Away from the fault plane, competent layers of graywacke in the Knoxville were reduced to blocks because of deformation during flow. The chaotic structure of the melange started to develop as ductile flow began. It was greatly enhanced once upward flow began and as exotic blocks were emplaced and began to sink.

Oblique Convergence and Mixing

Long-term subduction is made evident by the continuity of plutonism from the latest Jurassic through Late Cretaceous in the Sierra Nevada, but through much of this time, convergence may have been at an oblique angle rather than head on (Jones and others, 1978). If convergence was at an angle to the continental margin, the component of motion parallel to the strike of the complex would cause the paths followed by particles in the melange to be helical. Therefore, oblique convergence may account for the dispersal along strike of the complex of the distinctive blocks of eclogite and high-grade blueschist from a few localized areas deep within the Franciscan Complex.

Block Concentrations

While most of the previous discussion has emphasized how the flow model accounts for the mixing of the melange, certain factors, such as the subduction rate, plate dip, and the location of the wedge apex, may interrelate to cause some types and sizes of blocks to be unusually abundant or restricted to small parts of the melange belt. For example, blocks of blueschist, 100 m in diameter, that were metamorphosed at a depth of 20 km can only be uplifted when the wedge apex is located deeper than 20 km *and* the subduction rate is sufficiently fast to carry these large blocks upward faster than they sink. Certain types of blocks may be unusually abundant in a part of upwelling melange that is downstream from a point where those types of rock protrude from the wall of the wedge. This is because plucking would be concentrated at such irregularities, analogous to zones in glaciers where quarrying occurs. Thus, concentrations of high-grade blocks such as are found at Tiburon (Dudley, 1969), Healdsburg (Borg, 1956), and at spots along the western margin of the melange belt (Jones and others, 1978) would be expected in a flow melange. This may also account for the ability of some workers to discern melange units on the basis of included block types in some areas (Hsü, 1969, Gucwa, 1975).

The Flow Melange near the Surface

In this model, most of the chaos in the Franciscan melange belt reflects deformation deep (>10 km) within the subduction zone. If upward flow occurs and the size of the wedge is constant, then melange that flows up past the fore-arc high must turn and head downslope toward the trench axis. This downslope motion is in striking contrast to that proposed by many workers who envision trench sediments being uplifted by imbricate thrusting (Karig and Sharman, 1975; Seeley and others, 1974; Moore and Karig, 1976) but in agreement with that suggested by Hamilton (1977). Seismic studies offshore of Washington and Oregon and farther to the south indicate that there is some imbrication of sediments deposited in the present trench axis (Kulm and Fowler, 1974; Page and others, 1978), but the relative importance of these contrasting motions has not been ascertained for the Franciscan during the late Mesozoic. There was probably a transition zone between the zone of imbrication and downslope flow or creep.

Seismic profiles and drilling show that most accretionary wedges are mantled by a blanket of slope sediments (Seeley and others, 1974; Moore and Karig, 1976; Karig, 1980). The wedge of Franciscan melange was probably largely covered, even though it may have been moving downslope. Because of the slope cover, only minor amounts of blueschist-bearing melange were ever exposed at the surface. Hence, it is not surprising that clasts of blueschist are so rarely reworked in Franciscan sandstones and conglomerates.

On the trench wall, local depressions underlain by melange would have become sediment traps. A few of the less-deformed basins that developed in Late Cretaceous and early Tertiary time have recently been identified in the Franciscan (Maxwell, 1974; Bachman, 1978; Underwood, 1977; Smith and others, 1979). Older basins and slope sediments could have been continuously "kneaded into" the unstable, upwelling melange basement upon which they were deposited and thus have been destroyed (Maxwell, 1974; Hamilton, 1979; Scholl and others, 1980). This near-surface deformation would have shuffled unmetamorphosed sediments with the high-pressure metamorphics and shale matrix that had flowed to near-surface levels from considerable depth.

Return flow from deep within the Franciscan complex must have stopped during the latest Cretaceous or early Tertiary time because no blocks of high-pressure metamorphic rocks showing Tertiary ages of metamorphism are presently exposed at the surface. Several factors, such as slower subduction rates or a change in plate dip and wedge angle, may have stopped upward flow. Possibly the change in plate dip, inferred from the fact that volcanism became widespread in the western United States during the early Tertiary (Atwater, 1970), caused the wedge apex to open. Once opened, upward flow would stop and the melange belt would behave as a wide, ductile fault zone with the shear due to subduction being dissipated through the entire melange (Hsü, 1971). Another important change at this time was the filling of the late Mesozoic fore-arc basin in which the Great Valley sequence was deposited (Ingersoll, 1979). After the submarine fans migrated seaward past the fore-arc high, large volumes of coarse clastic sediment were deposited on top of the melange wedge and in the trench axis. The change in type of subducted sediment may have contributed to the cessation of deep, upward flow. However, small melanges still developed in the Coastal belt (Bachman, 1977). After subduction ended, the relatively low density melange buried beneath the mantle of the overriding plate rose buoyantly (Ernst, 1970). This late diapiric rise is probably still continuing (Berry, 1973) and is the last event along with localized zones of strike-slip faulting in the history of the Franciscan melange belt.

SUMMARY

The primary constraints on the formation of the Franciscan melange belt are: (1) the large size of the melange belt, (2) the large magnitude of ductile flow in the melange matrix, and (3) the metamorphism of most blocks and matrix, compatible with a range in conditions of $100\,^{\circ}C < T < 250\,^{\circ}C$ and $2\ kb < P < 8\ kb$.

It is proposed that many of the pelitic matrix Franciscan melanges are zones in which flow in the sediment pile was driven by the movement of the down-going plate. When this flow occurred in a low-angle corner formed between the descending oceanic plate and the mantle of the overriding plate, a forced convection drove material back toward the surface and caused the upward transport of blocks such as blueschist and eclogite that were plucked from the walls of the wedge. Modeling shows that this circulation can account not only for the uplift of rocks from depth but also for the chaotic mixing characteristic of the melanges. Laminar flow causes blocks of rocks to be dispersed. Most of the deformation and breakup of blocks occurs when the melange turns the corner. Under the high confining pressures near the apex, rounded blocks are formed by the boudinaging of larger fragments. Mixing is enhanced due to different rates at which blocks of different size, shape, and density settle through the deforming matrix. Blocks of varying metamorphic grade could be shed into the flow melange from many points along the walls of the wedge. The degree of mixing could also be affected by changes in the subduction rate, plate dip, position of the wedge apex, and obliqueness of convergence. Material in a mature flow melange will follow both downward and upward P-T paths that are almost the same. This similarity of P-T paths explains the retrograde blueschist facies metamorphism of blocks of amphibolite and eclogite that formed at the beginning of subduction.

In conclusion, one reason the Franciscan may be such a distinctive subduction complex is simply because it had the largest flow-melange system that carried blocks up from the greatest depths. Because there are several processes that can create disrupted or chaotic deposits that could be called melanges, it is important to evaluate each possible formative process for every occurrence of "melange." Other complexes that contain chaotic zones that lack exotic blocks may have developed as the result of flow in a shallow, wide-angle wedge, but if they lack exotic blocks, such flow may be difficult to demonstrate. Even if a melange contains exotics, it may be difficult, if not impossible, to differentiate from a pile of deformed olistostromes. As a closing note, flow need not always produce a "chaotic product." For example, a higher thermal regime may cause the ductility of different rock types to be more equal. In these cases, the original layering may not be lost, and upwelled material may appear near the surface not as a chaotic melange but as a structurally complex zone characterized by isoclinal folding.

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