Zeitschrift: Eclogae Geologicae Helvetiae

Band: 93 (2000)

Heft: 3

Artikel: Chronology of deformation of a Franciscan melange near San Francisco (California, USA)

Autor: Jeanbourquin, Pascal

DOI: https://doi.org/10.5169/seals-168828

0012-9402/00/030363-16 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 2000

Chronology of deformation of a Franciscan melange near San Francisco (California, USA)

PASCAL JEANBOURQUIN

Key words: Franciscan, deformation, cement, deformational mechanisms, soft rocks, fluid pressure, hydrofracture, melange, olistostrome, wildflysch

ABSTRACT

The Permanente Terrane at Pacifica (a part of the Franciscan Complex SW of San Francisco, California, USA) is a melange with big slices and blocks bounded by a matrix of sheared polymictic breccia. This matrix results from a multistage evolution made of several episodes of fracturing, brecciation, shear and fluid flow. The microstructures and the cement stratigraphy allow at least four stages of deformation to be separated: I) a first group of pre-melange structures lacking in silica/calcite cements testifying to brecciation and sill-dike injection (syn-depositional to early accretion?), IIa and IIb) two important groups cf accretionnary deformations comprising a wide range of structures and several episodes of cement (IIA with K-feldspar), and III) a last group of post-melange deformation structures clearly overprinting older structures (late strike-slip motion of the San Andrea Fault system). The observations indicate that hydrothermal activity was associated with melange development. This activity may be related to the late Cenozoic hydrothermal activity in the region or an earlier hydrothermal history, possibly as old as the beginning accretion of the Franciscan Complex. In addition, the data presented indicate that the fluid pressure was high, influencing the mechanisms of deformation (hydrofracture and particulate flow) and they demonstrate the tectonic origin for the melange breccia although its texture is that of a pebblymudstone.

RESUME

Le mélange de Pacifica est constitué d'éléments de toute taille, essentiellement de grauwacke, de basalte et de calcaire, soudés par une matrice détritique fine intensément cisaillée par les mouvements tectoniques. L'étude des structures de la déformation, des ciments et de la matière organique a permis de mettre en évidence au moins quatre groupes de déformations : I) déformations précoces, synsédimentaires ou marquant la la naissance du prisme d'accrétion (enregistrée par des filons synsédimentaires et des brèches intraformationelles); IIa et IIb) deux groupes de déformations plus ou moins cassantes, associées à la déformation du prisme (underplating et offscrapping), le premier se distinguant par un ciment feldspatique mêlé à du bitume (activité hydrothermale); et III) des failles et des veines, qui recoupent toutes les autres structures, et qui sont associées à des épisodes récents de la faille de San Andreas.

Le mélange de Pacifica permet de documenter tout un éventail de structures de la déformation typiques des mélanges. Ces structures démontrent que la pression des fluides a souvent été anormalement élevée, provoquant de la fracturation hydraulique et favorisant des mécanismes de déformation par glissement à la surface des grains (ainsi que des injections) aux dépens de l'écoulement cataclastique. Ce type de déformation conduit à la fluidisation de certaines zones et à la formation de roches de type «pebblymudstone» (un conglomérat supporté par de la boue) dont les textures convergent parfaitement avec celles observées dans les olistostromes ou les wildflyschs alpins.

I. Introduction

The deformed clastic sequences of the eastern Pacific active margin (western North America) are the classic localities for modern discussions about definition, genesis and significance of melanges (e.g. Hsü 1974). From central California to northern Washington and Alaska (Kodiak), medium to large-scale structures have been described within these melanges (e.g. Cowan 1985). Many geological processes have been invoked to explain the origin and evolution of melanges. The proposed processes range from large-scale gravitational sliding (sedimentary melanges or olistostromes) to tectonic shearing (tectonic melanges) or diapiric flow (diapiric melanges) (e.g. Hsü 1974, Cloos 1982, see Cowan 1985 for a complete review). Most of these articles consider large-scale Franciscan tectonic/sedimentary features related to the subduction of the Pacific plate beneath the American plate (e.g. Hsü 1974, Aalto 1989); some of these papers also consider theoretical aspects of flow modeling within subduction zones (e.g. Shreve & Cloos 1986). However, little has been published about the petrographic evolution (cement crystallization/alteration) during melange formation in order to outline a chronological framework of the deformation and to understand the relationships between the observed structures and deformational processes. Approaches combining small-scale structural observations with considerations on the diagenetic evolution and deformational history at

Av. du Rond Point 19, CH–1007 Lausanne, Switzerland. E-mail: p.jeanbourquin@bluewin.ch

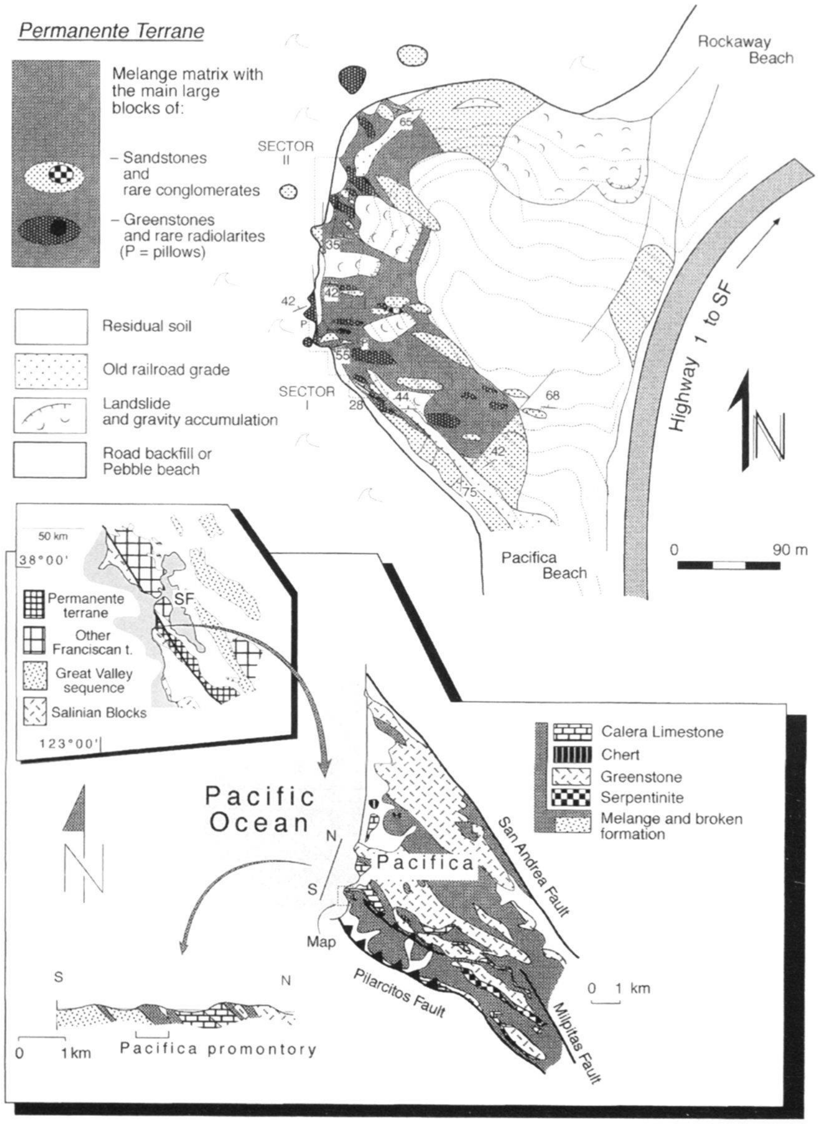
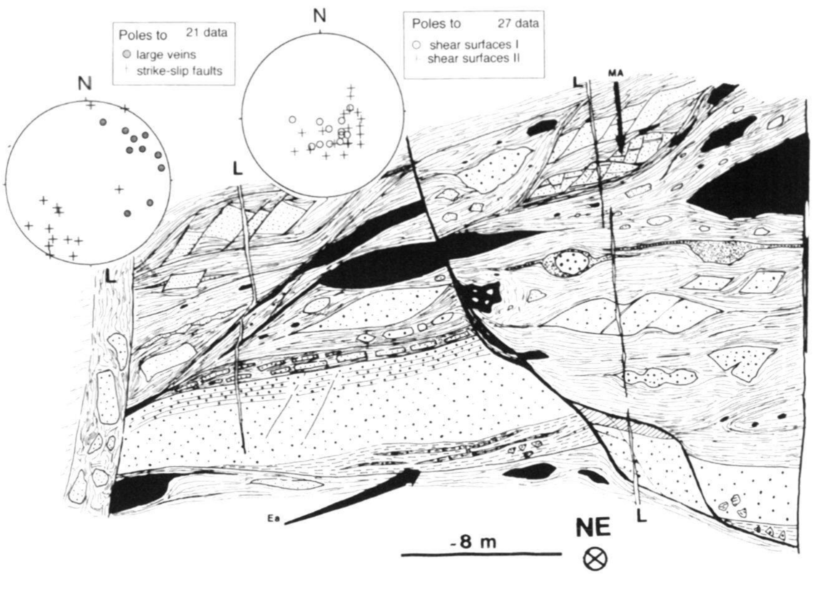


Fig. 1. Geological map of coastal promontory at Pacifica and the location of the Permanente Terrane south of San Francisco (location modified from Larue et al. 1989; detailed map from P. Jeanbourquin 1991–1997).

different depths of burial are still rare (e.g. Agar, 1990, Byrne & Fisher, 1990). Therefore, the very accessible well-exposed coastal outcrops of the Pacifica melange of coastal California has provided a remarkable opportunity to: 1) describe the deformational structures and microfabrics in details, 2) associate a cement stratigraphy with the deformational history of the melange and 3) document a remarkable occurrence of K-feldspar cement closely associated with the melange structures.

II. Geological setting of the Pacifica melange

The melange of Pacifica (Fig. 1) is a part of the Permanente terrane (Blake 1984), a part of the Franciscan assemblage. South of San Francisco, this Terrane forms a narrow zone delimited by two faults of the San Andreas (SA) system: the San Andreas fault to the east and the Pilarcitos fault and thrust to the west (Fig. 1). The melange is a polymictic melange of type III (Cowan 1985). It is composed of a disorganized amalgam of grains, pebbles, blocks and slivers of graywacke (and conglomerates), rare serpentine, greenstone (and greenstone breccia), rare metamorphic rocks (amphibolite and epidote amphibolite that are variably retrograded to blueschist, Wakabayashi unpubl. data), cherts and hemipelagic limestone which are supported by a dark foliated muddy matrix. Its fabric commonly resembles a weakly deformed pebblymudstone (polymictic disorganized muddy-gravel or mud-supported breccia, Pickering et al. 1990) with locally a diamictic aspect when the clasts are rounded and polished.



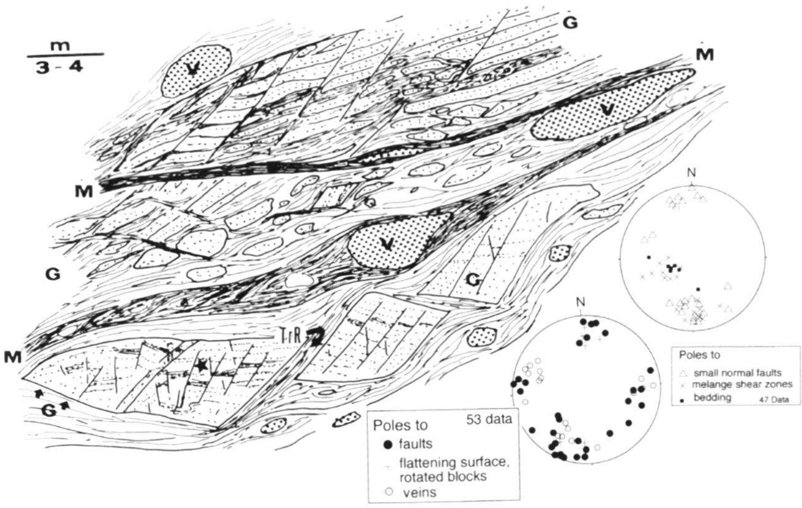


Fig. 2a. Sketch of an outcrop from sector I. The melange structures of class II (stereogram right) are well preserved within fault packets delimited by high angle late faults and veins (L, class III, stereogram on the left). The black blocks are greenstones and the tails of chlorite/basalt mush (chemical/ cataclastic remobilization) are approximately parallel to the foliation. Ea= structures of the class I (dikes, sills). (Present day position, equal area stereonet, lower hemisphere).

Fig. 2b. Protomelange showing packets of dismembered turbidites (top) separated by zones of polymictic breccia (M) containing grains to pebbles of shale, graywacke, and greenstone (V) and cherts. The graywacke blocks in the protomelange (G) exhibit well preserved extensional structures associated with K-feldspar cements and bitumen migration. These extensional structures (TrR) are possibly reactivated by younger melange deformational features (Equal area stereograms, lower hemisphere, present day orientation for a and b). * = location of the figure 12. The oreintation is given by stereograms.

The graywackes and the fine-grained matrix are interpreted to have formed in a trench turbidite system (Larue et al. 1989). The material is made of clays, quartz and andesite lithoclasts likely originated in a forearc region (Larue et al. 1989, Jayko and Blake 1984)). The slices of limestones have been interpreted as a Cretaceous seamount subducted and underplated within the melange (for a more detailed description of the lithic types see Larue et al. 1989, 223–225). Greenstones are common and consist of altered oceanic basalt with local pillow textures, basalt conglomerates, and associated cherts. Most of the greenstone blocks have a brecciated structure at the outcrop-scale, the basalt clasts being supported by a lithified cataclastic mud made of chlorite.

The melange matrix is a dark foliated shale, which may include some fine siltstone (up to 20–30% quartz). Similar to most sedimentary rocks of the melange, the melange matrix may also contain up to 1% organic matter (dispersed or as thick bitumen or tar) with a present-day composition marked by a terrestrial organic source (Larue 1986).

The geologic and tectonic history of the Pacifica area are constrained by micropaleontologic, metamorphic, geochemical and geomagnetic data (e.g. Larue et al. 1989; Wakabayashi 1999). These authors have proposed a model by which the melange has evolved during 1) the underthrusting and the underplating of the Pacific plate beneath the North American one, and 2) the strike-slip deformation of the SA fault system. The P-T conditions for the deepest deformation (underplating) have been estimated between 150°–225 °C and 5–6 kb (based on vitrinite, pyrolysis, jadeite-paragenesis and isotope data). Larue et al. (1989) have also remarked that, regardless the fact that the blueschist paragenesis occurs in greenstone "exotic" blocks, one can tentatively postulate that the whole melange underwent these conditions. They also present data on isotopic signatures showing that calcite in veins is strongly related to the lithic types of the surrounding rocks; these isotopic data also suggest a precipitation temperature of 75°–175 °C.

Since the Miocene, exhumation processes and strike-slip movements of the SA system have been competing. Both of them may have affected the melange structure. One can tentatively postulate here that the subvertical faults and discrete calcite veins crossing the earlier fabrics testify to late stages of strike-slip movement (Larue et al. 1989) or thrust nappes related to convergence within the strike-slip zone (Wakabayashi & Moores 1988, Wakabayashi 1999). Anyway, these late faults determine fault-packets in which the structural orientations are consistent within individual outcrops. In regard to these works, one can speculate that the latest deformational structures are related to the neo-deformation phase of the SA transform, and the earlier deformational structures are related to the accretionary deformation, or to the transition between accretion and strike-slip. This study focuses on deformational fabrics within some of these fault packets.

III. Description of the deformational structures

The promontory between Pacifica and Rockaway beach contains good coastal outcrops of the melange with a well-developed pebblymudstone fabric (Fig. 1) within two sectors (I and II, Fig. 1 and Fig. 2 a and b). Three main classes of structures can be observed:

I – structures of the early deformation,
II – structures of the melange formation,
III – structures of the late deformation.

This classification aids in understanding the melange structures (Fig. 2a) and it facilitates the fieldwork. In addition, it is important to introduce the concept of cement stratigraphy and to link it with these three classes of deformational structures. For this purpose, the present paper uses the diagenetic classification presented by Burley and others (1985): eogenesis, mesogenesis and telogenesis. Eogenesis refers to diagenesis occurring right after deposition, mesogenesis incorporates all the diagenetic processes of burial and starting exhumation, and telogenesis corresponds to phenomena commonly occurring during uplift and superficial weathering.

Class I– Early deformational structures: intrusions and breccias during eogenesis

Some remains of thick turbidites in slivers or small blocks of graywacke exhibit neptunian injections associated with intraformational breccias and dewatering structures ("dish and pillar" structures associated with "webs"). Sandstone sills intrude

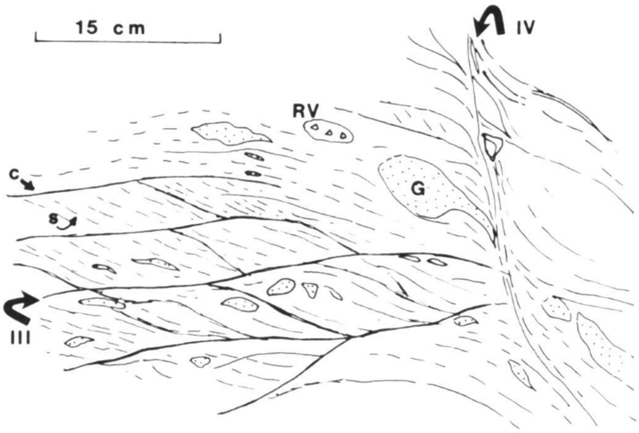


Fig. 3a. Line drawing of the scaly fabric grading to a S-C geometry in melange matrix (RV= greenstone, III= melange-forming structures and IV= recent melange structures (late SAF) with transposition of older structures, c = C-shear surface, s = S-foliation (orientation is similar to Fig. 2a).

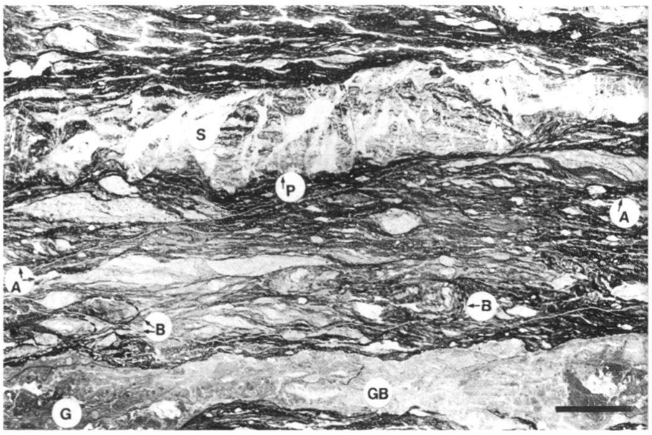


Fig. 3b. Microfacies of deformation in the polymictic melange matrix, which presents a pebblymudstone aspect at the outcrop-scale (large thin section 6 × 4 cm). The foliation is marked by significant development of shear zones (A = shear surfaces). There are microfolds preserved between shear bands (B), different style of clasts, and boudins (S = graywacke boudin characterized by pressure solution, tensional fracturing and veining (quartz, calcite and barite). P marks zones with quartz cement affected by crystal plasticity and possibly syn-deformational epidote). Note the string of greenstone at the bottom of the photo (G = greenstone, GB = greenstone breccias) (orientation is similar to Fig. 2a). Scale bar is approximately 6 mm.

fine-grained parts of the turbidites and infrequent dikes bridge the arrays of sills. They are centimeter-thick and are up to three or four meter long (rarely more). The sills are anastomosing and they tend to parallel the beds. Both sills and dikes display internal microstructures, such as dark shear zones (sometimes with an anastomosing geometry resembling "webs") or coarse plugs with fine sorted rims. The geometry of the sills, paralleling the bedding, suggests that they intruded

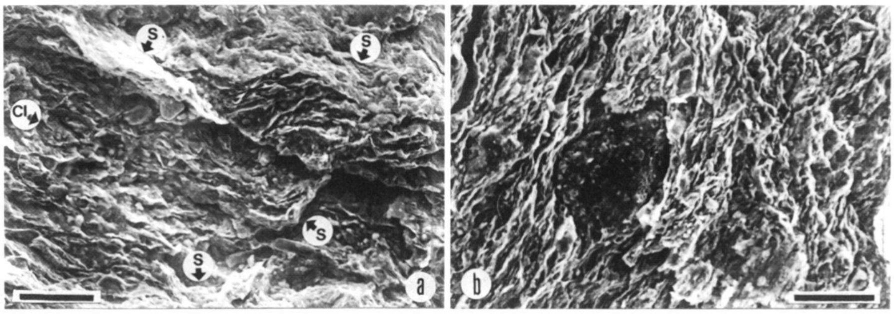


Fig. 4. SEM microfabrics of the protomelange matrix (a) and the melange matrix (b).
a) S = discrete fracture interpreted as microscopic shear zone (scaly fabric) within well-oriented clays (Cl = compactive fabric); scale is 30 micrometers.
b) Clay microfabric with a clast in a shear zone, scale is 33 micrometers.

by hydraulic fracturing under low confining stress. Many graywacke blocks and slivers show rough brecciated fabrics, progressively grading into sandy intrusions mentioned above. Usually, the clasts are coarse to fine sandstones within a finer and darker matrix of poorly sorted silt or fine sand. Conversely, clasts of dark silt are also observed, but they are uncommon. These breccias are closely associated with discrete dewatering structures characterized by a greater proportion of fine particles. Although a few evidences of clay and chlorite crystallization have been observed (clay rim with the optical microscope, crystallization of existing clay aggregates or aphanitic volcanic debris detected with BSEM), the early diagenetic evolution of this material remains poorly constrained. One can tentatively consider that these clay transformations occurred during an early diagenetic stage (eodiagenesis), coeval with compaction. Conversely, early ferroan calcite cements, usually described in this type of diagenetic stage (e.g. Orange et al. 1993), were not observed here. The compaction within the graywacke blocks have formed a weak foliation (the SEM and BSEM observations show traces of pressure solution, an orientation of the phyllosilicates and also broken phyllosilicates).

Class II – structures related to the melange formation (meso-deformation(s)).

As most of the deformational structures of the Pacifica melange are common in melanges, this section will not discuss an exhaustive list of fabrics. Rather, it will focus on selected structures, which illustrate special topics of the Pacifica melange evolution and its mechanical behavior during and after fragmention and mixing. For more information about melange fabrics, the reader can refer to Cowan (1985) or Maltman (1994).

The class II structures are associated with the development of much of the present day fabric of the melange (Fig. 2). Indeed, most of these structures are intimately associated with the "block-in-matrix" texture of the melange responsible for their mixed aspect. Two types of cement assemblages permit separation of at least two phases of deformation characterized by different sources of fluids controlling the deformation (mesogenesis phases A and B).

The melange foliation

The main eye level scale structure is the melange foliation marked by: 1- a penetrative cleavage that affects the dark shaly matrix of the melange, 2- the „flattening" surfaces of clasts and boudins (Fig. 2), and 3- the cataclastic tails of some blocks. Macroscopically, the aspect of the pervasive cleavage is closely dependent on the clast frequency, the size of the clasts, and the occurrence of shear zones. The cleavage may form an array of discrete anastomosing shear surfaces resembling the scaly fabric (Fig. 3a); sometimes, this scaly fabric clearly evolves into C-S structures characteristic of mylonitic shear zones (Fig. 3). The surfaces of these scaly surfaces may be shiny and may present infrequent scratches. Microscopically, an ubiquitous array of anastomosing seams dominates the shaly matrix. The extent, spacing and thickness of these cleavage lamellae are variable. The seams may have sharp or graduational boundaries; they may terminate diffusely or coalesce, forming thicker volumes. Their geometry ranges between two end members apparently dependent on the amount of simple shear: – a dominating asymmetric shear pattern marked by shear bands often associated with localized shear zones in graywacke (S-C, Fig. 3b), – and a rare pressure solution pattern fitting the edge of some clasts. Both exhibit dark microscopic zones (sometimes web like) in which the clay residue is below the resolution of the microscope (mostly clays).

In between the seams, the small phacoids made of graywacke or dark shale display a microscopic foliation strongly dependent on the rock composition. In the coarser lithologies (graywackes and wackestones pebbles or blocks), the cleavage is weakly developed. It is a pressure-solution cleavage marked by clay-rich zones; slightly sutured contacts between detrital grains (observed with the microscope and the BSEM) attest to pressure solution and dissolution; this phenomenon is locally enhanced by the presence of organic matter. The pressure solution may be accompanied by grain reorientation and possibly mechanical crushing during burial (Galloway 1974). This pervasive cleavage is locally transposed by later faults as shown in the figure 3a. Within the finer and darker lithologies, the optical microscope and the SEM reveal well-oriented grains of clays and chlorite (Fig. 4).

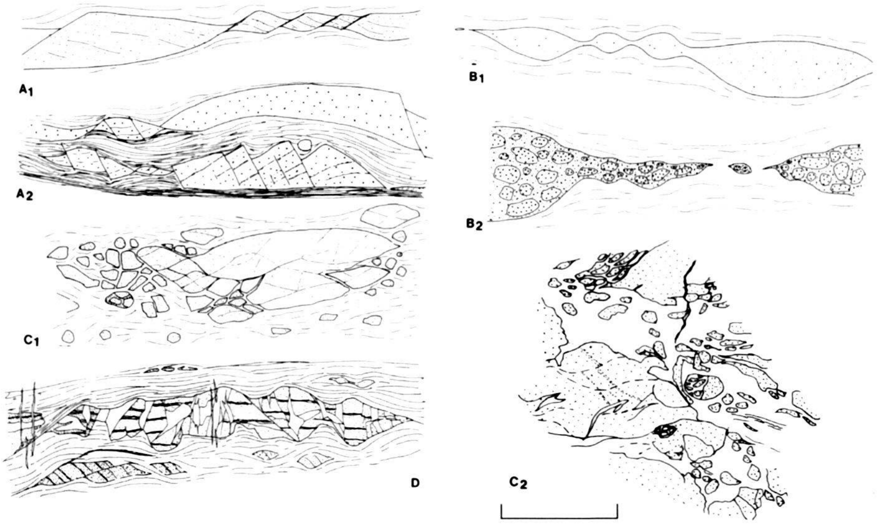


Fig. 5. Different types of boudins illustrating the evolution from "strata to boudin or breccia" during shear with localization behavior of the deformation (LS, A1 and A2, left) and distributed shear deformation (DS, B1 and B2, right). C1 and C2- illustrate the transition from localization to distributed (DLS; localization – disaggregation – distributed deformation) and D- a late stage of boudinage mostly accommodated by veining in a graywacke strongly affected by pressure. The scale bar is approximately 5 cm.

Flow and cataclasis in the melange

In the melanges, one can observe three types of shear flow at the macroscopic scale: localized shear (LS), distributed-localized shear flow (DLS) and finally distributed shear (DS). Simultaneously, one must consider two main types of cataclasis depending on the fact that the grain-breakage may affect mostly the quartz grains (or lithoclasts) or the weak matrix.

Narrow shear bands (up to a few cm thick) that occur either in the matrix or in blocks (Fig. 3b, Fig. 5A, D and fig. 6) characterize the localized shear (LS). The bands are small faults that exhibit an ubiquitous finer texture than the bulk rock; they commonly present microfabrics attesting to cataclasis with unambiguous grain-breakage and grain rotation. They often display a remarkable S-C pattern (Fig. 3). The LS may be organized into a complex anastomosing array that evolves to the distributed-localized shear (DLS) when it becomes denser.

The distributed-localized shear (DLS) is a deformational pattern marked by a sum of anastomosing localized shear surfaces. It affects larger volumes of rock than LS and it may also define small faults, depending on the scale (Fig. 5C1 and C2). In turn, the DLS is the common shear flow of protomelanges, whereas the LS is more significant within strata or blocks. Both LS and DLS contrast to the distributed flow (DS).

The distributed shear (DS) refers to diffuse flow occurring in the pebblymudstone lithologies. There are neither visible indications of cataclasis nor apparent localization of flow (Fig. 5B). Therefore, the main flow mechanisms appear to be the intergranular particulate flow (IPF) affecting a disaggregated sedimentary rock. In turn, the cataclasis associated with the DS affects only the weakest phases of the parent rock represented by the clay matrix in the clastics and relics of sandy parent rocks attesting to different stages of consolidation (e.g. Fig. 5B1, Fig. 2a). The DS flow appears to be a very important process during melange mixing as shown by zones of pebblymudstone separating protomelange (M, Fig. 2b). It may become the dominant deformational mechanism at any time as long as the pore fluid pressure remains high enough to favor the disaggregation and the cataclasis. In the greenstone, the large blocks of breccia grading into narrow strings swirling in the black matrix illustrate also the significance of the DS (Fig. 2a or GB in the Fig. 3b). In this latter lithology, the DS is closely associated with fluid and mineralogical transformations, mostly the formation of chlorite. This will be described below (greenstone deformation).

Many stages of shear and vein formation are observed in the blocks and in the matrix (Fig. 3b, 7), as indicated by small quartz veins broken and/or folded in the matrix, isolated microfolds within phacoids (e.g. B, fig 3b), or chunks of ribbon quartz (Fig. 8). The flow in the matrix locally induced rotation of clasts and their erosion. This phenomenon seems ubiquitous in most melanges (Orange 1991), notably when the clasts are equi-dimensional; but it is here extremely difficult to estimate correctly the magnitude of the rotation because the melange is lacking in incremental markers of deformation.

Block shapes

The Pacifica melange displays a large variety of clast shapes suggesting several modes of clast fragmentation. The configuration of blocks ranges from slightly broken formations with lens-shaped blocks and ghost bed surfaces (relics of protomelange, Fig. 2b) to isolated polygonal blocks or even tectonically rounded clasts (Fig. 2a, 6 and 8). At any scale, most of the elongated clasts are oriented and they follow the matrix foliation. Many places in the melange display progressive fragmention and mixing of clastic rocks with a gradational contact to

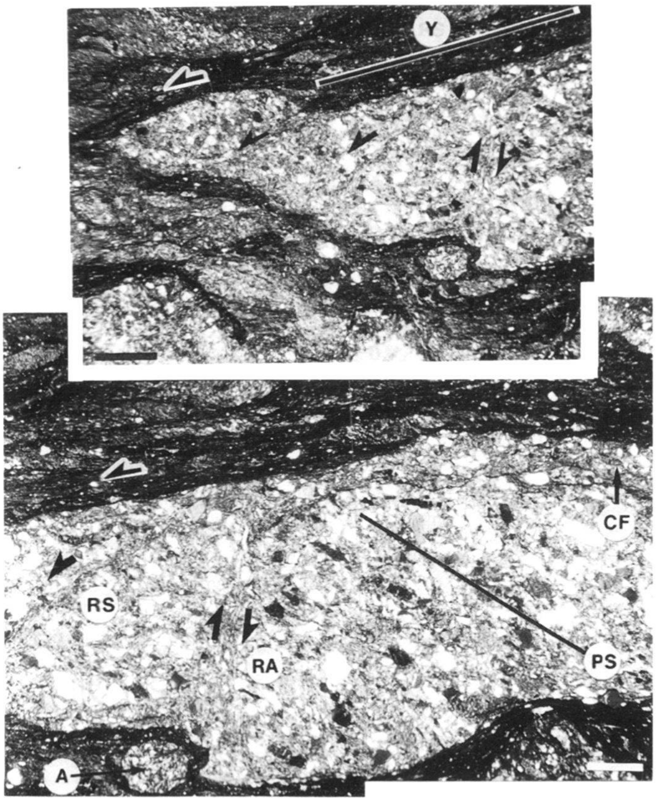


Fig. 6. Cataclastic shear in a graywacke block (figure 5A1 or A2) and detailed view beneath. Within the bulk sediment, the grain-breakage is distributed and the fracture orientations are commonly consistent with the pressure solution (PS); it may show variably rotated grains paralleling the pressure solution (PS). The cataclastic flow is confined within narrow borders along the clast surface (CF, corresponding to main shear surface = Y-shear) and within narrows bands following a Riedel geometry, (RA) antithetic Riedel shear with strong reorientation of the elongated grains, (RS) synthetic Riedel shear. The CF border zone is strongly "erosive" on the upper side of the block, suggesting that the shear flow is heterogeneous and asymmetric. Note also a "proto-phacoïd" (upper-left) and a rounded clast of greenstone preserved in a pressure shadow area (A). Scales are 1mm (above) and 0,6 mm (below) (orientation of the pebble is parallel to the main foliation of Fig. 2a).

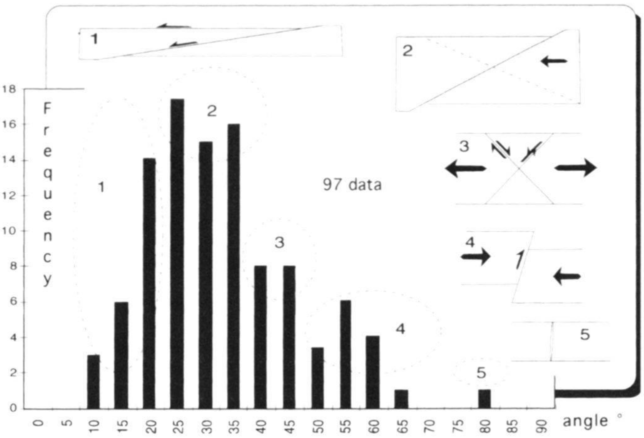


Fig. 7. Histogram of the orientation of shear surfaces of the graywacke clasts in respect to the long axis of clasts (usually corresponding to the bed surface), sector I.
1- Synthetic Riedel fractures initiated in a lithified sediment, 2- Classical orientation of fractures around the principal stress axes, 3- fractures in an unconsolidated rock (μ = 1), 4- Anthitetic Riedel fracture in lithified rock, 5- Perpendicular extension.

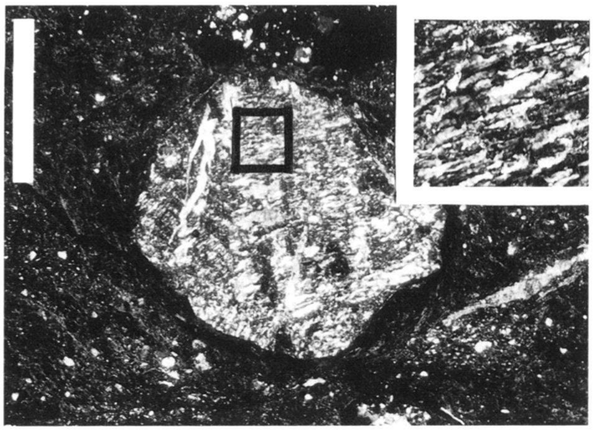


Fig. 8. Spherical clast with quartz ribbon (plastically deformed quartz) indicating that fragmention, mixing, and tectonic abrasion occurred during the melange genesis, after significant deformation. The scale bar is 0.6 mm.

the pebblymudstone matrix. Several singular configurations can be recognized and testify to specific mechanisms of faulting and fracturing (Fig. 7).

1) A first type of block shape is the polygonal shape related to shear zones paralleling the bedding associated with more or less developed antithetic or synthetic Riedels faults (Fig. 7, fig 6, Fig. 5A_1 and A_2, A Fig. 3b). This Riedel geometry, very common in the melange, is characterized by discrete zones in which the deformation is accommodated by cataclastic flow (Fig. 5 and 6). These Riedel zones usually exhibit features that suggest a preliminary cataclasis (moderate to strong grain breakage of grain and matrix, Fig. 6) possibly followed by disaggregation of the parent rock and its remobilization. Significant disaggregation of the parent rock occurs within narrow bands bounding the clasts, often smoothing the diamond shape (band y, Fig. 6). In this case, these bands may be the source of small wisps of sandy material that form swirling patterns in the melange matrix.
2) There are also polygonal shapes due to extension parallel to the bedding (Fig. 3b and Fig. 5D): this arrangement, also very common, is evidenced by veins (tensional fractures) and the development of steep microfaults (mostly with a normal component). These extensional structures are restricted to the scale of the beds; sometimes they display their own Riedels'geometry. As they are often related to

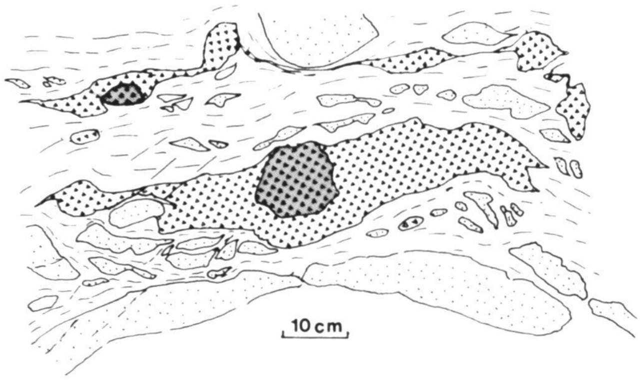


Fig. 9. a) Line drawing from photos of cataclastic tails of chlorite/celadonite breccia around a basalt clast (dark gray). The pressure shadow zones have a dark green-blue color that is characteristic of abundant amounts of celadonite. Note the sandstones (dots) are experiencing the transition between localized to distributed deformation (DLS, bottom left).

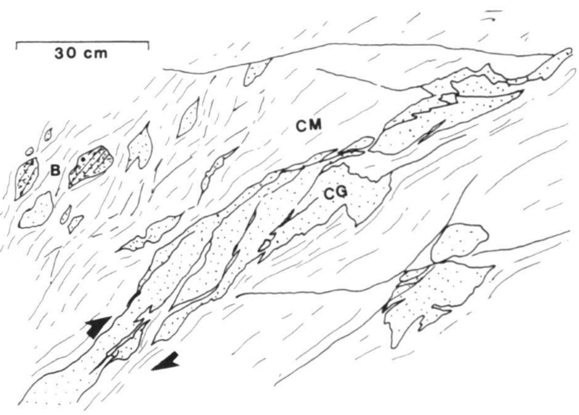


Fig. 10. Line drawing from a photo showing shear zones within cataclastic greenstone breccias. CM = light green chloritic matrix of the youngest generation of breccias. CG = breccia with lesser chloritic matrix, B- clasts of fresh basalt.

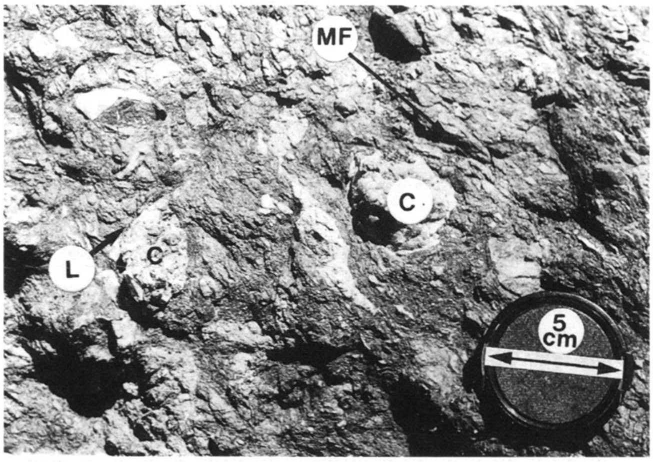


Fig. 9. b) Spot of a greenstone clast with asymmetric tails made of a chlorite breccia produced by cataclasis. C = Chert, MF = melange foliation, L = late structure cutting across the older (oreintation: foliation is the melange shear zone of Fig. 2b).

K-feldspar cement, more details are available in the K-feldspar section below. Pinch and swell structures and boudins, displaying apparent ductile deformation, suggest a weak lithification of the parent rock or its preliminary disaggregation (Fig. 5 B_1 and B_2). Small normal faults oriented at 45° to the bedding support this assumption.

3) There remain lens shaped clasts related to anastomosing arrays of shear zones diffusing in the matrix (Fig. 5C_1 and C_2): certain small clasts are detached from larger blocks affected by anastomosing arrays of localized shear zones. These illustrate a preliminary stage of mixing at block- to outcrop scale (Fig. 2b and Fig. 5 C1–C2).

4) The Pacifica melange exhibits remarkable rounded clasts, sometimes with a spherical shape (greenstone or graywacke Fig. 6, Fig. 8). There is much evidence that these clasts result from abrasion during rotation within the flowing melange matrix: these pebbles are tectonically rounded. Furthermore, certain fragments are surrounded by thin dark films that appear to be the result of continuous gouging around the clast.

Greenstone deformation

The greenstones and the related cherts are very important components of the melange. They are mostly altered basalts with infrequent pillow structures. Most of the blocks are composed of altered breccias intimately associated with the melange deformational structures. These breccias are made of chlorite mixtures supporting dispersed preserved basalt cores (Fig. 10). At the eye level scale observation, the mush looks like it originated by grounding down of parent basalts. Observation of the mush microtexture with the BSEM and the optical microscope, shows variably rounded clasts of basalts (with their preserved microlithic texture, Fig. 11). They are supported by a very fine mush made of chlorite or chlorite-smectite clays (light gray in Fig 11) with rare remains of broken phenocrystals (dark gray). The proportion of clay minerals (including chlorite) is much greater in the mush than in the parent basalts (three times or even more). This suggests that the cataclasis and the accompanying fluids trigger a chemical alteration of basalts into a chlorite mush. The cataclasis acts as a catalyst because it increases considerably the surface of reaction. Therefore, some competent basalt rocks may evolve to non-cohesive ductile wet mush suggesting strain-softening deformation. This mechanism explains the important variability in thickness and shape of these greenstone breccias in most of melanges. Indeed, important changes of shape occur common-

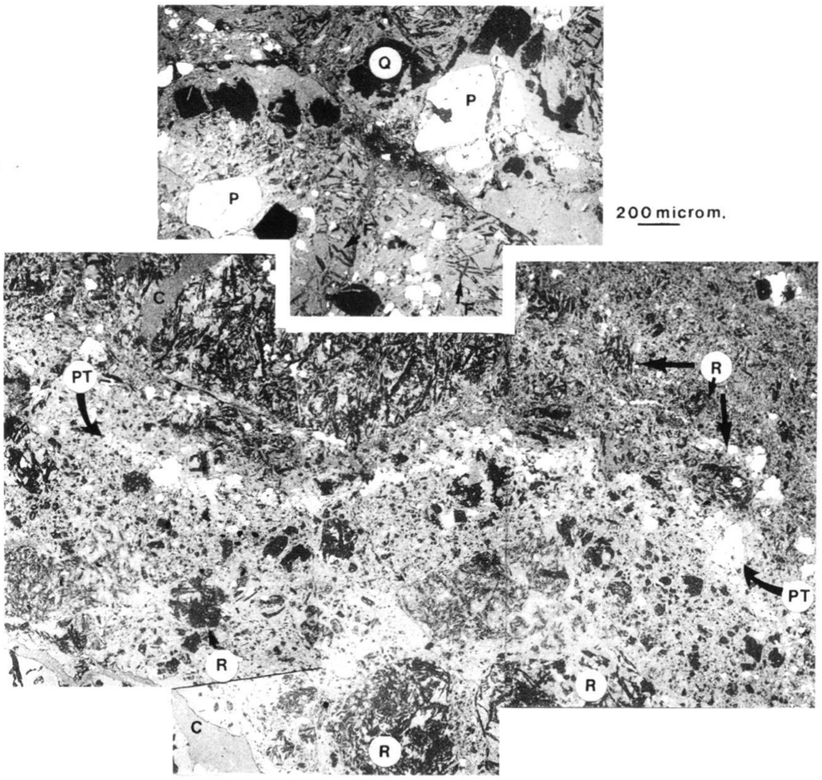


Fig. 11. Backscattered images demonstrating chemical cataclasis within greenstones. The brittle grains (P = pyrite, Q = quartz, probably from cherts) are commonly broken and they form strings (PT) swirling within the cataclastic breccia. Most of the greenstones clasts are rounded (R). The original microlithic fabric, outlined by the feldspars, is destroyed within the matrix; the grain-size decreases significantly and the matrix is enriched in clay minerals, mostly chlorite. Some calcite veins (c) are cut by clasts surfaces.

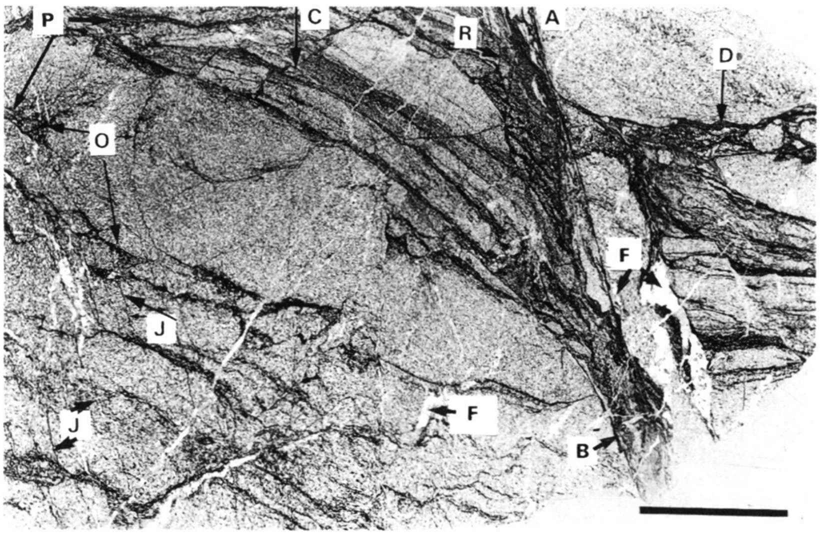


Fig. 12. Large thin section of a graywacke block located at the star mark in bottom left of the Fig. 2b. It illustrates most of the deformational structures associated with the KF cement. P is a weak irregular pressure-solution cleavage underlining the bedding.
The parent sediment contains incipient fractures and veins oriented from 90° to 45° (Fig. 17); all are marked by a dark selvage made of clays with organic matter and bitumen (O). Some of these structures exhibit injection of disaggregated sediment (C and D).
On the right, it is cut by a shear zone with a normal component (outcrop observation). KF cement fills fractures (F) throughout the thin section. All bright veins are K-feldspar with minor quartz; calcite veins are almost absent in this section. The straight dark lines (A to F and around B) mark gouge mostly made of grounded KF.
(R) = Synthetic Riedels. A) approximate location of Fig. 14 feldspar veins, mush and gouge); B) location of the Fig. 15; C) Location of Fig. 16 (sediment/bitumen injection cut by a KF vein). Scale bar is 1 cm.

ly without discontinuity. Isolated fragments or large blocks grade (locally over very short distances) into irregular wisps of chlorite breccia swirling in the dark shaly matrix (Fig. 2a, 3b). Therefore, the blocks are often connected by centimeter to millimeter-thick strings.

The greenstone breccias and the shaly matrix are often intimately mixed. Shear bands and asymmetric tails affecting both lithologies are observed (Fig. 2a, 10); these bands may define a crude cataclastic lineation. Otherwise, infrequent exposures of greenstone breccia display incipient localized shear zones overprinting swirling contacts between two phases of breccias (Fig. 10). The breccia texture is not consistently orientated due to simple shear (Fig. 3b and 10); only certain clasts exhibit a narrow border with strongly shear-oriented chorite texture. Some basalt clasts exhibit either single veins of chlorite and calcite or 3-dimensional dilatational arrays of chlorite veins.

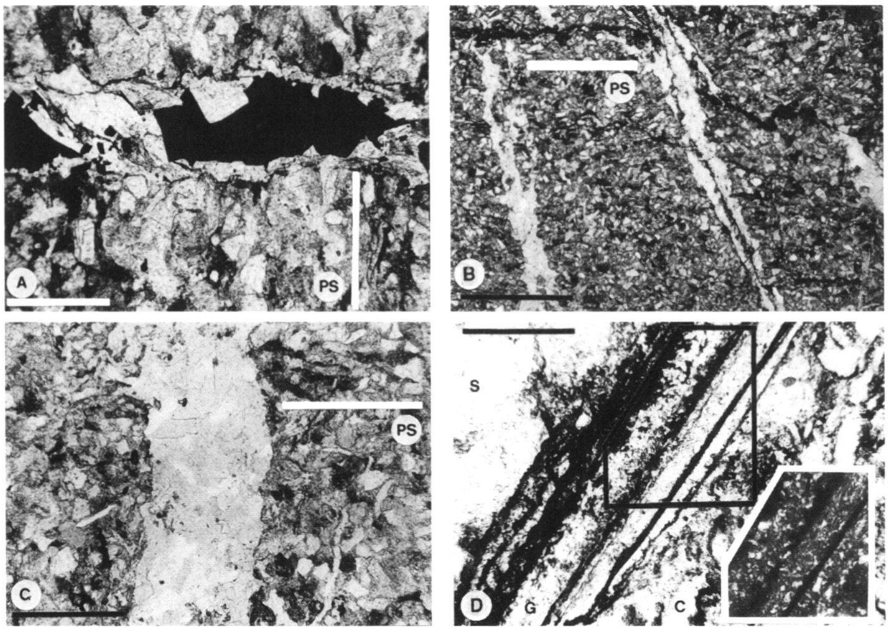


Fig. 13. A) Bimodal infill of K-Feldspar/minor quartz and bitumen with adularia. Transmitted light (Tl). PS: trace of the pressure solution cleavage, scale bar is 0.25 mm. B) Pre- and post-pressure solution cleavage K-Feldspar veins and infill with a median line of rock fragments suggesting hydraulic fracturing, Tl, scale bar is 1 mm. C) Monomineralic K-Feldspar veins perpendicular to the incipient pressure solution cleavage, Tl, scale bar is 0.25 mm. D) K-Feldspar laminated gouge in a shear zone, dark zones are completely ground mixture of K-Feldspar and sediment grains, Tl with polarized light for the detail, scale bar is 0.1 mm.

Dilatational patterns of fracture are commonly associated with brittle cherts where fractures are cemented by quartz and/or by mud of the shaly matrix. Dilatational fracture and cataclasis affect also pyrite grains (as well as quartz) which may form locally wisps forming swirling patterns in the chlorite mush (e.g. Fig. 11).

Certain large blocks of greenstone breccias exhibit a bimodal composition marked by matrices of differing green color. The dark green zones are rich in celadonite (Fig. 9), a ferric phyllosilicate close to glauconite. The same sort of swirling contacts, associated with shear, are observed in between these variably colored facies within these breccias (Fig. 10).

Class III- structures of the San Andreas system

The class-III structures are characterized by discrete steep faults (or thrusts) and veins striking roughly North (Fig. 1, stereogram on the left of Fig. 2a, IV on Fig. 3a). These fractures cut sharply across all the preceding structures and they separate the melange in fault packets (Larue et al. 1989), locally reorienting the older structures (Fig. 3a). They do not strongly affect structures within the fault packets. One can tentatively postulate that these structures might be very recent components of SA system or they have formed during some late stages of exhumation.

IV. Cements, veins and cement stratigraphy.

The above-described deformational structures are coupled with several cements and neogenetic minerals. Their relationships allow proposing at least two main phases of deformation regarding the composition of tectonic fluids. K-feldspar cements (KF) predominate the first phase and the calcite and quartz prevail in the second.

K-F cements

The K-feldspar cement has precipitated mostly in open fractures in the graywacke blocks (e.g. G, Fig. 2b in the sector I). It appears less common within the shaly matrix, possibly because the deformation of the weak lithologies is stronger. Figures 12 and 13 illustrate most of the typical occurrences of KF crystallization. Many veins are infilled by KF and minor quartz (Fig. 13 b, c, 14a), KF-quartz with bitumen, and KF with calcite (Fig. 14a), calcite always crystallizing after KF. The KF veins have a wide range of orientation (Fig. 12 and 17) and they commonly overprint older discontinuities. The fracture orientation (with respect to the cleavage, Fig. 16) reveals three main groups: 1) the 75–95° tensile fractures, 2) the 55–60° shear zones related to extension affecting lithified sediments (the extension paralleling the bedding), and 3) the 40–50° structures possibly associated with deformational structures bearing within unlithified sediments.

In addition to the discrete veins, the KF cementation is intimately associated with the cataclastic deformation in shear zones where it may form laminated gouge. This is illustrated in the figures 12 to 15 where the shear zones define small faults recording several episodes of movement. Episodes of cataclastic shear are separated by KF precipitation within pore fracture as shown by:

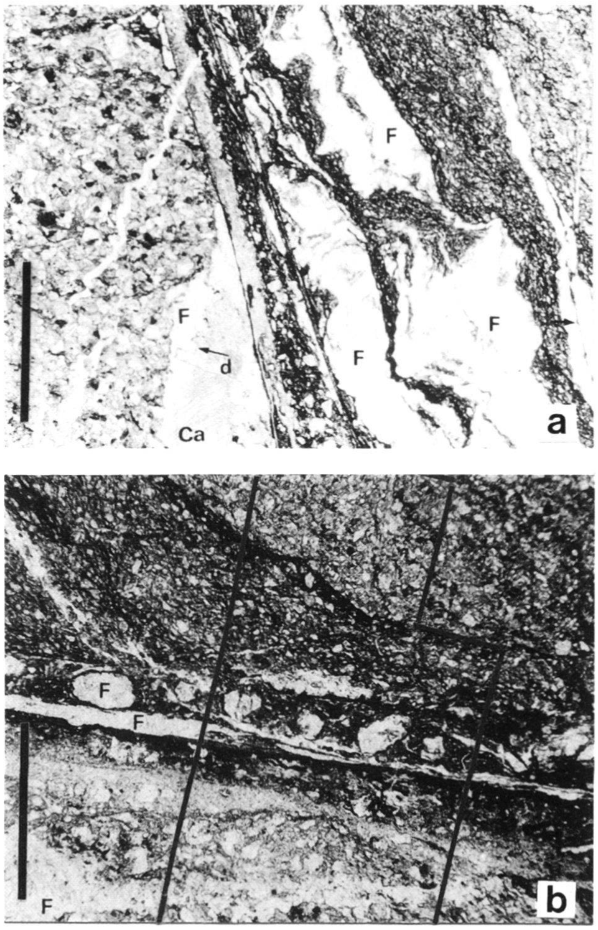


Fig. 14. Polycyclic shear zones (location B, Fig. 12). a) Large volumes of KF cement (F= K-Felspar) associated with several generations of gouge and cataclasite. K-Felspar crystallized between every step of shear and some late veins show antitaxial structures (arrow on the right) indicating hydraulic fracturing. When late calcite infills (Ca) are present, the KF are corroded (d).
b) The same kind of shear zone involving gouge and cataclasite with ground KF-clasts and rounded clasts of KF. The dark zones are mainly composed of ground KF and residue of OM. Scale bar is 1 mm in both photos.

(1) Laminated K-feldspar gouges (Fig. 13c, 14a and b),
(2) Cataclastic sediment mixed with a mush made of KF and rounded clasts of K-feldspar (Fig. 14b), and
(3) Several generations of veins that pre- to post-date the shear (Fig. 14b).

Some fractures cut the laminated gouge zones; they are oriented close to the bedding. These fractures are injected by a sediment mixture (Fig. 15). Sediment mixtures invade fracture and cleavage surfaces in the bulk sediment (centimeter-tick injections), and are cut by veins (Fig. 16). Certain zones of the sediment show a slightly disrupted fabric which attests to cataclastically enhanced remobilization with a weak grain-breakage (D, Fig. 12). These features illustrate multistage faulting. Each faulting cycle might be the consequence of a slow increase in fluid pressure leading to short tensile hydrofracture events and also shear failure in the 60° shear zones due to the drop of fluid pressure in the fractures. That process may be comparable to the fault-valve mechanism (e.g. Sibson 1981).

The KF is monoclinic (Orthoclase), and many crystals have the habit of Adularia (Fig. 13A). It consists of pure K-F with some crystals also containing Barium (close to Celsian). The KF associated with bitumen probably contains organic components as suggested by the microprobe analysis (possibly buddingtonite, NH_4-KF). The veins containing polymodal infill (silicate-carbonate) show authigenic KF with corroded shapes, which indicate that an important dissolution preceded the calcite precipitation. These corroded crystals are Na-enriched close to their rim possibly suggesting higher temperature fluids. The fact that Barium goes into KF instead of barite, together with the possible presence of Ammonium, indicate that K-F crystallized during somewhat reducing fluid conditions.

The age of the K-Feldspar cement has been determined by Argon/Argon method by B. Hacker (Unpubl. Data, Stanford University). The weighted mean age of 17.4 ± 2.5 Ma can be cautiously interpreted as the age of at least some of K-Feldspar cement.

Calcite cement and other neoformed minerals

Calcite is confined to veins within the entire melange. Its volume is notably common in its association with the recent structures cutting across all other structures. When the KF is present, the carbonate cements are always observed in cavities characterized by corroded KF rims (Fig. 14 A). No calcite preceding KF has been observed.

The calcite is chemically very pure and contains less than 1000 PPM of iron, magnesium and manganese (WDS analysis). The cathodoluminescence images have an ubiquitous very bright yellow luminescence and shows that the Mn/Fe ratio is relatively high and constant. The isotopic composition suggests that the source of the material was the parent graywacke (Larue et al. 1989). The habits of calcite vary from blocky calcite to rare fibrous crystals. Twin lamella and local development of subgrains also attest to crystal plasticity.

Other cements and neoformed minerals

The other common cement is mostly quartz. Quartz veins have sharp boundaries with the host rock, as noted above (Fig. 3b). In rare occurrences, quartz cement replaces sediment matrix with gradational boundaries around the area of cementation. The quartz may exhibit a ribbon texture (Fig. 8) and the crystals are commonly strained (undulous quartz). This demonstrates overprinting by crystal plasticity. Fibrous habits are infrequent. A few occurrences of barite in the clastics are present; they are mostly confined within fracture pores.

The shaly matrix and the graywackes display a clay parage-

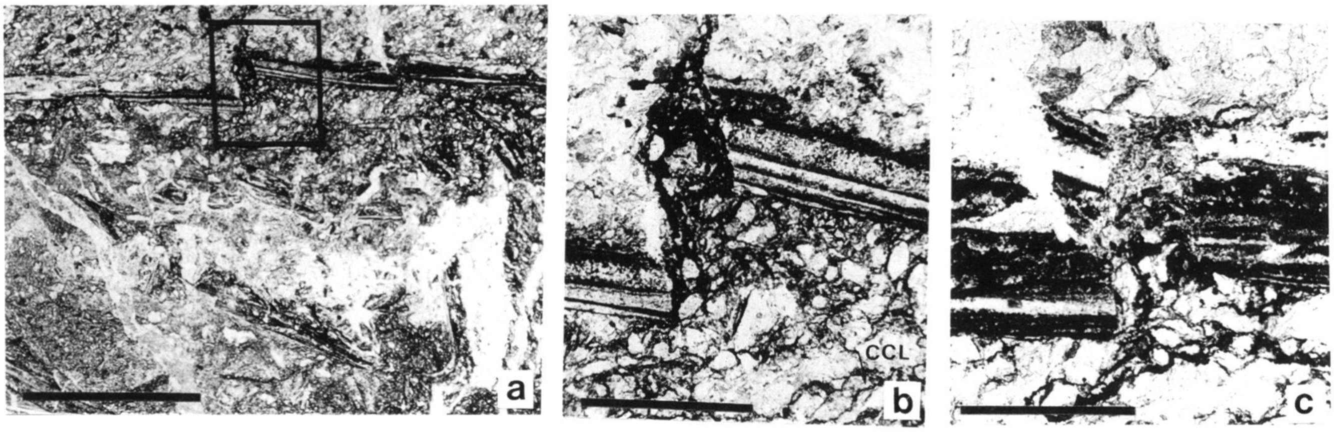


Fig. 15. Fractures and injections of disaggregated sediments showing remobilization. a) Part of the normal fault of the figure 12 (location B) with a shear zone (laminated KF-gouge) cut by hydrofractures and injection of liquefied sand. Note the large amount of KF-cement invading the cataclasite (bright zones), this latter including clasts of laminated gouges (some being folded), chunks of KF, pieces of sediment and folded remobilized sand. Laterally, the fine-grained cataclasite evolves to a gouge with clasts of K-Feldspar (fig. 14b). Scale bar is 1 mm. b and c) Details of hydrofractures with injected liquefied sediment (note the fracture orientation close to the bedding). Scale bar is 0.25 mm.

nesis made of mixed-layered clays (mostly smectite-chlorite instead of illite, and minor smectite-illite, Jaboyedoff & Jeanbourquin 1995) that may indicate the deepest burial of the melange matrix. This clay composition suggests that the temperatures were very low during the melange genesis (around 100°–200°C) and is consistent with the data of Larue et al. (1989). In the brecciated volcanics, the mush composition is chlorite and a mixed-layered chlorite/smectite. Calcite veins, with possible epidote, are present. The celadonite is ubiquitous in the greenstones. Some parts of the melange, notably in certain cataclastic tails, display a dark green color due to a large abundance of celadonite grains. Pumpellyite is also present; unfortunately it has been impossible to correlate its crystallization with the other cements. Finally, the occurrence of barite and celadonite indicates a somewhat oxidizing fluid condition.

V. Discussion

The Pacifica melange is characterized by a well-developed eye-level scale brecciated textures (breccia or pebbly-mudstone). The present study suggests that most of these textures result from fragmentation and mixing due to intense shear. The protoliths of the melange rocks were sequences of fine clastics with intercalated graywackes, basalts, cherts and locally limestones. The combination of the cement stratigraphy and the micro-structural study constrains the chronological evolution of the melange deformation as presented in the figure 18. It enables identification of two phases of deformation that characterize the melange genesis and its intense shear (class IIA and class IIB of the Fig. 18). Two other classes of deformation are readily recognized in the melange: very early structures (class I) and late structures (class III). It has not been possible to identify intermediate deformational stages between class I and II in the study although there is an inferred gap of significant time between class I and II structures.

Early structures (class I)

The knowledge of the early deformational history is sketchy because it is based on isolated observations of structures in the blocks or in the protomelange (broken formations). All the structures testify to deformation of differentially consolidated clastics, either 1) poorly lithified sediments (poorly compacted and uncemented), or 2) very mobile sediments due to liquefaction of sands (possibly turbulent).

The apparent dominance of sills, relative to dikes, suggests that the injections occurred in a tectonic regime with a weak deviatoric stress and a subvertical minimum stress with possible enhancement by hydrofracturing. Such an environment is common in accretionary prisms, notably in the frontal thrust region of an accretionary prism and in the protothrust zone as illustrated by recent data from ODP (Carson et al. 1993). At Pacifica, the features of these early structures are similar to earthquake induced structures (Obermeier et al. 1990). Hence their genesis is interpreted to be a consequence of seismic events while the sediment pile was still shallowly buried in the accretionary prism.

Interpretation of the melange deformations (class II)

The history of the polymictic melange, combining all lithic types, is characterized by brittle and ductile deformational events. Fragmention and mixing are significant. Once the block-in-matrix texture was formed, the weakest phase (the matrix) apparently controlled the melange rheology and pref-

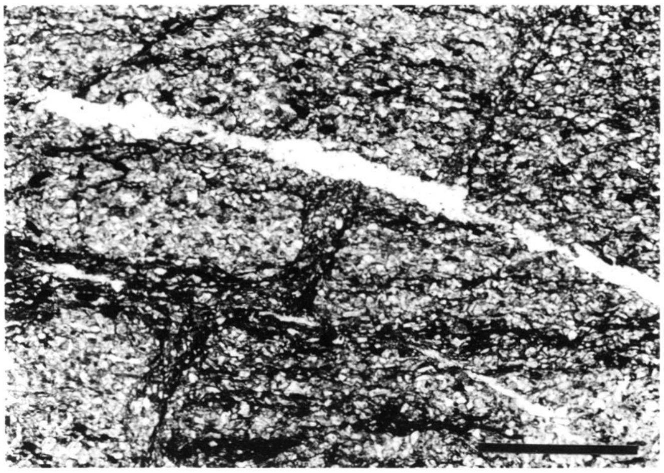


Fig. 16. Injection of a fluidized sand cutting across the foliation (bedding and the compaction/pressure solution). Neither significant grain-size reduction nor increase of fractured grains is observed. Note the subsequent KF vein paralleling the foliation that also suggests hydrofracturing. The scale bar is 0.7 cm.

erentially accommodated the deformation. This assumption, suggested by many authors (e.g. Handy 1990), is supported by the present data. This suggests that the structures within the blocks should survive overprinting by younger deformation.

Within the fault packets, the sense of movement inferred from shear structures or tails is not very consistent due to heterogeneous distribution of rocks in the melange and the complex interrelations between deformational structures. The upper part seems to move commonly toward west but this movement must be interpreted very carefully depending on the situation.

Deformation and cement stratigraphy

Among the four stages shown in the figure 18, class II features may be interpreted in terms of the melange genesis, i.e. fragmentation and mixing. The main melange-forming event is the melange deformation B; it combines fracturing, pervasive simple shear, mixing of the oceanic sequence with trench clastics, disaggregation of primary textures, and tectonic erosion (tectonic rounding and metamorphic reactions). The early melange deformation (class IIA) could result from pre-mixing events, causing the genesis of protomelange ("broken-formation"). These events could locally weaken the clastic sequences, favoring subsequent deformation in these zones.

The cement stratigraphy of the Permanente Terrane at Pacifica indicates that major crystallization of cements was intimately associated with the deformation as shown in the figure 18. Two lines of evidence, the occurrences of KF cements within the blocks and the KF-corroded border in calcite veins, suggest that the deformational structures of the class IIA clearly preceded the class IIB structures (melange fabric) during melange genesis. Therefore, at least two main types of fluids were associated with the melange. They indicate chemically reducing conditions followed by oxidizing conditions. The K-Feldspar indicates that the solutions were enriched in potassium and barium during the reducing phase. Its occurrence within fractures favors an *exchange reservoir model* to explain these cements, rather an *isochemical model* (Kastner & Siever 1979). This means that the cementation was related to significant metasomatism. Although the remobilization and the concentration of K and Ba by dewatering fluids of the oceanic sequence (or of the shallower portions of trench clastics) is a plausible hypothesis, a large scale metasomatism related to hydrothermal fluids seems to be a better explanation. Indeed, K-enrichment of fluids with respect to other cations like Ca^{++} and Na^{+}, together with Ba-enrichment, supports the latter premise. Such potassium-enrichment is well documented in several geodynamic settings similar to Franciscan melanges. For example, authigenic KF related to altered basalts of the Pacific Ocean crust is noted by Kelts & McKenzie (1986, DSDP Leg33, Central Pacific). Ramseyer et al. (1993) describe another setting of early diagenetic KF cement with buddingtonite in oil-bearing deposits of the San Joaquin basin. Also, many hydrothermal deposits with crystallization of KF are related to large-scale right-slip displacement within the Coast Range (e.g. McLaughlin et al. 1996). These articles, and the data from the Pacifica melange suggest two scenari.

Scenario 1: the measured $^{40}Ar/^{39}Ar$ age of KF is the age of cement crystallization.

The features of authigenic K-feldspar could be consistent with a late hydrothermal event occurring in the SA system (with K- and Ba-enriched solutions). Nevertheless, there are very few ore minerals at Pacifica. The 17.6 Ma age could correspond to hydrothermal events related to the beginning of the San Andreas fault strike-slip or its stagnation (e.g. McLaughlin et al. 1996). Simultaneously, it should be noted that the KF crystallization precedes certain important melange forming structures. Consequently, in this scenario the present day aspect of melange outcrops (the pebblymudstone facies) would result from movements and deformations related to the SAF system: it would be a strike-slip melange. In this case, the melange deformations remain very sensitive to physical factors depending on the maturation of organic matter and the evolution and migration of the fluid. The combination of these latter will considerably influence the creation of over-pressured cells and will allow deformation mechanisms such as IPF. Unfortunately, an important consequence of this scenario is that it should exist an important gap of deformation between the early deformation (class I) and the melange mixing following the KF (class IIA and B). This seems unlikely in regards to the large spectra of observed structures in this paper. Furthermore, it is inconsistent with the subduction history known is that region and the subsequent transform fault system (Wakabayashi 1999).

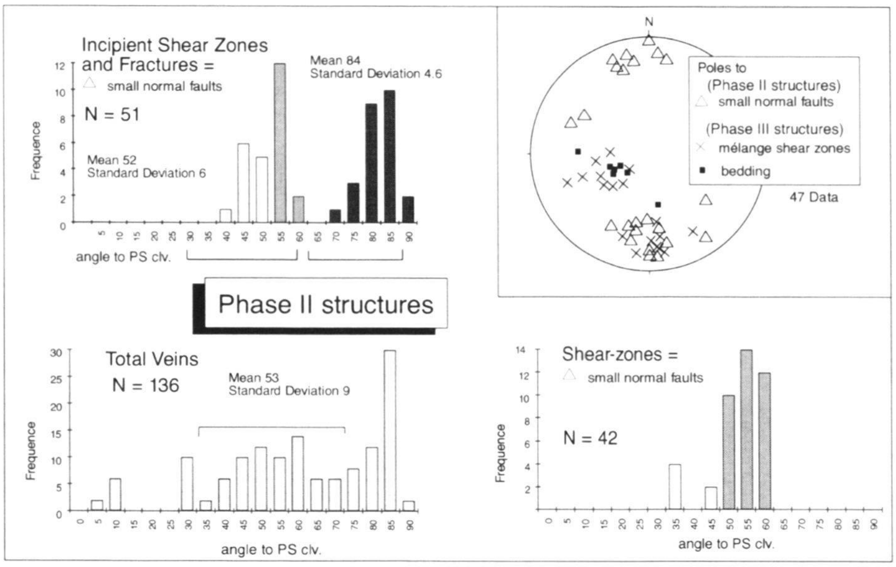


Fig. 17. Frequency histograms of the orientation in a vertical plane oriented NNW of KF-related microstructures measured with respect to pressure-solution cleavage. The stereogram shows the present day position of these structures (Equal area stereogram, lower hemisphere).

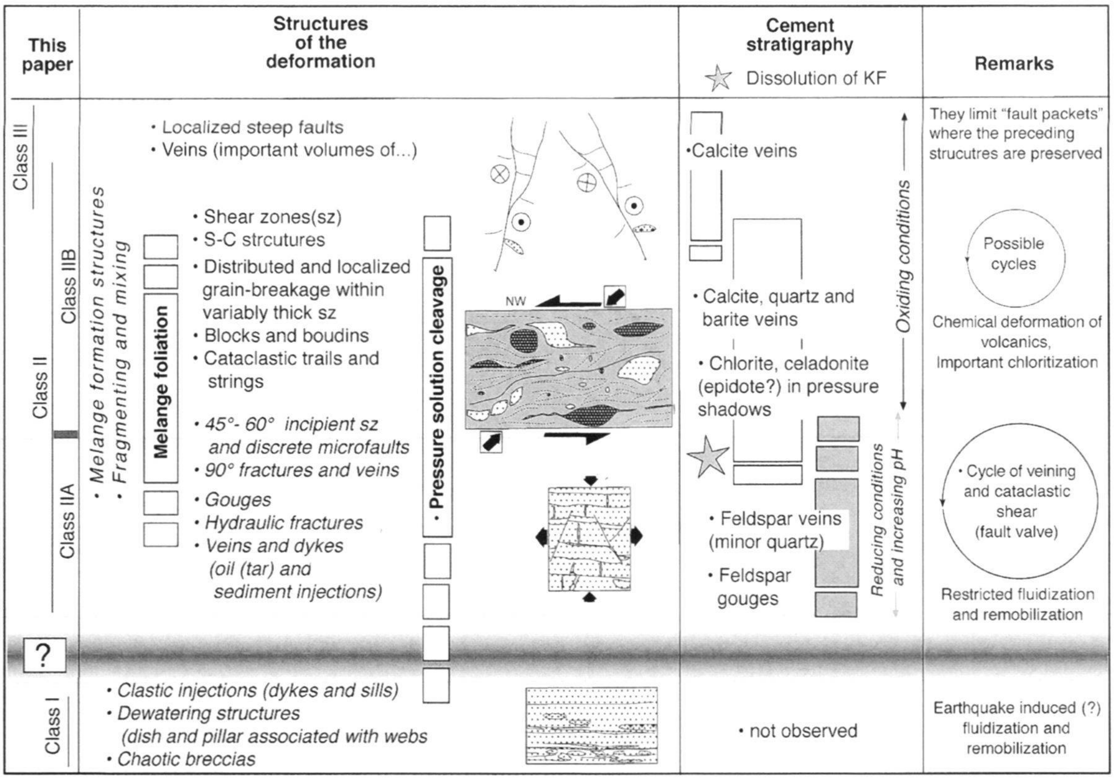


Fig. 18. Synthetic chronology of the deformation.

Scenario 2: the $^{40}Ar/^{39}Ar$ measurements do not indicate an age of crystallization but the age of a mixture or a young thermal overprint.

This scenario assumes that localized flows of hydrothermal solutions may occur several times during the plate evolution. For example, flow across the Pacific plate, with authigenic KF crystallization, is mentioned by Kelts & McKenzie (1986). Another possibility of subduction-age hydrothermal systems in the Franciscan accretionary prism is the occurrence of small igneous intrusions that intrude Franciscan grauwacke or melange.

One can imagine that, during the burial under the accretionary prism, fluids were derived from underthrusted sediments of the downgoing plate, from offscraped clastics or from small intrusions. According to Kastner & Siever (1979), temperature, pH and concentration of the alkalis control authigenic feldspar formation. The dissolved carboxylic acids, generated during oil maturation, decrease the pH of fluid. This significantly retards precipitation and even favor the dissolution of both feldspars and carbonates (Surdam et al. 1989, Boggs 1992), while enhancing the solubility of Al (formation of chelates). One could postulate that the downgoing sediments, attached to the oceanic crust, would reach „high" temperature (>80°-120°C) more rapidly than the overlying underthrusted trench clastics (Cloos 1982). In moving upward throughout the deforming trench clastic sequence, the fluids would escape along the basal decollement of the accretionary prisms. The solutions flowing upwards would encounter new conditions characterized by lower temperatures and mixing with higher pH fluids expelled from the compacting sediment, triggering the precipitation of K-feldspar cement.

The relatively continuous deformational evolution is consistent with this second scenario. In addition, the data in this paper may provide a link between the KF data collected within the Coast Range (coastal hydrothermal systems) and those gathered in the Pacific oceanic plate (Kelts & McKenzie 1986).

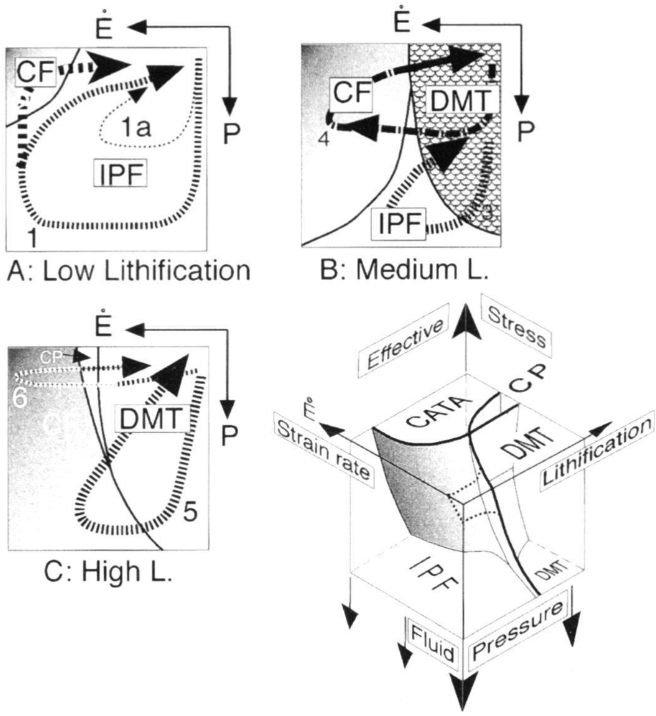


Fig. 19. Knipe's deformation diagram, 3D view and three details at different lithification with several examples of deformation pathes (after Knipe 1986, modified).

VI. Deformation mechanisms, deformation paths and tectonic pebblymudstone (or how to explain the large variety of deformational structures).

The Pacifica melange exhibits a very large range of deformational structures featuring the mechanisms of melange deformation and the different paths of deformation associated with deformational domains. According to Knipe (1986), the main deformation mechanisms encountered in melanges are cataclastic flow (CF), intergranular particulate flow (IPF), crystal plasticity (CP) and diffusive mass transfer (DMT). The boundaries between these mechanisms are strongly dependent on three physical factors: fluid pressure, strain rate and degree of lithification. Knipe (1986) illustrates this concept with a well-done 3D-graph combining these three factors and limiting the four domains of deformation (see Fig. 19). This graph shows that IPF is a very important process in the compacting sediments. As its significance increases as the fluid pressure increases, this process may occur in lithified sediments of overpressured cells of thrusts (e.g. Brown 1994) where it may be associated with hydraulic fracturing (Fig. 15) and fault valve processes (Sibson 1981). The IPF mechanism competes also with cataclastic flow (CF), particularly when shear rate rises or when the degree of lithification increases. When the degree of lithification is high, IPF vanishes and the other deformational mechanisms become more efficient. However, one must consider that the cataclasis, notably under high fluid pressure (high enough to produce hydraulic fracture), can result in the disaggregation of certain volumes of rock and decrease considerably the lithification in these zones (this is particularly true for the weaker phases that usually constitue the matrix). Therefore, Knipe's diagram is (Fig. 19) quite applicable to interpretation of the structural development of the Pacifica melange or melange in general. In addition, this diagram allows to understand the singular convergence of many textural aspects of melanges, olistostromes and wildflyschs since IPF is a dominant mechanisms under many physical conditions. This is a very important clue for interpreting melanges in mountain belts such as wildflyschs in the Alpine Chain.

VII. Conclusion

This study documents the large variety of deformational structures of the Pacifica area. Despite the complexity of the melange, it is possible to deduce a chronology of melange genesis based on the relationships between structures and cement stratigraphy. The data favor a main "subduction history" although a strike-slip history could be very important. In the former case, the K-feldspar cement could be interpreted as a bridge between the Pacific plate volcanism and the coastal range intrusions and volcanism.

Finally, a main issue of this paper is that the pebblymudstone texture of melange texture is not forcefully related to sedimentary processes, but it has here a tectonic origin. It is a very important outcome for the melange-olistostrome-wildflysch understanding.

Acknowledgment

I am very grateful to J. Casey Moore from UCSC, for his support and the stimulating discussions. I thank Jonathan Krupp and Wilfred Betham of the UCSC-Electron Microscope-Lab for assistance during microscopic imaging. M. Jaboyedoff (Institute of the Mineralogy and Petrography, University of Lausanne, Switzerland) is acknowledged with thanks for Xray diffraction analyses and for many helpful advices. The author acknowledges the Swiss National Foundation of Sciences (Grant # 8220-30694) and the UCSC for partial financing, and the UCSC for accommodations during this work. Finally, I thank J. Wakabayashi and B. C. Burchfiel for their very stimulating and helpful review.

Available data on request

The following chemical data are available on request:

1- whole rock analysis of the melange matrix (X-ray fluorescence)
2- rock and clay analysis (X-ray diffractometry)
3- microprobe analysis of K-feldspar
4- Argon/Argon analysis of K-feldspar.

REFERENCES

Aalto, K. R. 1989: Franciscan complex geology of the Crescent city area, Norther California. In Geologic evolution of the Northernmost Coast Range and Western Klamath Mountains (Ed. by Aalto, K. R. & Harper, G. D.). 28th. Int. Geol. Congr. Guideb. 308, 21–45.

Agar S. M. 1990: The interaction of fluid processes and progressive deformation during shallow level accretion: Examples from the Shimanto Belt of SW Japan. J. geophys. Res. 95, 9133–9147.

Bagnold, R. A. 1954: Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proc. r. Soc. London, Mat. 225, 49–63.

Blake, M. C. Jr. 1984: Franciscan geology of Northern California. Soc. econ. Petrol. Mineral. Pacific section 43.

Boggs, S. Jr. 1992: Petrology of sedimentary rocks. Maxwell Macmillan international.

Brown, K. M., Bekins, B., Clennell, B., Dewhurst, D. & Westbrook, G. 1994: Heterogeneous hydrofracture development and accretionary fault dynamics. Geology 22, 259–262.

Burley S. D., Kantorowicz J.D. & Waugh, B. 1985: Clastic diagenesis. In: Sedimentology: recent developments and applied aspects (Ed. by Brenchley, P. J. & Williams, B. P. J.). Blackwell, London.

Byrne, T., and Fisher, D. 1990: Evidence for a Weak and Overpressured Décollement Beneath Sediment-Dominated Accretionary Prisms., J. geophys. Res. 95, 9081–9097.

Carson, B.; Westbrook, G. & Musgrave, R. 1993: Cascadia margin, Science operator report. Joides J. 19, 11–16.

Cloos, M. 1982: Flow melanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. Bull. geol. Soc. Amer. 93, 330–345.

Cowan, D. S. 1985: Structural styles in Mesozoic and Cenozoic melanges in the western Cordillera of North America. Bull. geol. Soc. Amer. 96, 451–462.

Galloway, W. E. 1974: Deposition and diagenetic alteration of sandstone in Northeast Pacific arc-related basins: Implications for graywacke genesis. Bull. geol. Soc. Amer. 85, p. 379–390.

Handy, M. R. 1990: The Solid–State Flow of Polymineralic Rocks. J. geophys. Res. 95, 8647–8661.

Hsü, Kenneth J. 1974: Melanges and their distinction from olistostrome. In: Modern and ancient geosynclinal sedimentation (Ed. by Dott, R. H. J. R. & Shaver, R. H.). Spec. Publ. Soc. econ. Paleont. Mineral. 19, 321–333.

Jaboyedoff, M. & Jeanbourquin P. 1995: Mixed layer clays and scaly fabrics as indicators of overpressures within accretionary prisms and melanges. Terra nova 8, 127.

Jayko, A. S. & Blake M. C. Jr. 1984: Sedimentary petrology of graywackes of the Franciscan complex in the northern San Francisco region, California. In: Franciscan geology Of Northern California (Ed. by Blake, M. C. Jr.). Soc. econ. Petrol. Mineral. Pacific section 43, 121–134.

Kastner, M. & Siever, R. 1979: Low temperature Feldspars in sedimentary rocks. Amer. J. Sci. 278, 435–479.

Kelts, K. & McKenzie, J. A. 1976: Cretaceous volcanic sediments from the line Island Chain: Diagenesis and deformation of K-Feldspar. In: Initial Reports of the deep sea Drilling ProjectDSDP Leg 33, Hole 315A and site 316 (Ed. by Schlanger, S. D., Jackson, S. D. & al.). 789–803.

Knipe, R. J.; Agar, S. M. & Prior, D. J. 1991: The microstructural evolution of fluid flow paths in semi-lithified sediments from subduction complexes. Phil. Trans. r. Soc. London A335, 261–273, 1991.

Knipe, R., 1986: Deformation mechanism path diagrams for sediments undergoing lithification. In: Structural Fabrics in Deep Sea Drilling Project Cores from Forearcs (Ed. by Moore, J. C.). Mem. Geol. Soc. Amer. 166, 151–160.

Larue, D. K., 1986: Organic matter in limestone and melange matrix from the Franciscan and Cedros subduction complexes. In, Cretaceous stratigraphy, western North America (Ed. by Abbott, L.). 211–221.

Larue, K. D.; Barnes, I. & Sedlock, R. L. 1989: Subduction and accretion of the Permanente Terrane near San Francisco, California. Tectonics 8, 221–235.

Maltman, A. J. 1994: The geological deformation of sediments: introduction and overview. Chapman & Hall, London. 1–34.

McLaughlin R.J., Sliter, W. V., Sorg, D.H., Russell, P. C. & Sarna-Wojcicki, A.M. 1996: Large-scale right-slip displacement on the East San Francisco Bay region fault system, California: Implications for location of late Miocene to Pliocene Pacific plate boundary. Tectonics 15, 1–18.

Moore, J. C., & Lundberg, N. 1986: Tectonics overview of Deep Sea Drilling Project transects of forearcs. In: Structural Fabrics in Deep Sea Drilling Project Cores from Forearcs (Ed. by Moore, J. C.). Mem. Geol. Soc. Amer. 166, 1–12.

Moore, J. C.; Roeske, S.; Lundberg, N.; Schoonmaker, J.; Cowan, D.; Gonzales, E., and Lucas, S., Scaly fabrics from Deep Sea Drilling Project cores from forearcs. In: Structural Fabrics in Deep Sea Drilling Project Cores from Forearcs (Ed. by Moore, J. C.). Mem. Geol. Soc. Amer. 166, 55–73.

Obermeier, S. F.; Jacobson, R. B.; Smoot, J. P.; Weems, G. S.; Gohn, G. S.; Monroe, J. E. & Powards, D. S. 1990: Earthquake-induced liquefaction features in the coastal setting of South Carolina and in the fluvial setting of the New Madrid seismic zone. U.S. geol. Surv. prof. Pap. 1504.

Orange, D., Geddes, D. & Moore, J. C. 1993: Structural and fluid evolution of a young accretionary complex: the Hoh rock assemblage of the Western Olympic Peninsula, Washington. Bull. geol. Soc. Amer.105, 1053–1075.

Ramseyer, K., Diamond L.W. & Boles, J. R. 1993: Authigenic K-NH4-Feldspar in sandstones: a fingerprint of the diagenesis of organic matter. J. Sed. Petrol. 63, 1092–1099.

Pickering, K. T.; Hiscott, R. N. & Hein, F. J. 1989: Deep marine environments – Clastic sedimentation and tectonics. Unwin & Hyman, London.

Sibson, R. H. 1981: Fluid flow accompanying faulting: field evidence and models. In: Earthquake prediction: an international review (Ed. by Simpson D. W. & Richards, P. G.). Amer. Geophys. Union, Maurice Ewing Ser. 4, 593–603.

Shreve, R. L. & Cloos, M. 1986: Dynamics of sediment subduction, melange formation and prism accretion, J. geophys. Res. 91, 10229–10245.

Surdam, R. C.; Crossey, E. S.; Hagen, E. S. & Heasler, H. P. 1989: Organic-inorganic interactions and sandstone diagenesis. Bull. amer. Assoc. Petroleum Geol. 73, 1–23.

Wakabayashi, J. 1999: Distribution and displacement on and evolution of a young transform fault system: The northern San Andreas fault system, California. Tectonics 18, 1245–1274.

Wakabayashi, J. & Moores E. M. 1988: Evidence for collision of the Salinian block with the Franciscan subduction zone. J. Geol. 96, 245–253.

Manuscript received August 31, 1999
Revision accepted August 15, 2000