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New interpretation of the Franciscan mélange at San Simeon coast, California: tectonic intrusion into an accretionary prism

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Many concepts and interpretations on the formation of the Franciscan mélange have been proposed on the basis of exposures at San Simeon, California. In this paper, we show the distribution of chaotic rocks, their internal structures and textures, and the interrelationship between the chaotic rocks and the surrounding sandstones (turbidites). Mélange components, particularly blueschists, oceanic rocks, including greenstone, pillow lava, bedded chert, limestone, sandstone, and conglomerate, have all been brecciated by retrograde deformation. The Cambria Slab, long interpreted as a trench slope basin, is also strongly deformed by fluidization, brecciation, isoclinal folding, and thrusting, leading us to a new interpretation that turbiditic rocks (including the Cambria Slab) represent trench deposits rather than slope basin sediments. These rocks form an accretionary prism above mélanges that were diapirically emplaced into these rocks first along sinistral-thrust faults, and then along dextral-normal faults. Riedel shear systems are observed in several orders of scale in both stages. Although the exhumation of the blueschist blocks is still controversial, the common extensional fractures and brecciation in most of the blocks in the mélanges and further mixture of various lithologies into one block with mélange muddy matrix indicate that once deeply buried blocks were exhumed from considerable depths to the accretionary prism body, before being diapirically intruded with their host mélange along thrust and normal faults, during which retrograde deformation occurred together with retrograde metamorphism. Recent similar examples of high-pressure rock exhumation have been documented along the Sofugan Tectonic Line in the Izu forearc areas, in the Mineoka belt in the Boso Peninsula, and as part of accretionary prism development in the Nankai and Sagami troughs of Japan. These modern analogues provide actively forming examples of the lithological and deformational features that characterize the Franciscan mélange processes.

Keywords: mélange; accretionary prism; isoclinal fold; Riedel shear; mud intrusion; fluidization; duplex

Introduction

Historical review of mélange research from the San Simeon coastal area

Many papers on the Franciscan mélange at San Simeon, central coastal area of California, have been published since the earliest paper of Hsü (1968). From the conceptual ideas to detailed description, this area has been one of the classical sites to examine structural, petrological, and sedimentological processes at convergent margins (Figures 1 and 2). Some studies have evaluated how high-pressure metamorphic rocks were emplaced into a muddy mélange matrix (Hsü 1968; Cowan 1978; Cloos 1982, 1984, 1986; and many others).

Hsü (1968) introduced the mélange concept based on the occurrence of chaotic rock assemblages and concluded that mélanges were tectonic in origin. Cowan (1978), however, pointed out that the differences of metamorphic grades and deformation features among the mélange blocks (particularly the blueschist blocks) and muddy (argillaceous) matrix were so big that no other phenomenon than sedimentary incorporation, such as debris flow or olistostromal emplacements, would be responsible for their juxtaposition.

On the contrary, Cloos (1982, 1984) and his co-authors identified abundant evidence for high stress and strain rates, and tectonic shearing and flowage likely associated with diapiric flow (return flow) within a subduction channel. They proposed that channel flow was responsible for bringing up high-pressure rock blocks (blueschist) to the surface, which produced a flow mélange.

According to Cloos (1982), during the combined up and down movements in a subduction channel return flow, blocks might have been exhumed to shallower levels, finally forming the present muddy matrix mélange mixture. For the depth and setting of blueschist formation, Ukar's (2012) detailed observation of the actinolite rinds in the rims of minerals in blueschist blocks indicates well

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This paper is dedicated to late Professors Kametoshi Kanmera, Noriyuki Nasu, and Kazuo Kobayashi, who passed away after great contributions to accretionary prism study and marine geosciences.

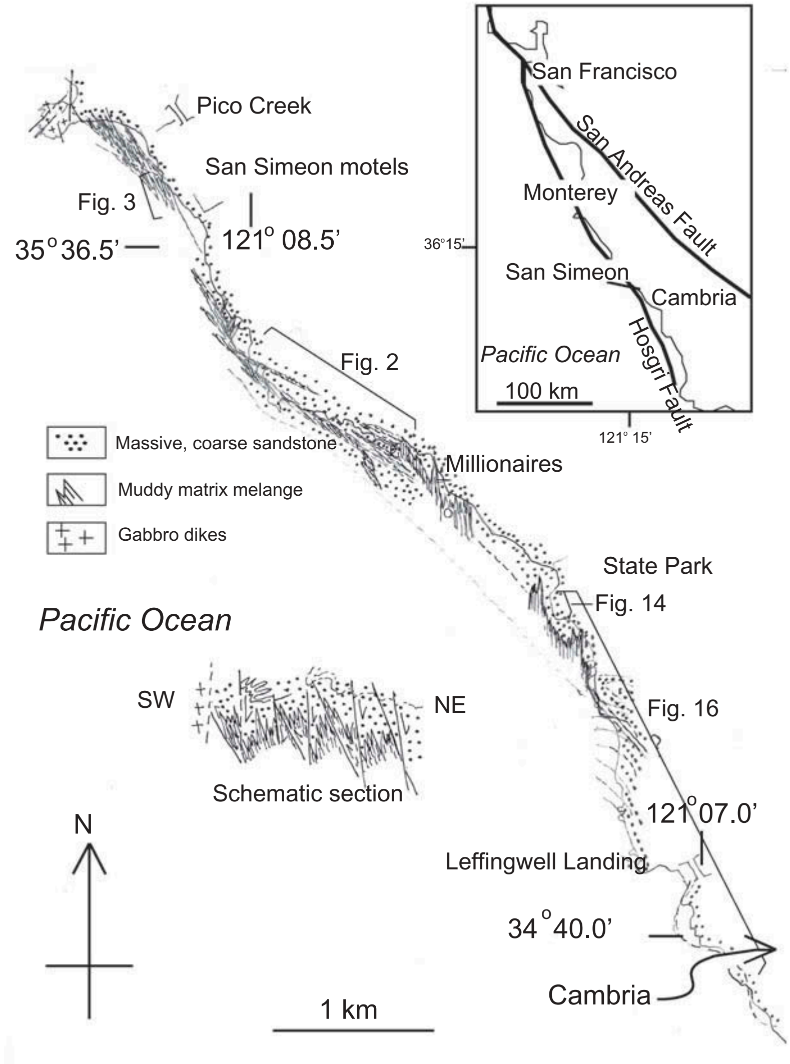

Figure 1. Index map with schematic cross section of the main study area from Pico Creek (north of the San Simeon motel area) to south of Leffingwell Landing point, north of Cambria. The general distribution of mélange and sandstone is shown. Locations of detailed maps in Figures 2, 3, 14, and 16 areas are indicated.

the metasomatic reaction between the serpentinite in the hanging wall and metamorphic rocks (blueschist) in the footwall. However, the mélange muddy matrix displays only lower metamorphic grade assemblages of pumpellyite-prehnite facies rather than blueschist (Cowan 1978). Thus it is difficult to explain the mélange formation by a single-stage process, such as by thrusting, debris flow deposition, or diapirism of blueschist and enclosing serpentinite into the present mud matrix mélanges, so multiple stages of lithological mixing appear likely.

Recently, Singleton and Cloos (2012) proposed a syntectonic shear history dominated by sinistral thrusting from the San Simeon outcrops, but below we show that dextral oblique normal faulting followed the sinistral oblique thrust faulting.

Concerning the relationships between the mélange bodies and surrounding sandstone, Smith *et al.* (1979) showed a structural section of turbidites at Abalone Cove off Cambria in which the two lithologies are repeated by faults. Becker and Cloos (1985) described the nature of contacts between the mélange and surrounding sandstone bodies (the Cambria Slab) and interpreted that the latter are trench slope deposits lacking strong deformation. They showed that the mélange intruded by diapirism along the fault planes into the Cambria Slab. According to them, the diapiric intrusion into the Cambria slab represented a secondary emplacement of the mélange, after the first large-scale diapiric intrusion of high-pressure rock-bearing original mélange to the shallow levels. Underwood and Laughland (2001) showed many isoclinal folds of

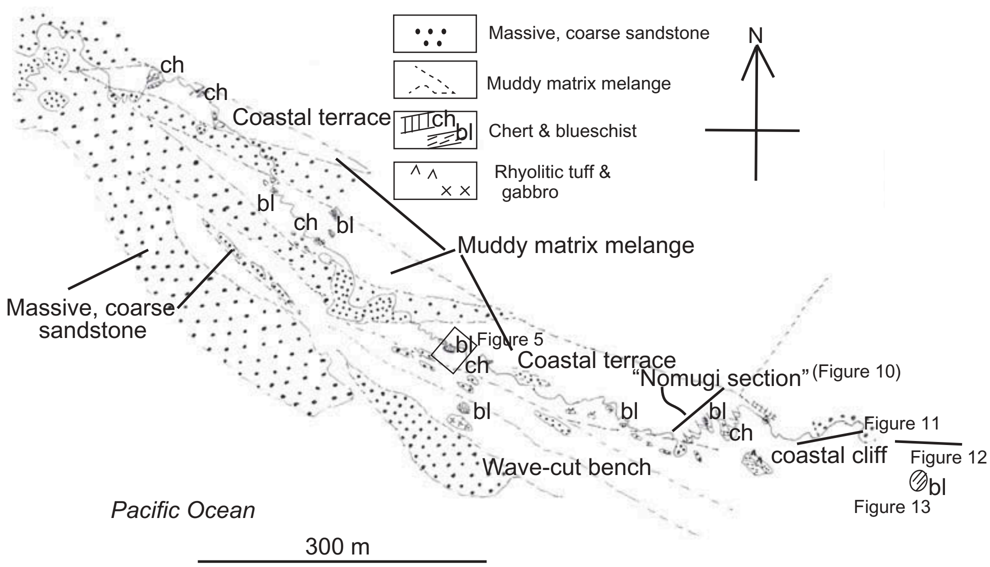

Figure 2. Distribution pattern of mélange and sandstone from south of the 'San Simeon motel area' to north of the 'Millionaire area'. The sparse dotted pattern is the inferred distribution of sandstone on wave-cut benches. The intercalations of mélange and sandstone are mostly by means of faulting as is well observed in the 'Nomugi section' in Figure 10. Maps of other important outcrop areas in Figures 5, 10, 11, 12, and 13 are indicated.

turbidites that they interpreted as being deposited at a trench and offscraped into an accretionary prism. However, only they showed this conceptually.

Scope of this paper

As reviewed above, there remain many problems unsolved. Only a few papers examine the relationship between the mélange bodies of San Simeon and the surrounding turbiditic rocks. Most of the papers interpreted the Cretaceous turbidite beds, called the 'Cambria Slab' (further to the south, the 'Point San Luis Slab'), as trench slope cover or an accretionary body above the mélange zone. Only Smith *et al.* (1979) and Underwood and Laughland (2001) considered the structural features, and then only from the Abalone Cove section off Cambria and at the San Luis Obispo coastal area, respectively. The latter is not accessible to the public at present.

We mapped the mélange as well as the turbidite beds (sandstones) along the San Simeon coast, mostly from Pico Creek to the north of the San Simeon motel area to the Leffingwell Landing point area at the north off Cambria in the south (Figure 1). We also examined the outcrops in the Old San Simeon village and Abalone Cove areas. We observed numerous way-up indicators in turbidite rocks to show the general attitudes of beds, including various-scale isoclinal folds, and in some places duplex structures. After examining the structural relationships, including both the mélange- and sandstone-dominant units, we have concluded that the turbidites were trench deposits that were offscraped and underplated into an accretionary prism then intruded by muddy matrix mélange during at least two stages of deformation.

Most of the blueschist blocks record retrograde metamorphism from actinolite-bearing assemblages to glaucophane-bearing ones (blueschist facies), and finally pumpellyite and lawsonite-bearing assemblages as described later. The muddy matrix corresponds to the lowest grade of the above retrograde metamorphism, but the same muddy lithology is represented by phyllitic fragments and layers of the matrix incorporated within the sheared, folded and brecciated blueschist blocks as described below.

We lastly compare the geology of the Franciscan Complex as observed in the San Simeon and San Luis Obispo areas with the Neogene contemporary, on-land and submarine accretionary prisms of Japan, including the metamorphic rock assemblages in the Izu forearc region. We then present a realistic mélange model for subduction zones.

Structural description

Several sites along the coast were chosen to represent the critical areas for displaying the relation between the mélange units and turbidite beds as well as the structure and shape of blocks. These sites (from north to south) are (1) the frontal San Simeon motel area, (2) south of San Simeon motel area, (3) north of millionaire area (Nomugi section), (4) south of millionaire area, (5) north of State Park area (duplex section), and (6) south of State Park area to Leffingwell Landing point area (thick turbidite section) (Figure 1). The Abalone Cove area is only for simple description. Finally, sandstone petrography is added. Tectonic interpretations follow the descriptive section.

Frontal San Simeon motel area

In the frontal San Simeon motel area, the wave-cut benches are exposed during low tide, displaying critical contact relations between mélange units and turbiditic sandstones (Figures 3 and 4). The contact between the upper massive sandstone and the lower muddy mélange displays key structural features to better understand and document the deformational processes (Figure 4). Laminated sandstone beds with small elliptical mudstone clasts are folded (Figure 4(A) and (B), inlet). Blocks of such laminated sandstone beds are also included in the subjacent mélange units (Figure 4(A)).

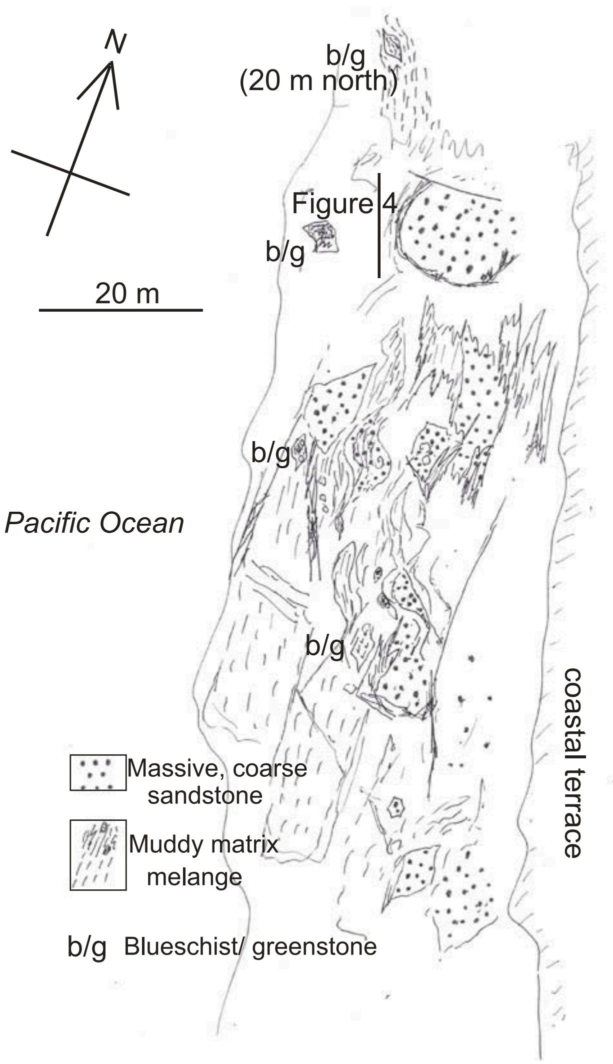

Figure 3. Sketch map of the wave-cut bench at the frontal San Simeon motel area showing a zigzag pattern of intercalated structural relations between mélange and sandstone bodies, and some blueschist or greenstone (altered basalt) blocks.

Other sandstone bodies in this area lack original sedimentary structures and are brecciated. Jigsaw-puzzle structure with a muddy matrix is common in these sandstone occurrences (Figure 4(D)). Blueschist, greenstone, and chert blocks locally occur within the muddy mélange. The shape of these blocks is phacoidal with tails, commonly displaying apparent sinistral shear with rare dextral shear on the plan view (Figure 3).

South of San Simeon motel area

The approximately 3 km-long coastline from the south end of the San Simeon motel area to just north of the millionaire area (mentioned in the next section) makes up one of the classic-type localities of the Franciscan mélange since the initial studies of Hsü (1968), Cowan (1978), and Cloos (1982). Blueschist, greenstone (altered basalt), and chert blocks from 1 to 10 m in diameter are embedded within a slickensided muddy matrix. Sandstone fragments, blocks, and slabs (>500 m in length) are also found mostly in NW-trending tracts that interfinger with tracts of sandstone-poor mélange along low-angle contacts (Figures 1 and 2).

We find three stages of metamorphism in the surface crust of a blueschist body (Figures 5 and 6; sample number SS-12-59), the same block of #45 of Ukar (2012) and Ukar and Cloos (2013). Electron microprobe and petrographic analyses (Figure 6) documented the occurrence of three metamorphic assemblages: the first stage is actinolite + albite, the second stage is glaucophane ± phengite (albite diminished), and the third stage is lawsonite + pumpellyite + quartz. The muddy matrix surrounding the blueschist blocks is also metamorphosed to phyllite. Due to compositional differences, it is difficult to delineate the actual metamorphic grade, but the Franciscan mudstones here are interpreted as prehnite-pumpellyite facies (Cowan 1978). The deformation style of the last stage metamorphism is brecciation with a distinctive cataclastic texture.

A phyllitic muddy rock fragment forms part of the blueschist block of #45 of Ukar (2012). The texture of this fragment is characterized by preferred alignment of mica grains defining a schistosity consisting of irregular anastomosing shear zones (Figures 5 and 7(A) and (B), sample number SS-12-61). This texture is the same as that of the surrounding muddy matrix (Figure 7(C) and (D), sample number SS-12-58).

In other outcrops, matrix flow fabrics differ in shear sense to those found in the blocks (Figures 8-1 and 9 for representative examples of blocks of blueschist and greenstone). Some blueschist blocks show turtle shapes (Figure 9 (A) and (B)) with their tails displaying sinistral sense of shear in plan view (Figure 9(C)). In some greenstone blocks, rotational sense varies between sinistral (Figure 9(D)–(F)) and dextral (Figure 9(G) and (H)) sense of shear.

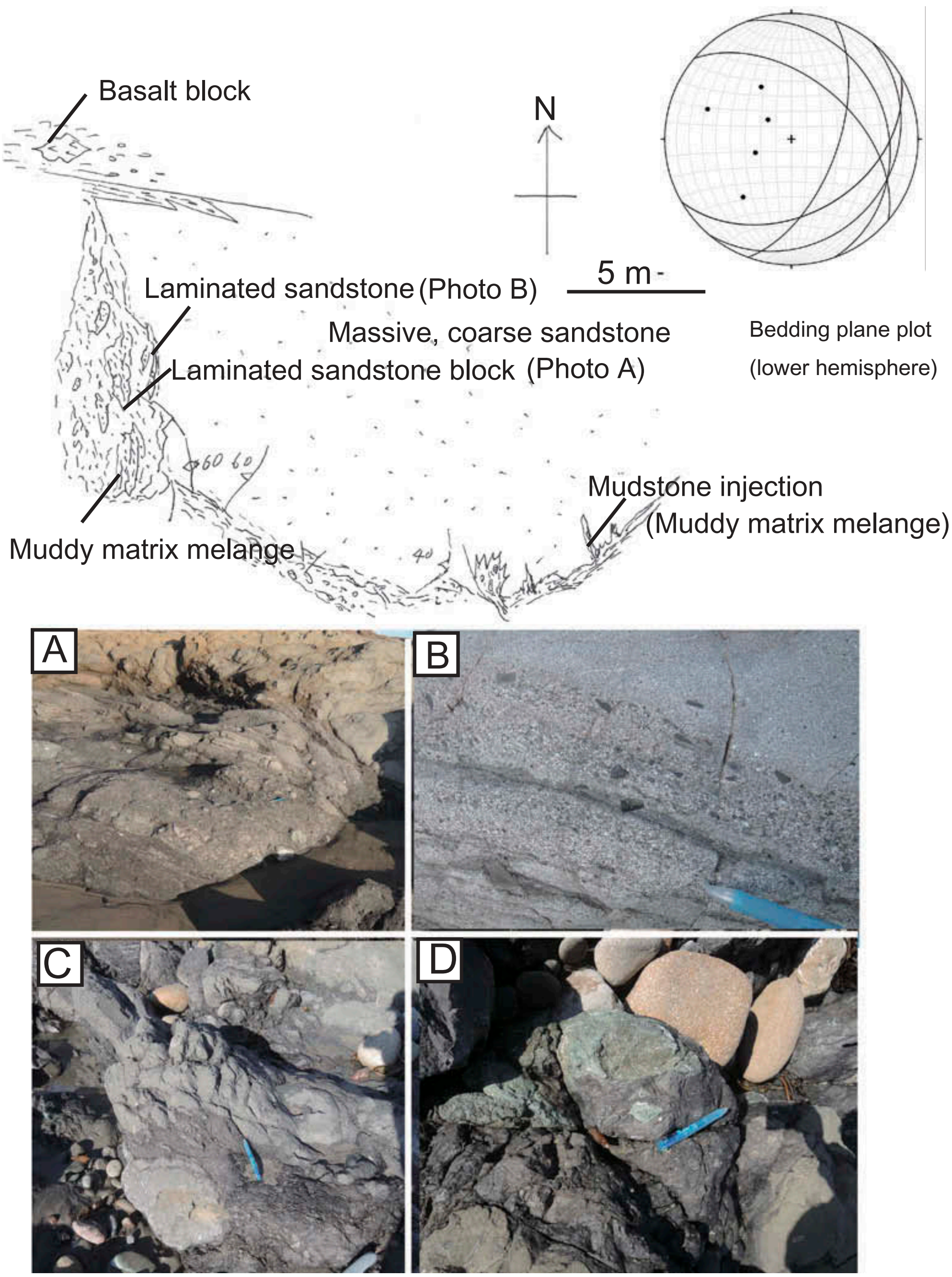

Figure 4. Sketch map and outcrop photos of coarse, massive sandstone of the frontal San Simeon motel area. (A) and (B) occur at the base the sandstone unit. Secondary deposits of laminated, elliptically shaped mud-clast-bearing coarse sandstone are situated in between massive sandstone (above) and muddy matrix mélange (below) as in (B). Some of these beds encased (dropped) within muddy mélange bodies below (A). The lower hemisphere stereograph is of bedding planes and poles to planes at the base of the sandstone body, which indicates broad folding. These outcrops show mud injection into overlying sandstone beds, including sandstone blocks (C), and greenstone (altered basalt) blocks (D).

Fragments and blocks of sandstone show characteristic layer-parallel extension with in pinch-and-swell structures of original layers, and boudinage with mud matrix intruded between separated layers (Figure 8-2) as also documented earlier by Cowan (1978). In some blocks, boundaries between pulled apart sandstone layers and the muddy matrix are diffuse. Indication of rotational shear is also found in areas dominated by layer pure-shear-related layer-parallel extension.

North millionaire area (Nomugi section)

This 30 m-long outcrop, tentatively called the 'Nomugi section', may be one of the best places to observe for

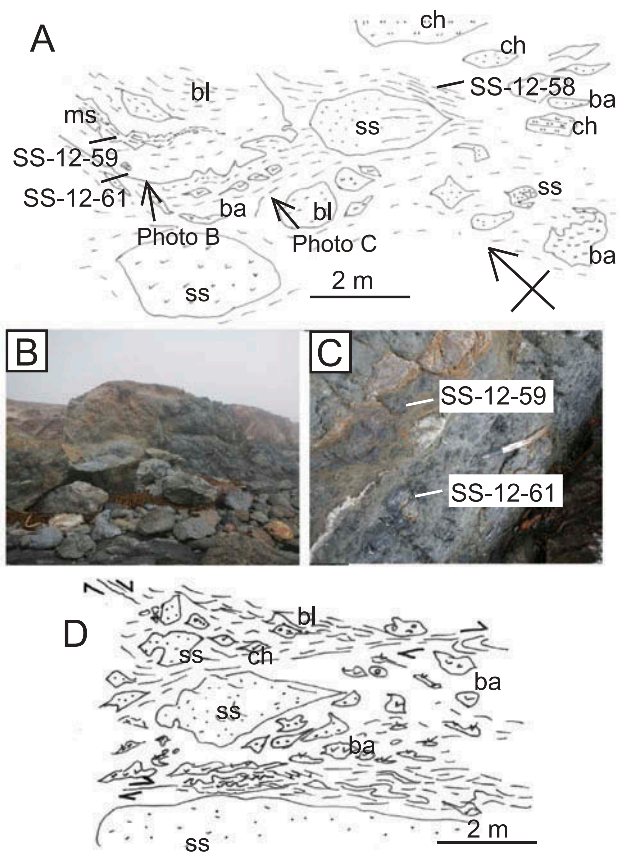

Figure 5. Typical blueschist blocks found in the area south of the motel. (A) and (D) show the distribution of various types of blocks: bl, blueschist; ba, greenstone; ch, chert; ss, sandstone; ms, mudstone. Photomicrographs in Figure 7 are taken from SS-12-58, 59, and 61, respectively. Note that a muddy sedimentary rock ribbon (now largely sheared) is involved within the brecciated and sheared blueschist block as in SS-12-59 (#45 block of Ukar 2012). Sketch map of (D) is at 20 m SW of (A). It also shows elliptical or phacoidal blocks encased in a sheared muddy matrix. Note dextral shear sense of block deformation on the horizontal outcrop of wave-cut bench.

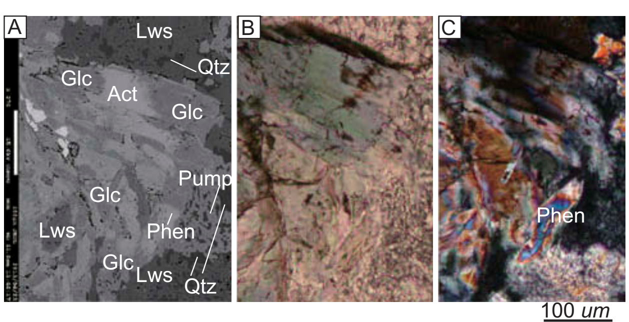

Figure 6. Back scattered image (A) for analysis of major elements of metamorphic minerals and open and crossed nicol photomicrographs of the same position of thin section ((B) and (C)) from sample SS-12-61 in Figure 5. Shapes and relationships between grains indicate the following three stages; 1st, actinolite (Ca-amphibole), albite; 2nd, glaucophane and phengite (former albite diminishes); 3rd, lawsonite, pumpellyite and quartz.

mélange structure because the coastline is perpendicular to the strike of the mélange zone. Various kinds of rocks are repeated, mostly by early SW-vergent thrusting with later northeastward normal faulting (Figure 10(A) and (B)). Turbiditic beds are repeated by faults and intermixed with mélanges, alternating with coherent and broken mélange units.

Sandstone similar to those of the Cambria Slab is brecciated into jigsaw-puzzle structures, commonly containing angular to subrounded greenstone and chert fragments in the parts where mud matrix is dominant (Figure 10(C) and (D)).

South millionaire area

In this area, a nearly continuous section reveals the relationship between mélange and sandstone units. The transition from mélange to sandstone is also well observed. Internal deformation within a blueschist block is well observed in the 'Mixed rock' as described later.

Mudstone injections occur in places including greenstone and chert clasts along fault boundaries with normal and reverse slip. In a single fault zone, a thrust fault is cut and dislocated by a normal fault, indicating that normal faulting occurred after thrust faulting (Figure 11). Thrust faults are oriented NW to WNW, but normal faults strike N–S or NE–SW.

Pinch-and-swell structures of sandstone layers are common in this area with both sinistral and dextral shear senses. Turbiditic beds are homogeneous and massive, and have lost the original sedimentary structures. Conglomeratic units are also found within the sandstone (Figure 12), but rounded pebbles and cobbles are scattered in sandstone (not concentrated as in the common conglomeratic beds), and are dislocated by microfaults.

A thrust duplex structure observed in the field shows NW sense of displacement (Figure 12). Along the base of the coastal cliffs, several injection bodies of mud including fragments and blocks of basalt, chert, and even blueschist are observed to be spatially associated with N–S or NE-oriented normal faults.

Two large pillow lava blocks, two large bedded chert blocks, and two large blueschist blocks (all >10 m in diameter) occur as mounds on the sand beach. It is likely that these blocks are part of an injection mélange zone that the wave action has eroded the matrix from. A 10 m long blueschist block provides one of the best examples of how these blocks are incorporated into mélange. This block, called the 'mixed rock', is a composite block consisting of a mixture of structures and textures of blueschist, calcareous schist, and pelitic schist (Figure 13). All of these rock types are isoclinally folded and brecciated. The block is surrounded by cataclastically ground, fine clasts (Figure 13(B)).

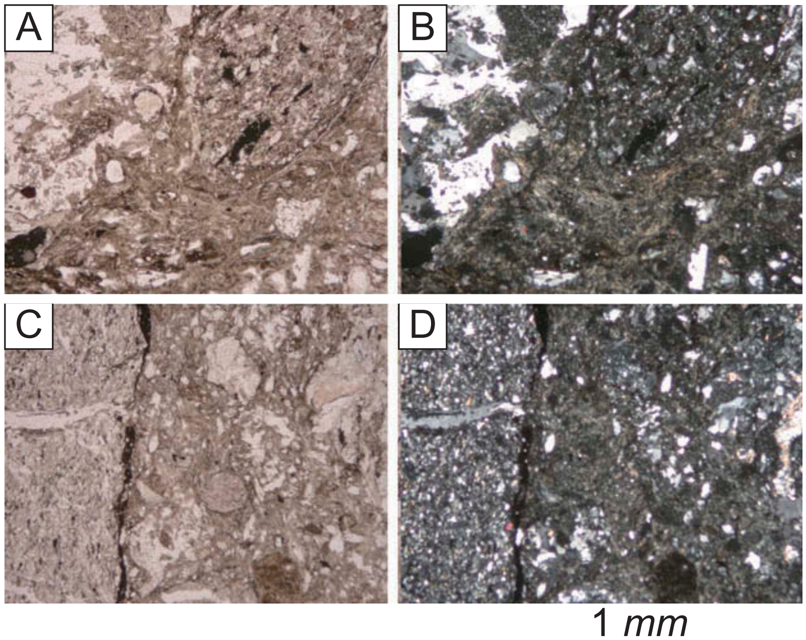

Figure 7. Plain (left) and polarized (right) light photomicrographs of muddy material. (A) and (B) is of mud enclosed within blueschist blocks (from #45 block of Ukar 2012, Figure 6, SS-12-59). (C) and (D) is mud in the mélange matrix (Figure 5, SS-12-58).

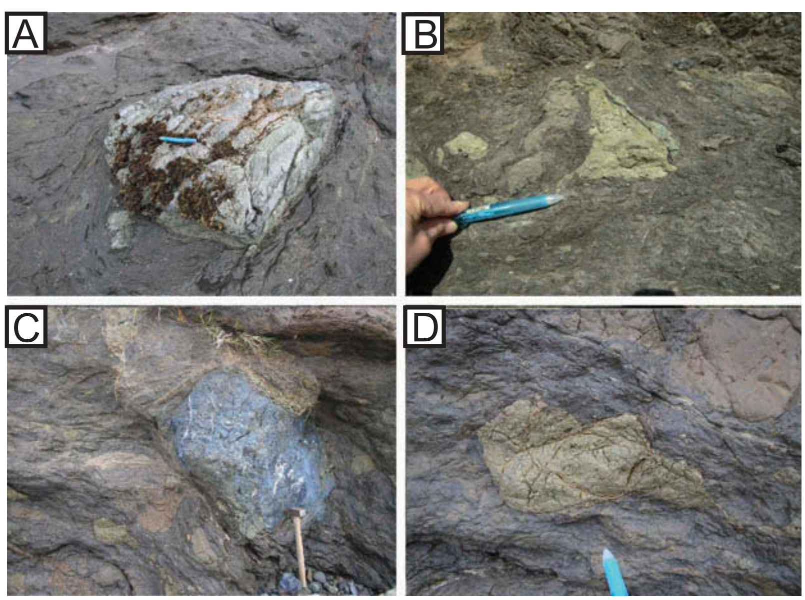

Figure 8. Representative shapes of blocks in muddy matrix exposed on wave-cut benches mostly on the south of the motel area. 1, metamorphic blocks. (A) Altered blueschist block with turtle shape long-axis-trending NW. (B) Greenstone with both sides sheared in a bulge of a fold. (C) Rotated blueschist block with sheared boundary. (D) Greenstone block dislocated by Riedel shears. 2, sandstone blocks: note how muddy matrix injects into sandy blocks to form pinch-and-swell structures. In places, block/matrix boundaries are diffuse. Tail or fish, and Riedel shears indicate sense of shear. (B) is characteristic of transposed structure of the later stages of deformation.

A pelitic schist block at the west of the ‘mixed rock’ is in contact with a block of calcareous schist and blueschist (Figure 13(C)). The inclusions of sedimentary rocks with blueschist indicate the same history of deformation of shearing and mixture as in the #45 block of Ukar (2012).

North of State Park area (duplex section)

This outcrop is found to the south of San Simeon, close to the parking lot off the State Park on route #1. It is a continuous section of turbidite beds of various attitudes and deformation styles. Although highly deformed, the

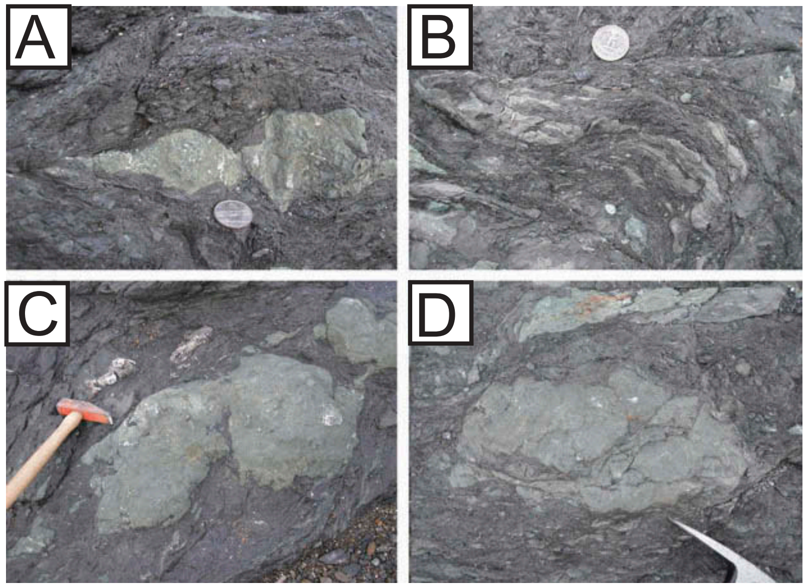

Figure 8. (Continued).

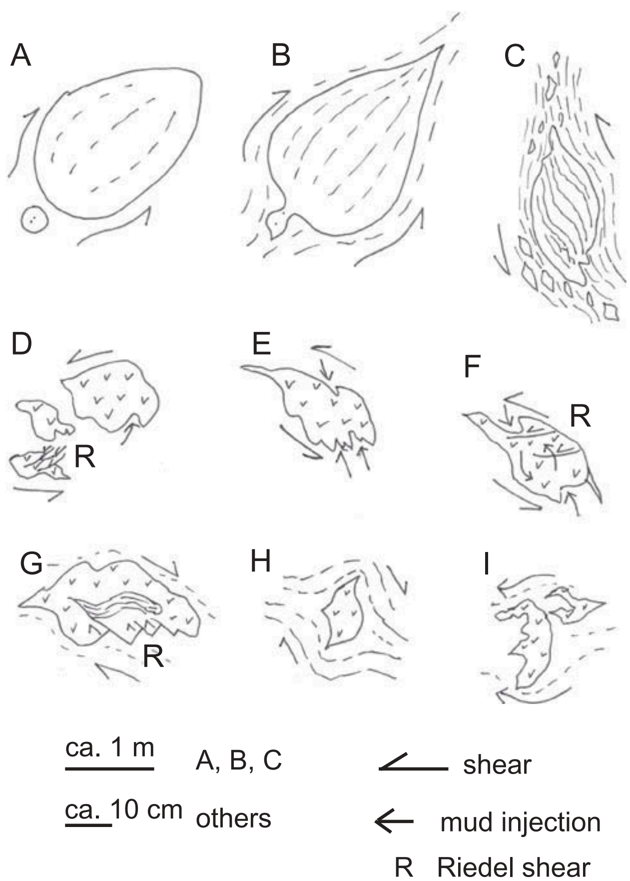

Figure 9. Summary of block shapes with interpretation of sense of shear, rotation, or flow matrix flow directions. (A), (B), and (C) Blueschist or greenstone. (D), (E), and (F) Greenstone with thrust shear sense. (G) and (H) Normal shear sense-bearing. (A), (B), and (I) are both sides shear indicating Poisuilles flow. R, Riedel shears.

strata retain original facing directions, as indicated by graded and cross-bedding from which we could recognize overturned strata in isoclinally folded and faulted beds (Figures 14 and 15). Above a semi-horizontal fault on the cliff section on the north, the beds are mostly right-side-up with the exception of some recumbent folds. Below the fault, however, beds are largely overturned with metre-scale recumbent folds with many minor, 10 cm-scale ones. These beds show large- to small-scale overturned fold structures that are further faulted along a series of gently dipping faults (Figure 14-2 inlet section).

Kinematic indicators such as drag features in sedimentary beds and overturned folds document SW-directed thrusting. The complete structure is part of a duplex system. Measurements of fold axes indicate NE–SW horizontal maximum stress (Figure 14-1 inlet). The recumbent nature of many folds indicates high amounts of shear strain.

The systematic coherent folds of the turbidites in the northern part of the outcrops (Figure 14-2, from (A) to (C)) change to lenticular beds at the south of this continuous section. Sedimentary structures are mostly obliterated due to large magnitudes of shearing. However, these beds still retain grading, which shows mostly right-way-up structure with local overturned folds (Figure 14, from (C) to (E)).

Just in front of the parking lot on the south of route #1 off the State Park (Figure 14-2, (E)), there are two, metre-scale, oceanic rock blocks, one is composed of basalt and another of chert within muddy, sheared sediments, which intrude northeastward into the turbidite sections (Figure 15(D)). Further south, a large bedded chert block is in fault contact with a folded turbidite section (Figure 16).

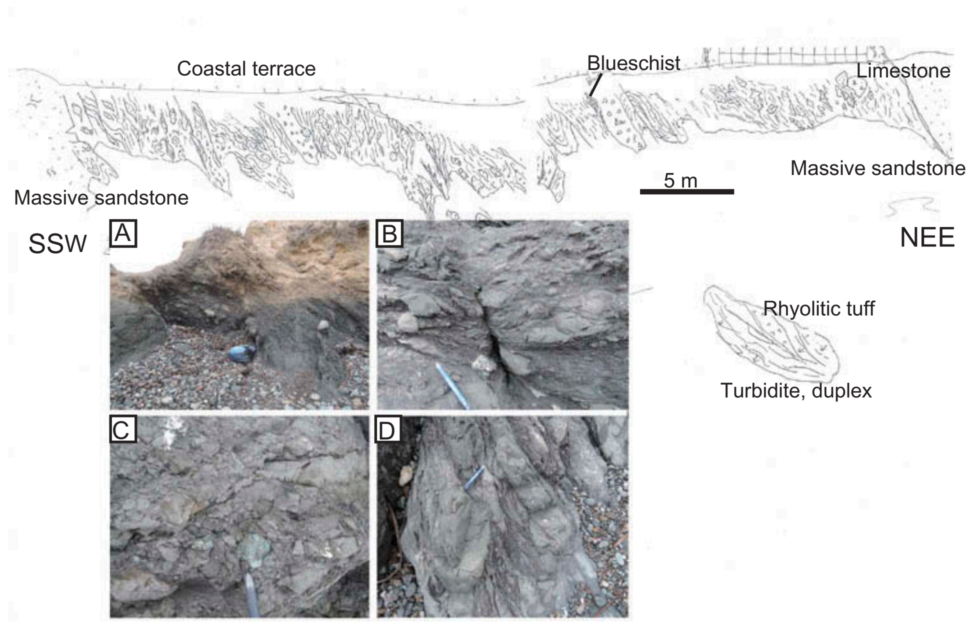

Figure 10. Typical section of San Simeon mélange outcrops of the southernmost motel area, just north of the millionaire area, called the 'Nomugi section'. Note patterns of shear drag indicating thrust shear sense, which is dragged and dislocated by later normal faulting. (A) and (B) show late faulting overprinting earlier stage deformation. (C) Sandstone breccia that includes green-coloured chert and basalt fragments in muddy or finer grained sandstone facies mélange. (D) Sheared muddy units bearing blocks that were injected into sandy units.

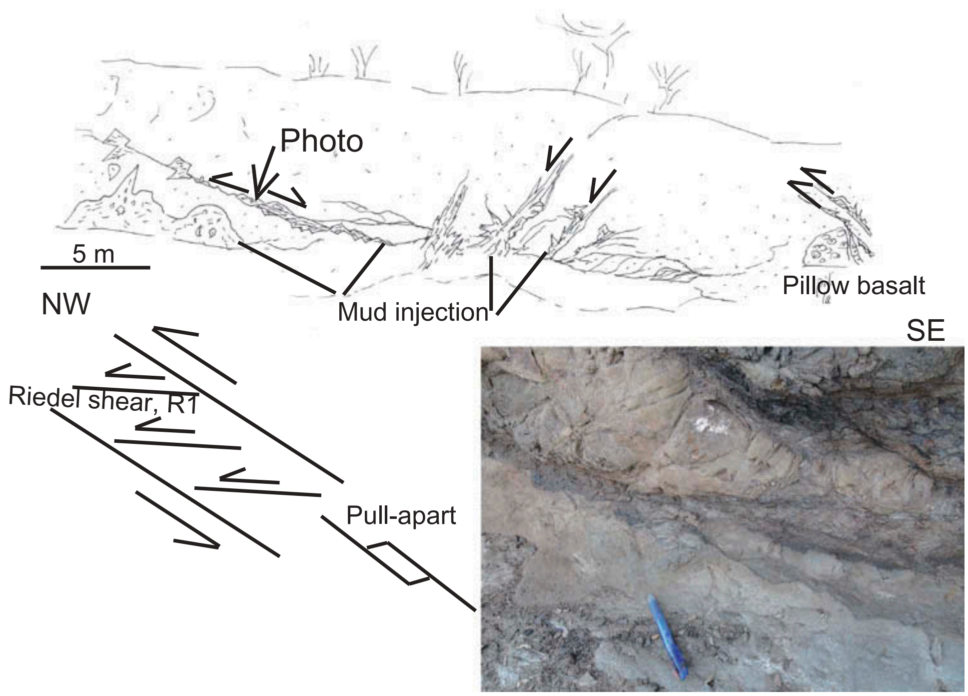

Figure 11. Typical section of mud injection into cross-cutting thrust and normal faults in the south millionaire section just south of the Nomugi section. Southwestward thrust faults are generally cut by north or northeastward normal faults with oblique slip (photo). Riedel shears associated with the faulting and mud injection disrupt, drag, and dislocate sandstone layers. In the photograph, first thrust fault, next normal faults are recognized by cutting relation. Refer to Figure 20 in the discussion section.

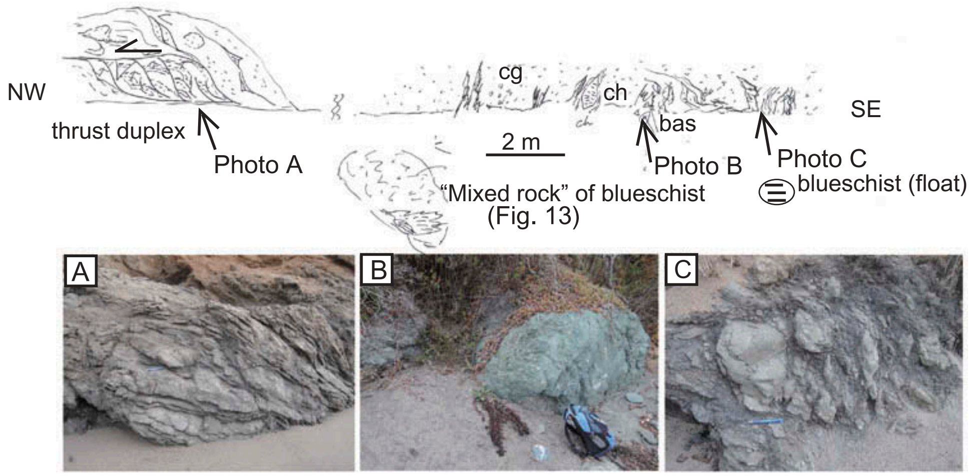

Figure 12. Outcrop sketch of part of the south millionaire section. (A) Photograph of thrust duplex structures of bedded turbidites in massive, coarse sandstone bodies. Pebbles and cobbles are scattered (on the left) as drop-stones into fluidized units. (B) Further south of the seashore cliff are mud injection bodies into massive sandstone. The mud bears various kinds of blocks of basalt (photo), chert, and blueschist.

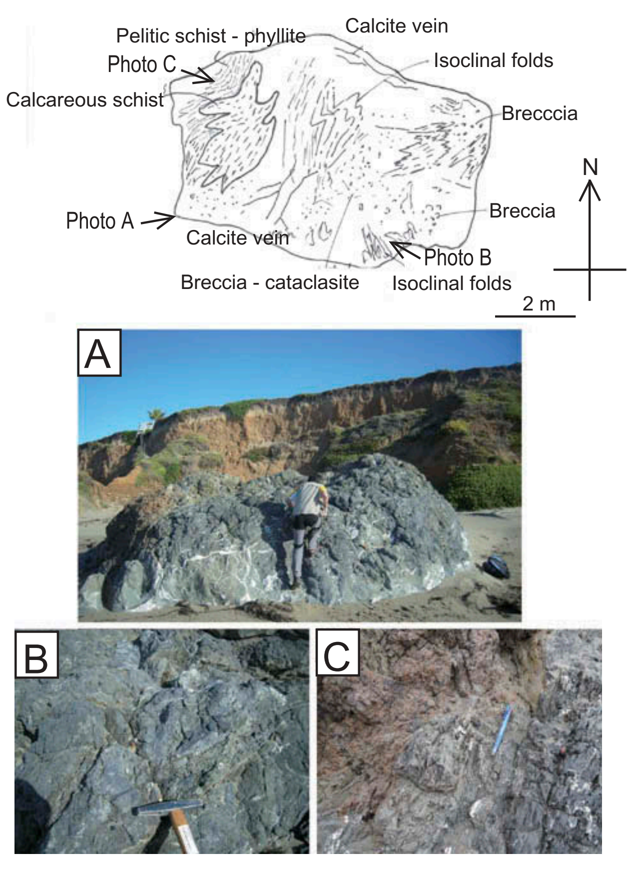

Figure 13. Sketch and photographs of a blueschist block ('mixed rock', photo A) at the southern millionaire area. Breccia is more prevalent in coarse parts of blueschist, which are interpreted as metagabbro. Finer grained matrix is cataclastically ground materials (photograph B). On the west corner, folded calcareous schist (orange in colour) is intercalated with phyllitic fine sandstone to mudstone involved within blueschist body (photograph C).

South of State Park to Leffingwell Landing point area (thick turbidite section)

Turbidite outcrops around the State Park have been called the Cambria Slab by many authors (Cowan 1978; Underwood and Laughland 2001). Most of the outcrops consist of pinkish to grey arkosic sandstone. Within the turbidites are many fluidization and dewatering structures, such as loss of original sedimentary layering, water escape (pillar structure), dish, and web structures. However, graded bedding and cross-lamination are locally retained, particularly in the turbidites on the north and south of the Leffingwell Landing point area (Figure 17). Our careful observation of way-up indicators shows various attitudes of beds for isoclinal and some recumbent folds larger than tens of metres in size (Figure 16).

Abalone Cove area

The outcrops at Abalone Cove, off the Cambria coastal area, were studied by Smith *et al.* (1979) and Becker and Cloos (1985), the former noting repetition of fold structures of the Cambria Slab above the mélange bodies, whereas the latter interpreted monotonous turbidites with diapiric intrusion of the mélange into the semi-horizontal, lightly deformed slope sediments. Becker and Cloos (1985) stated that intrusion of mélange occurred along normal faults. However, based on our detailed way-up identification, the structure more closely resembles the interpretations of Smith *et al.* (1979) as most of the turbidite beds are tightly and multiply folded, then faulted with local overturning. Thus the deformed turbidites are transposed in close relation to the faults and are intercalated with mélange bodies.

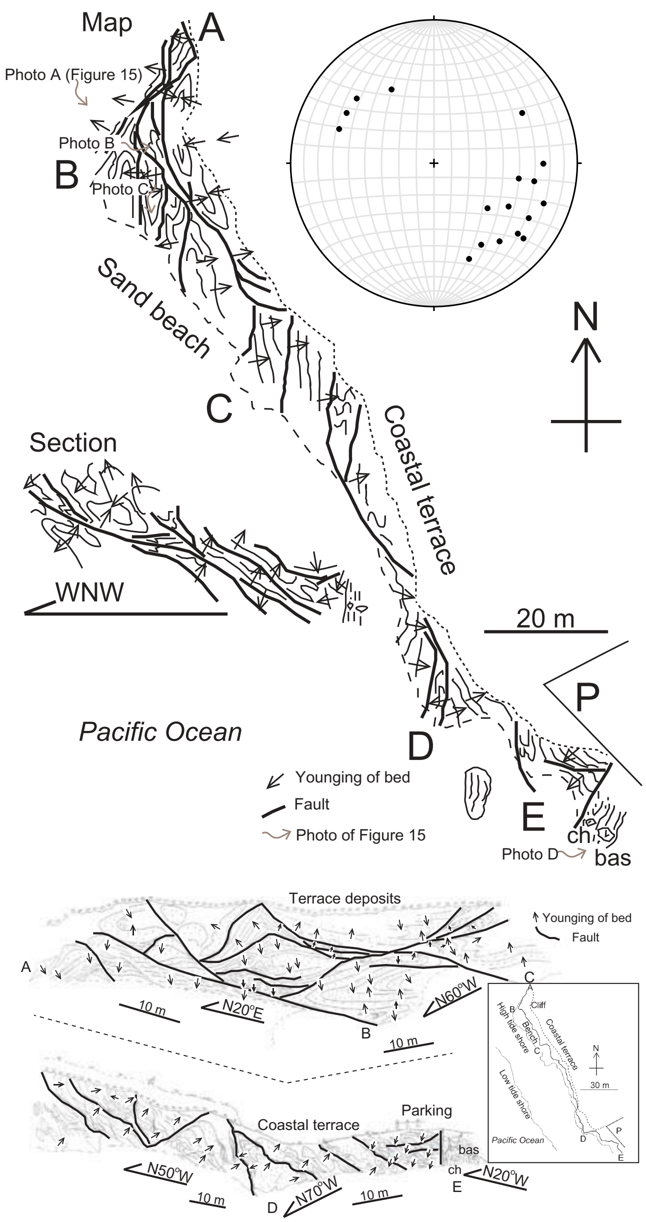

Figure 14. Generalized sketch map (1) and cross section (2) of the coastal cliff and wave-cut bench north of San Simeon State Park (duplex section), showing multiply folded and faulted turbidite sequences. (1) Map indicates generally N- to NW-striking thrust faults that appear in the NW–SE cliff section to verge SW. However, fold axis measurements (lower hemisphere stereograph inset) indicate a NE–SW horizontal maximum stress. Fold asymmetry show a SW vergence direction (see representative fold structures in Figure 15). Note mud injections along NE-trending faults with chert and basalt blocks on the southeast corner of the outcrop. Cross-sectional inset is for the entire length of the cliff exposure. P is for State Park parking lot on route #1. Note cross–sectional reference locations given from A to E for detailed section. (2) Detailed cross section showing how graded beds in the lower part of the outcrop are largely overturned, while in the upper part they are right way up. This consistent structural relation indicates that large-scale overturned fold systems are further duplicated by later stage semi-horizontal faults.

Comparison of sandstone

Sandstone in the study area was examined in thin section to compare compositions and test if those interpreted as 'Cambria Slab' are distinctive. Compositions range from greywacke to arkose, but as a whole, sandstone blocks in mélange areas are indistinguishable from those in 'Cambria Slab' (Figure 18). There are some sandstone blocks in mélange with a distinctive lithic greywacke composition and dark colour, and those included in metamorphic rock blocks are phyllitic, but the rest are like those of the 'Cambria Slab'. The 'Cambria Slab' was interpreted as distinctive based on degree of deformation, but as documented above, it transitions from gently deformed units to multiply deformed broken formation.

Interpretation of outcrop description

Scope of interpretation

The interpretation of our mapping is summarized here. (1) The mélange and turbiditic rocks are interfingered with each other at the outcrop scale (Figures 1, 2, and 3). The lithological boundaries between the mélange units and surrounding turbiditic rocks are everywhere sharp where exposed, characterized either by fault or diapiric intrusion. (2) Most of the turbiditic rocks show evidence for brecciation and fluidization that affected the original sedimentary structures, although some primary sedimentary structures such as graded bedding and cross-lamination are locally well preserved. (3) The breccia requires stresses great enough for massive, *in situ* hydrofracturing. In some outcrops, these turbiditic rocks are isoclinally folded and faulted, displaying duplex structures. (4) In general, the muddy matrix mélange units include metamorphic or oceanic rock fragments (10 cm or smaller in size) and blocks (10 cm and more) besides sandstone blocks. (5) We have not observed any original sedimentary contacts between the mélange units and turbiditic rocks except for some possible cases, where the turbidite beds are in close proximity to diapiric mélange bodies. (6) Conglomerate locally occurs in the turbiditic units, but these turbiditic conglomerates are different from those that show brecciation. (7) The 'Cambria Slab' turbidite sections are intruded by sheared mudstone in which mostly greenstone and chert blocks, and in some places blueschist blocks are included.

Distribution pattern of mélange and sandstone

As shown in Figures 1 and 2, mélange bodies interfinger with sandstone bodies in generally a NW–SE direction. The two bodies are extensive enough to show the map pattern, and the vertical cliffs reveal the contact relations. Both reverse (thrust) and normal faults are observed (Figures 10 and 11). The millionaire section exposes diapiric intrusive relations along faults (Figures 11 and 12).

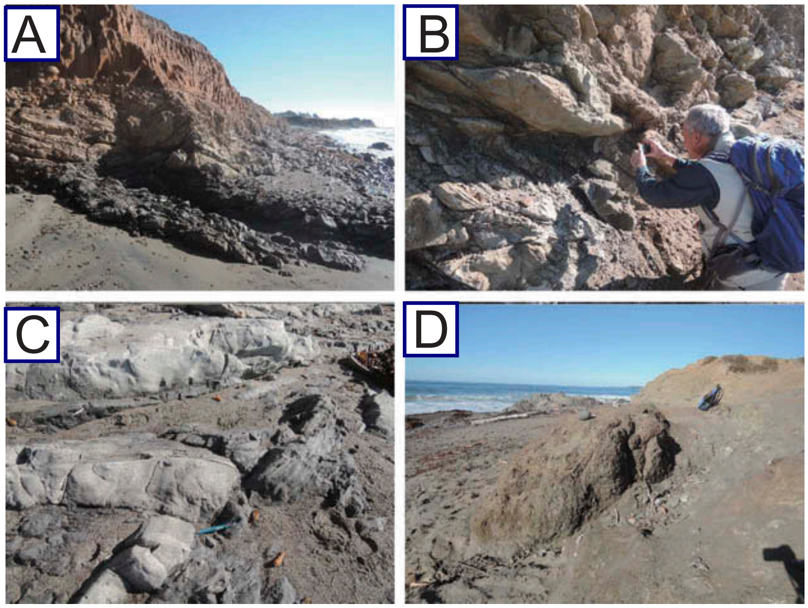

Figure 15. Representative outcrop photographs of fold structures (A)–(C) and a basalt block (D) at the duplex section in Figure 14. (A) View of the outcrops from the southwest. (B) Folded right-way-up beds by semi-horizontal fault above (top to the left or NE). (C) Tightly folded turbidite sequence with overturned limb. (D) Basalt blocks encased within sheared muddy matrix injected into turbidite section at the southern end of the outcrop.

Most faults show oblique slip with mostly sinistral motion along thrust faults and dextral motion along normal faults. Some of the minor scale injections of mudstone, which includes the surrounding mélange fragments and blocks, into sandstone beds are interpreted mostly along R1 planes as shown in Figure 11. In this particular outcrop, the cross-cutting relation indicates the first phase along sinistral-oblique thrusts, and the second phase along dextral-oblique normal faults.

Muddy matrix mélange bodies are close in proximity to diapiric bodies along faults as shown in the lower part of Figure 11. Combining with the observations in the frontal San Simeon motel area (Figure 4) indicates that muddy mélange bodies originally underlie the sandstone bodies before fluidization and injection into sandstone layers above, in some cases along faults mostly along Riedel shears.

The fluidization and injection process mixes many blocks of not only sandstone, but greenstone, chert, limestone, and even blueschist. Some blocks as large as 10 m in diameter of pillow lava, bedded chert, blueschist, and others observed on the sand beach off the south millionaire area were remobilized by diapiric injection from their original position into overlying sandstone units (Figures 4, 10, 11, and 12).

Shape of blocks and relation to the muddy matrix

Shapes of the pinched tail of blocks can reveal shear sense within the mélange, and in some cases the direction of sinking, as in the case of turtle- or drop-like shapes. Using block tails as sense of shear indicators, Singleton and Cloos (2012) report dominant sinistral shear during syntectonic movement in the subduction channel. However, we observed both sinistral and dextral shears with the former proceeding the latter. This interpretation differs from Cowan (1978), who concluded that the blocks underwent uniaxial compression by bedding-perpendicular compression during compaction without experiencing high tectonic stresses.

As shown in the typical shape sets in Figures 8 and 9, we observed at least three different shear modes, one is the simple shear within a fault zone, another is the intrusional shear with both ends curved in the same direction from plug flow (Poiseuilles flow), and a combination of fault-related shear and gravitational flow as summarized in Figure 19. The combination mode may be the result of what Cloos (1982) and Shreve and Cloos (1986) hypothesize as return flow. In this case, blocks sink in the subduction channel at the same time as they experience simple shear. Most of the metre-size blueschist blocks are elongated NW–SE. Other kinds of blocks, sandstone, greenstone, and chert have no consistent preferred orientation, suggesting that only blueschist and its derivatives are affected by gravitational sinking during exhumation.

Fluidization and brecciation of sandstone

Primary sedimentary structures are obliterated in most sandstone units incorporated into the mélange, but secondary sedimentary structures are well preserved. These structures mostly form during fluidization, causing pressure-related dish, pillar, and web structures. The high fluid pressures

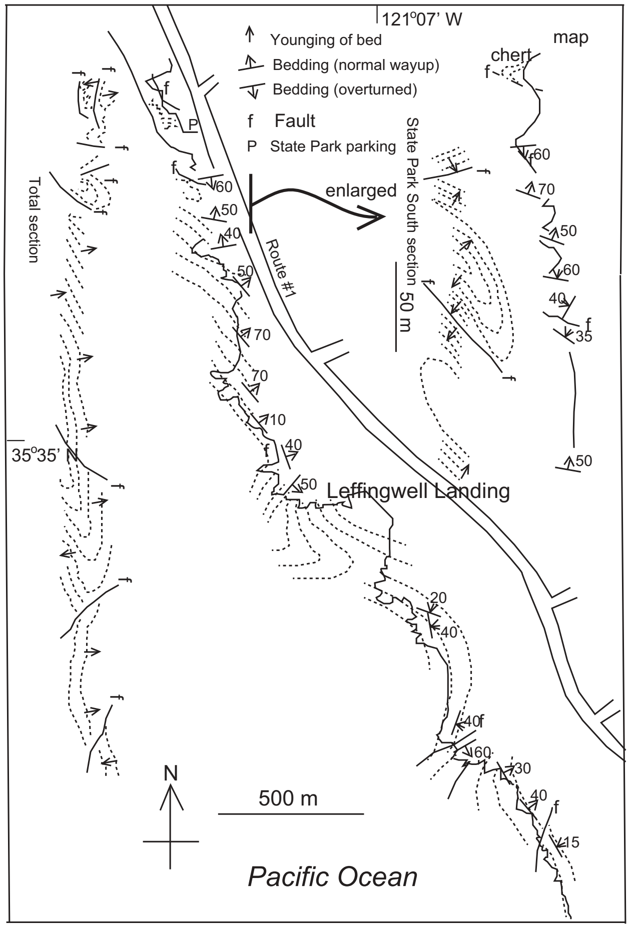

Figure 16. Sketch map of what is considered the 'Cambria Slab' from the south of the State Park to south of the Leffingwell Landing point area (close to the bay off Cambria). Note that overturned beds are not uncommon even though folds are broad in places. Original sedimentary structures are mostly lacking due to fluidization. Some graded bedding and dewatering structures (pillar structure, dish structure, etc.) are found that help determine right way up.

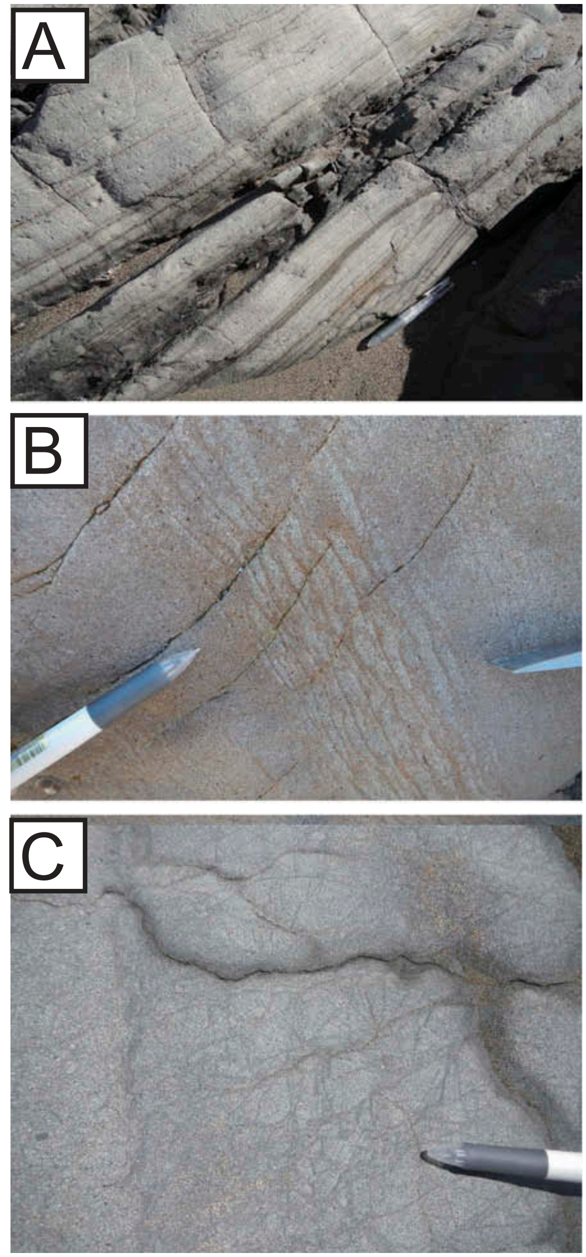

Figure 17. Typical way-up structures in turbidite beds on the north and south of Leffingwell Landing point areas. (A) Graded bedding with typical Bouma sequence of an overturned bed. (B) Dish structure (top to the upper-right). (C) Web structure of dewatering type (top to the upper-right).

arise due to compactional stresses during high turbidite sedimentation rates (Tsuji and Miyata 1987; Hirono 1996). The secondary structures diminish original grading and laminations. Preservation of original sedimentary structures is better in relatively thin turbidite beds, which are key for documenting way-up directions. Dish and pillar structures also indicate way-up directions (Tsuji and Miyata 1987).

In the frontal San Simeon motel area, a large (40 m diameter) bed of massive sandstone (some metres thick) overlies bedded turbidites that transition from broken formation into muddy matrix mélange with blueschist, greenstone, and chert blocks a metre in diameter (Figure 4). These stratigraphic relations could be interpreted as depositional contacts between the lower mélange bodies and the upper sandstone bodies. However, the basal part of the upper sandstone bodies is largely fluidized to obliterate the original grading and includes mudstone clasts. The sandstone blocks are secondarily deposited in laminated sandstone (Figure 5(A) and (B)). These contact relations indicate that the laminated sandstone is derived from the fluidized sandstone body above. Non-fluidized sandstone blocks and mudstone clasts sink to the bottom of the fluidized bed. In some cases, the muddy mélange bodies intrude into the superjacent sandy part (Figure 5(C)).

Therefore, we interpret that the sandstone may have been deposited above the muddy mélange bodies, then, by

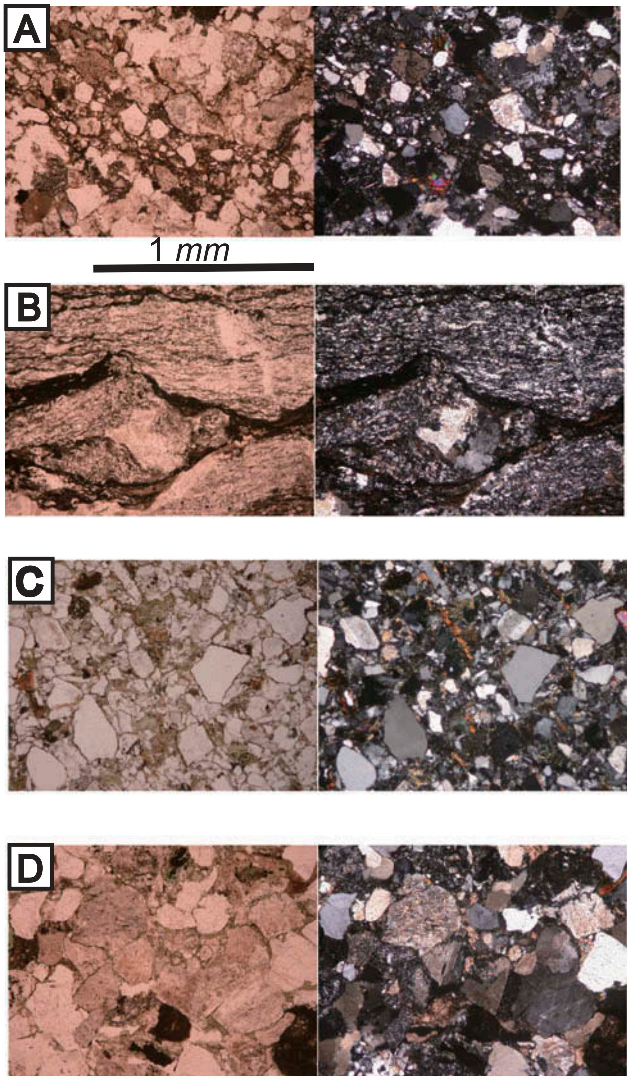

Figure 18. Photomicrographs of various sandstone units of the San Simeon area. Left and right are of open and crossed nicol, respectively. (A) From a large slab at the San Simeon motel area consisting of massive, fluidized coarse sandstone with diagonal shear zone showing evidence of independent particulate grain flow (web structure). Sample number SS-11-1-3. Blue grains of included and altered basaltic rocks. Chlorite laths intersect grains and matrix. (B) Psammitic phyllitic block within 'mixed rock' blueschist adjacent to calcareous schist. Sample number SS-11-5. (C) From sandstone slab faulted with mélange at the 'Nomugi section'. Sample number SS-12-65. Angular quartz, arkorsic greywacke lithic fragments are included. Calcite cement is found along sharp grain boundaries, which indicates that this rock is largely fluidized and brecciated. (D) From coarse fluidized massive sandstone in the 'Cambria Slab' at the Leffingwell Landing point area. Sample number SS-11-9. Course, rounded lithic-quartz-feldspathic greywacke that is largely fluidized. Rounding of grains is likely from abrasion due to fluidization.

means of increase of pore fluid pressure, caused fluidization in the sandstone part to diminish the primary sedimentary structure. Fluidization also formed a secondary

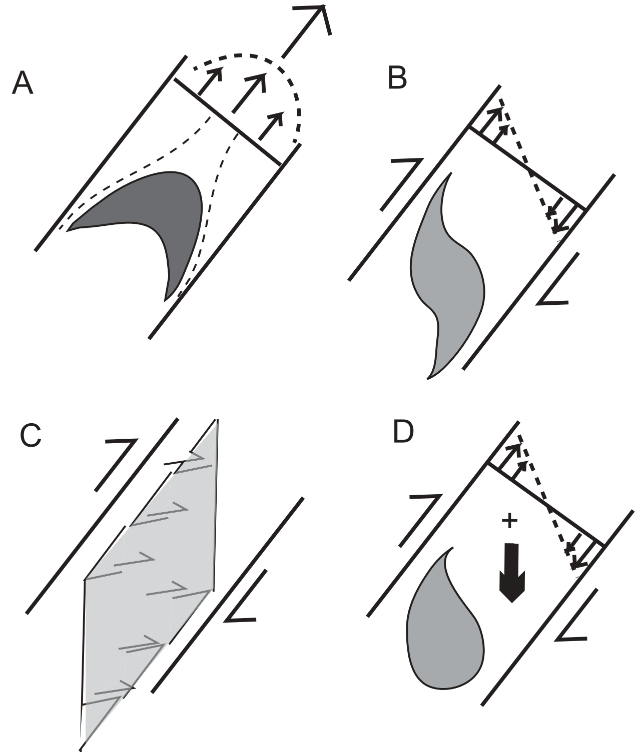

Figure 19. Summary of interpretation of flow fields within shear channels indicated by the shapes of the blocks as in Figures 8 and 9. (A) Poiseuilles flow. (B) Simple shear of both sides causing sigmoidal drag. (C) Development of Riedel shears in simple shear. (D) Gravitational drop effect as inferred by Cloos (1982).

lamination that may have been simultaneous with intrusion of the muddy mélange.

Similar secondary structures are found in other places with massive sandstones, such as the millionaire area where conglomeratic units are mixed in with massive sandstone next to the duplex structure (Figure 12). Pebbles and cobbles are scattered within the sandstone without any sedimentary layering. These mixing structures indicate that the original conglomerate layer was likely fluidized by high pore pressure causing separate pebbles and cobbles to sink independently into the underlying fluidized sandstone.

Brecciation is another diagnostic feature in the surrounding sandstone bodies, particularly in the frontal San Simeon motel area and the Nomugi section, where most of the sandstone blocks and layers show conglomeratic or brecciated features. In most cases, some greenstone and chert fragments are included. In addition, some pebbles, cobbles, and breccia are rounded, and some are angular (Figure 10 (C)). These structures are so pervasive that they could be interpreted as sedimentary in origin, but the sedimentary origin of these breccias can be ruled out due to (1) the compositions of the sandstone breccia are the same as the main sandstone body in which the breccia is included; (2) boundaries between the breccia blocks and the host sandstone are transitional; (3) no systematic roundness or sorting is found, rather, the fragments show a jigsaw-puzzle texture indicative of mechanical brecciation; and (4) greenstone or chert clasts are included only in mud dominant parts of the injections. Therefore, it is clear that they are hydraulically fractured under high fluid pressures. Rounding of clasts is likely due to abrasion during remobilization as muddy matrix and sandstone dikes or sills.

Large to small fold structures

Using right-side indicators in turbidites at the State Park (duplex section) and Leffingwell landing sections, we found consistent trends of fold axes (Figure 14-1 inlet) that indicate SW–NE-directed horizontal maximum stresses. Fold vergence indicates SW-directed recumbent folding and thrust faulting. Flow structures in many of the folds signify semi-lithified conditions of the turbidites. Slump folding is possible, but not likely based on the similarity of fold axis trends. There are some clear examples of intraformational slump folds with highly irregular shapes and different orientations to the south of these outcrops.

Metamorphism and deformation

Another controversial issue of the Franciscan mélange that is well expressed in the San Simeon area is the mixing of blocks of metamorphic rock, with differing protoliths, structure, and metamorphic grade, in a non-metamorphosed muddy matrix. Some of the blueschist blocks, for instance the #45 block of Ukar (2012) in the south motel area and the 'mixed rock' in the millionaire area, provide clues from their internal structure and contact relations to sedimentary rocks that provide a way to test various mélange emplacement mechanisms.

Most of the rocks in the blocks of the muddy matrix mélange bodies from the study area are more or less brecciated, not only sandstone blocks mentioned above but also blueschist and greenstone (Cloos 1982; Ukar 2012; Ukar and Cloos 2013). Some blueschist blocks show various stages of brecciation. In most cases, glaucophane, lawsonite, and other metamorphic minerals are pulverized into fine-grained matrix. The boundaries of the breccia fragments are commonly sharp, and shear strain is recognized by rotation of the breccias and flowage in the matrix.

Included in two blueschist blocks are sedimentary rock layers and fragments (slate, phyllite, or pelitic schist inclusions; Figures 5 and 13). Petrographic analysis of the inclusions shows they are indistinguishable from equivalent fragments in the muddy matrix of the mélange nearby (Figure 7). These occurrences indicate that brecciation, shearing, and involvement of the sedimentary rock inclusions occurred during the deformation of the blueschist blocks. In the 'mixed rock', even calcareous blocks are included (Figure 13). These observations strongly support

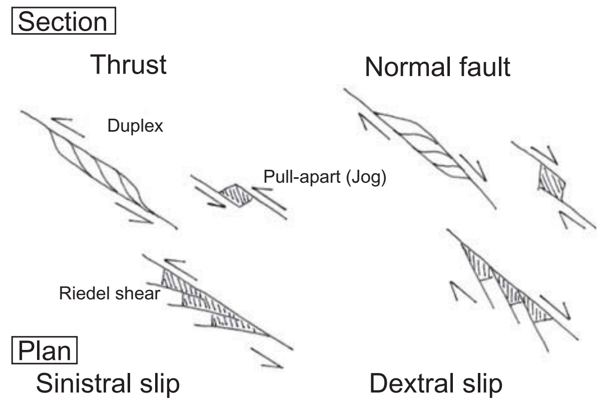

Figure 20. Schematic model showing how mud injections (dashed) relate to thrust and normal fault pull-apart structures. The upper two examples are for cross-sectional view, and the lower for plan view. Refer to the photograph in Figure 11 for an outcrop example.

that the blueschist blocks are not simply emplaced by sedimentary process such as sliding bodies from up slopes, but that emplacement involves high-shear stresses typical of processes common to a subduction channel, including internal brecciation and mixing with sedimentary rocks.

We propose that the emplacement of blueschist bodies was a multistage process that began at deep levels at which reactions occurred between blueschist and serpentinite, followed by upward subduction channel flow to shallow levels together with muddy matrix materials, associated with mixing by shearing with sedimentary rocks. Such muddy matrix mélange bodies were emplaced in the trench area where turbidite beds are deposited, then finally emplaced by intrusion along Riedel shears (Figure 20). During such emplacement to the shallower levels, retrograde deformation occurred with retrograde metamorphism.

Sedimentary or tectonic origin of the San Simeon mélanges: summary and discussion

Mélanges manifest a variety of deformational processes at a range of spatial and temporal scales. As known from many previous papers on the origin of the Franciscan mélanges in the San Simeon area, the outcrop scale reveals key compositional and structural relations for reconstructing the tectonic evolution. The key features we focus on for tectonic interpretation are the implication of the structures, textures, and shapes of the blocks in the mélange for the origin of emplacement, and relationship between the mélange and surrounding sandstone, and between blocks and the muddy matrix in the mélange.

Variations in amounts of shear strain within a mélange produce end members from the sedimentary blocks deposited by debris flows with only weak, surface deformational features (e.g. Cowan 1978) to completely disaggregated and thoroughly mixed units produced by very high shear strains from various depths along the subduction interface (e.g. Cloos 1982). It is difficult to designate pure end members, such as sedimentary, tectonic, or diapiric mélanges. Mélange in general should be defined as a descriptive word for chaotic rocks of various (or single) lithologies as a block-in-matrix structure of mappable scale (Raymond 1984). One of the key features of mélange is the degree of mixing, which can help determine which deformation mechanisms dominate. For example, is tectonic shearing the primary process responsible for the mixing or not? Was the mélange originally produced by submarine landslides with later tectonic shearing and mixing?

Structural implication of the geological structures

Folds and faults seen in the San Simeon area are similar to those in the Miocene and modern accretionary prisms in the Nankai and Sagami troughs and in the Miura-Boso areas of Japan (Hanamura and Ogawa 1993; Yamamoto 2006; Kawamura *et al.* 2009, 2011; Yamamoto *et al.* 2009; Anma *et al.* 2011; Michiguchi and Ogawa 2011a, 2011b; Muraoka and Ogawa 2011). The Cretaceous Shimanto Group of Japan is also similar to mélange and accretionary structures at San Simeon, with incorporation of oceanic crust blocks (but without blueschist).

Fluidization and hydrofracturing structures seen not only in the Cambria Slab, but in block-within-mélange-dominant areas, which are indicative of high pore fluid (or mud) pressure during semi-lithified conditions, are known from the Japanese Cenozoic accretionary prisms as the Nichinan Group (Tsuji and Miyata 1987) and Emi Groups (Hirono 1996) as well as from the modern Nankai accretionary prism (Kawamura *et al.* 2009; Michiguchi and Ogawa 2011a), all of them from the trench turbidites. Therefore, we interpret the sandstone-within-mélange sections and the Cambria Slab in the San Simeon area as trench turbidites. The turbidites were folded and faulted, and injected with muddy matrix mélange during incorporation into an accretionary prism.

In the Japanese examples, liquefaction and fluidization of sandstone are common, the former by co-seismic shaking, and the latter by gradual increase of pore pressure due to sedimentary and tectonic loading, as shown by experiments by Tsuji and Miyata (1987). In contrast to fluidization, high-fluid pressures cause brecciation (hydraulic fracturing) in more lithified sandstone. Therefore, it is concluded that most sandstone in the study area is subjected to high pore fluid pressure conditions causing fluidization and hydraulic fracturing depending upon the competency of the sandstone layer.

High-pressure rock exhumation model: comparison to Japanese examples

Mélange bodies in the San Simeon area show evidence of two stages and mechanisms of emplacement. Singleton and Cloos (2012) identified only a sinistral sense of shear in the mélange and suggest that the deformation is mainly caused by the adjacent sinistral (proto) Hosgri fault. However, we observe numerous dextral normal shears that truncate sinistral thrusting. We suggest that the former sinistral and later dextral shearing may indicate two different tectonic settings of this Hosgri fault.

The Izu–Mariana trench landward slope toe area has many muddy, serpentinite volcanoes containing blueschist blocks (Maekawa *et al.* 1992, 1993; Fryer *et al.* 1999, 2000). We compare our present model for the San Simeon area with the Izu–Mariana serpentinite volcanoes. Although serpentinite bodies are not distributed in the San Simeon coast, serpentine injections are abundant in the surrounding parts of the San Simeon area and to the north near Gorda, 40 km north of San Simeon (King *et al.* 2003; Hirauchi and Yamaguchi 2007). Therefore, it is reasonable to consider that the return flow comes first at the deeper level with serpentinite, then next at the shallower level mixed with muddy materials, finally to the trench area at the surface level as shown in Figure 21.

The best fit between the San Simeon area and the Izu Arc is the Ohmachi Seamount area. The seamount consists of high-pressure metamorphic rocks entrained in serpentinite diapirs close to the Palaeogene volcanic front (Ueda *et al.* 2004, 2011). One serpentinite body is tens of

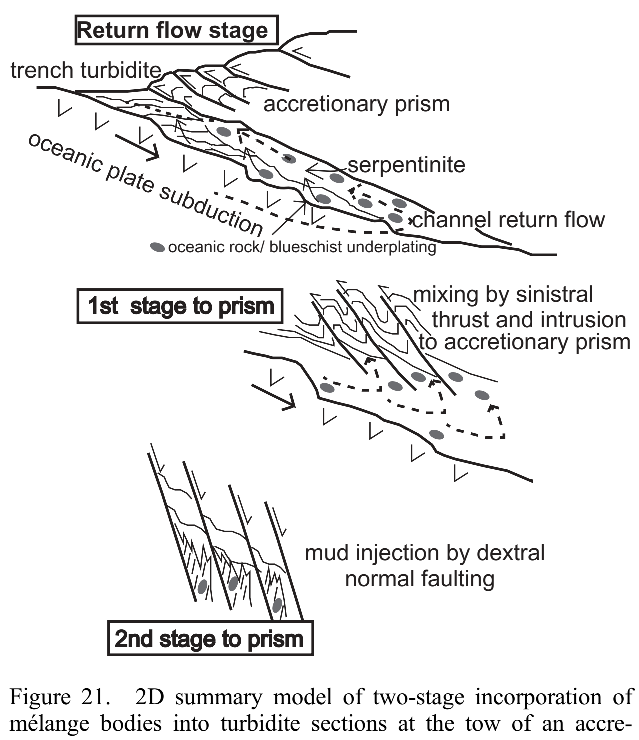

Figure 21. 2D summary model of two-stage incorporation of mélange bodies into turbidite sections at the tow of an accretionary prism. The return flow stage is associated with exhumation and mixing of blueschist, serpenitinite, and basalt fragments with muddy matrix. Early emplacement into the prism involves sinistral thrusting and folding. Later emplacement involves dextral normal faulting. Turbidites are considered as trench deposits.

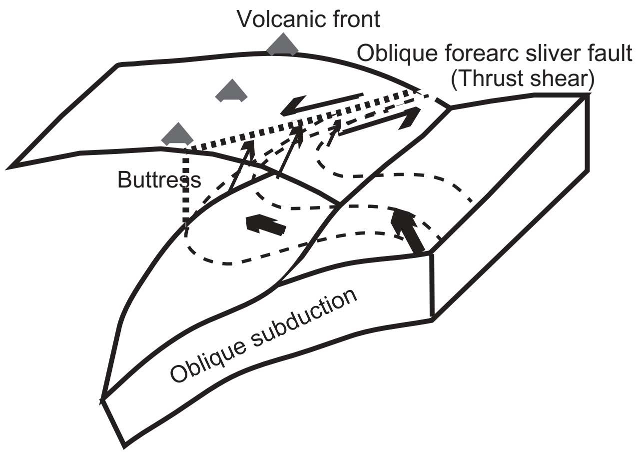

Figure 22. Oblique subduction model (looking south) for rapid exhumation of high-pressure metamorphic rocks from the chokepoint (buttress) of the subduction channel by return flow (corner flow) in the context of a sinistral oblique subduction system. This figure is adapted from studies of Iwamori (2003), where it is applied to occurrences of serpentinite encasing high-pressure blocks of Ueda *et al*. (2004, 2011) in the Izu forearc.

kilometres in diameter (of mostly wehrlite and dunite origin, now largely serpentinized into antigorite schist), which is associated with garnet-hornblende schist with eclogitic facies relics (Ueda *et al.* 2004, 2011). The relics show PT conditions of 2 ± 0.5 GPa, 600–800°C. The large mass of serpentinite intrudes to the surface along the Sofugan tectonic line, which is a Palaeogene transform fault that forms the backstop or buttress for subduction channel return flow at the very front of the Izu–Mariana forearc (Yuasa 1985; Mori *et al.* 2011).

After the 2D inferred return flow model in Figure 21, the 3D return flow along a forearc sliver fault is shown in Figure 22 after Iwamori (2003). The latter model shows that oblique subduction causes rapid return flow associated with a component of sinistral thrust shear of a forearc sliver fault. If blueschist facies metamorphic rocks are incorporated into the trench slope area by return flow, then they are free to mix with oceanic rocks (pillow basalt, bedded chert, limestone) and shallow subducting turbidites to form block in mud matrix mélange like the Franciscan mélanges at San Simeon. Rock assemblages similar to those of the Franciscan mélange are known from the present forearc sliver fault zone of the Mineoka belt, which is in the Boso Peninsula and north of the Sagami trough oblique subduction zone (Ogawa 1983; Ogawa *et al.* 2008; Mori *et al.* 2011).

The most important observation presented in this paper is that the mixing features of blueschist with muddy slate or phyllite layers are similar in texture to the muddy matrix of the mélanges. Such mixing textures lead us to conclude that whatever the original emplacement of exhumed blueschist was, whether by thrusting or diapirism, the blueschist blocks were finally incorporated in the muddy matrix by strong shearing, which also caused the brecciation seen in the various lithologies. This strongly supports some shearing during diapiric intrusion of blueschist-bearing mélanges that were further intruded into turbidite beds of the trench accretionary prism body as discussed above.

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References

Anma, R., Ogawa, Y., Moore, G., Kawamura, K., Sasaki, T., Kawakami, S., Dilek, Y., Michiguchi, Y., Endo, R., Akaiwa, S., and YK99-09, YK00-08, YK05-08 & YK06-02 Shipboard Science Parties, 2011, Structural profile and development of accretionary complex in the Nankai trough, off Kii Peninsula, Southwest Japan: Results of submersible studies, *in* Ogawa, Y., Anma, R., and Dilek, Y., eds., Accretionary prisms and convergent margin tectonics in the Northwest Pacific Basin, in the series: Modern approaches in solid earth sciences: Berlin, Springer-Verlag, v. 8, p. 169–196.

Becker, D.G., and Cloos, M., 1985, Melange diapirs into the Cambria Slab; a Franciscan trench slope deposit near Cambria, California: Journal of Geology, v. 93, p. 101–110.

Cloos, M., 1982, Flow melanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, p. 330–344. doi:10.1130/0016-7606(1982)93<330:FMNMAG>2.0.CO;2

Cloos, M., 1984, Flow mélanges and the structural evolution of accretionary wedges, *in* Laymond, L., ed., Mélanges: their nature, origin, and significance: Geological Society of America Special Paper 198, p. 71–80.

Cloos, M., 1986, Blueschists in the Franciscan Complex of California: Petrotectonic constraints on uplift mechanisms: Blueschists and Eclogites, v. 164, p. 77–94. doi:10.1130/MEM164-p77

Cowan, D.S., 1978, Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Geological Society of America Bulletin, v. 89, p. 1415–1423. doi:10.1130/0016-7606(1978)89<1415:OOBCRI>2.0.CO;2

Fryer, P., Lockwood, J., Becker, N., and Phipps, S., 2000, Significance of serpentine and blueschist mud volcanism in convergent margin settings, *in* Dilek, Y., Moores, E.M., Elthon, D., and Nichola, A., eds., Ophiolites and oceanic crust: New insights from field studies and ocean drilling program: Geological Society of America Special Paper 349, p. 35–51.

Fryer, P., Wheat, C.G., and Mottl, M.J., 1999, Mariana blueschist mud volcanism: Implications for conditions within the subduction zone: Geology, v. 27, p. 103–106. doi:10.1130/0091-7613(1999)027<0103:MBMVIF>2.3.CO;2

Hanamura, Y., and Ogawa, Y., 1993, Layer-parallel faults, duplexes, imbricate thrusts and vein structures of the Miura Group: Keys to understanding the Izu fore-arc sediment accretion to the Honshu fore arc: The Island Arc, v. 2, p. 126–141. doi:10.1111/j.1440-1738.1993.tb00081.x

Hirauchi, K., and Yamaguchi, H., 2007, Unique deformation processes involving the recrystallization of chrysotile within serpentinite: Implications for aseismic slip events within subduction zones: Terra Nova, v. 19, p. 454–461. doi:10.1111/j.1365-3121.2007.00771.x

Hirono, T. 1996, Web structure in the sandstone beds of the Emi Group in the southern part of the Boso Peninsula, central Japan: The Journal of the Geological Society of Japan, v. 102, p. 804–815. doi:10.5575/geosoc.102.804

Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan-Knoxville Paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074. doi:10.1130/0016-7606(1968)79[1063:POMATB]2.0.CO;2

Iwamori, H., 2003, Viscous flow and deformation of regional metamorphic belts at convergent plate boundaries: Journal of Geophysical Research, v. 108, no. B6, p. 2321–2345. doi:10.1029/2002JB001808

Kawamura, K., Ogawa, Y., Anma, R., Yokoyama, S., Kawakami, S., Dilek, Y., Moore, G.F., Hirano, S., Yamaguch, A., Sasaki, T., and YK05-08 Leg 2 and YK06-02 Shipboard Scientific Parties, 2009, Structural architecture and active deformation of the Nankai Accretionary Prism, Japan: Submersible survey results from the Tenryu Submarine Canyon: Geological Society of America Bulletin, v. 121, p. 1629–1646. doi:10.1130/B26219.1

Kawamura, K., Ogawa, Y., Hara, H., Anma, R., Dilek, Y., Kawakami, S., Chiyonobu, S., Mukoyoshi, H., Hirano, S., and Motoyama, I., 2011, Rapid exhumation of metamorphosed sediment with gravitational collapse in an active eastern Nankai accretionary prism, *in* Ogawa, Y., Anma, R., and Dilek, Y., eds., Accretionary prisms and convergent margin tectonics in the Northwest Pacific Basin, in the series: Modern approaches in solid earth sciences: Berlin, Springer-Verlag, v. 8, p. 215–227.

King, R.L., Kohn, M.J., and Eiler, J.M., 2003, Constraints on the petrologicstructure of the subduction zone slabmantle interface from Franciscan Complex exotic ultramafic blocks: Geological Society of America Bulletin, v. 115, p. 1097–1109. doi:10.1130/B25255.1

Maekawa, H., Shozui, M., Ishii, T., Fryer, P., and Pearce, J.A., 1993, Blueschist metamorphism in an active subduction zone: Nature, v. 364, p. 520–523. doi:10.1038/364520a0

Maekawa, H., Shozui, M., Ishii, T., Saboda, K.L., and Ogawa, Y., 1992, Metamorphic rocks from the serpentinite seamounts in the Mariana and Izu-Ogasawara forearcs: Ocean Drilling Program Leg 125: Scientific Results Leg, v. 125, p. 415–430.

Michiguchi, Y., and Ogawa, Y., 2011a, Dark bands in the submarine Nankai accretionary prism – Comparisons with Miocene–Pliocene onshore examples from Boso Peninsula, *in* Ogawa, Y., Anma, R., and Dilek, Y., eds., Accretionary prisms and convergent margin tectonics in the Northwest Pacific Basin, in the series: Modern approaches in solid earth sciences: Berlin, Springer-Verlag, v. 8, p. 229–246.

Michiguchi, Y., and Ogawa, Y., 2011b, Implication of dark bands in Miocene–Pliocene accretionary prism, Boso Peninsula, central Japan, *in* Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of formation and societal significance: Geological Society of America Special Paper 480, p. 249–262. doi:10.1130/2011.2480(12)

Mori, R., Ogawa, Y., Hirano, N., Tsunogae, T., Kurosawa, M., and Chiba, T., 2011, Role of plutonic and metamorphic block exhumation in a forearc ophiolite mélange belt: An example from the Mineoka belt, Japan, *in* Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of formation and societal significance: Geological Society of America Special Paper 480, p. 95–115. doi:10.1130/2011.2480(04)

Muraoka, S., and Ogawa, Y., 2011, Recognition of trench-fill type accretionary prism: Thrust anticlines, duplexes and chaotic deposits of Pliocene-Pleistocene Chikura Group, Boso Peninsula, Japan, *in* Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of formation and societal significance: Geological Society of America Special Paper 480, p. 233–247. doi:10.1130/2011.2480(11)

Ogawa, Y., 1983, Mineoka ophiolite belt in the Izu forearc area – Neogene accretion of oceanic and island arc assemblages in the northeastern corner of the Philippine Sea plate, *in* Hashimoto, M., and Uyeda, S., eds., Accretion tectonics in the Circum-Pacific Region: Tokyo, Terrapub, p. 245–260.

Ogawa, Y., Takami, Y., and Takazawa, S., 2008, Oblique subduction in island arc collision setting: Unique sedimentation, accretion and deformation processes in the Boso TTT-type triple junction area, NW Pacific, *in* Draut, A.E., Clift, P.D., and Scholl, D.W., eds., Formation and applications of the sedimentary record in arc collision zones: Geological Society of America Special Paper 436, p. 155–170.

Raymond, L.A., 1984, Classification of mélanges, *in* Raymond, L.A., ed., Mélanges: Their nature, origin, and significance: Geological Society of America Special Paper 198, p. 7–20.

Shreve, R.L., and Cloos, M., 1986, Dynamics of sediment subduction, melange formation, and prism accretion: Journal of Geophysical Research, v. 91, p. 10229–10245. doi:10.1029/JB091iB10p10229

Singleton, J.S., and Cloos, M., 2012, Kinematic analysis of mélange fabrics in the Franciscan Complex near San Simeon, California: Evidence for sinistral slip on the Nacimiento fault zone?: Lithosphere, v. 5, p. 179–188. doi:10.1130/L259.1

Smith, G., Howell, D.G., Mayerson, D., and Ingersoll, R.V., 1979, Late Cretaceous trench-slope basins of central California: Geology, v. 7, p. 303–306. doi:10.1130/0091-7613(1979)7<303:LCTBOC>2.0.CO;2

Tsuji, T., and Miyata, Y., 1987, Fluidization and liquefaction of sand beds: Experimental study and examples from Nichinan Group: The Journal of the Geological Society of Japan, v. 93, p. 791–808. doi:10.5575/geosoc.93.791

Ueda, H., Niida, K., Usuki, T., Hirauchi, K., Meschede, M., Miura, R., Ogawa, Y., Yuasa, M., Sakamoto, I., Chiba, T., Izumino, T., Kuramoto, Y., Azuma, T., Takeshita, T., Imayama, T., Miyajima, Y., and Saito, T., 2011, Seafloor geology of serpentinite – Eclogite complex in the Ohmachi Seamount (Izu-Bonin arc) as an exhumed subduction zone within the Philippine Sea, *in* Ogawa, Y., Anma, R., and Dilek, Y., eds., Accretionary prisms and convergent margin tectonics in the Northwest Pacific Basin, in the series: Modern approaches in solid earth sciences: Berlin, Springer-Verlag, v. 8, p. 97–128.

Ueda, H., Usuki, T., and Kuramoto, Y., 2004, Intra-oceanic unroofing of eclogite-facies rocks in the Omachi Seamount, Izu-Bonin frontal arc: Geology, v. 32, p. 849–852. doi:10.1130/G20837.1

Ukar, E., 2012, Tectonic significance of low-temperature blueschist blocks in the Franciscan mélange at San Simeon,

California: Tectonophysics, v. 568–569, p. 154–169. doi:10.1016/j.tecto.2011.12.039
Ukar, E., and Cloos, M., 2013, Actinolitic rinds on low-T mafic blueschist blocks in the Franciscan shale-matrix mélange near San Simeon: Implications for metasomatism and tectonic history: Earth and Planetary Science Letters, v. 377–378, p. 155–168. doi:10.1016/j.epsl.2013.06.038
Underwood, M.B., and Laughland, M.M., 2001, Paleothermal structure of the point San Luis slab of central California: Effects of late Cretaceous underplating, out-of-sequence thrusting, and late Cenozoic dextral offset: Tectonics, v. 20, p. 97–111. doi:10.1029/1999TC001153
Yamamoto, Y., 2006, Systematic variation of shear-induced physical properties and fabrics in the Miura-Boso accretionary prism: The earliest processes during off-scraping: Earth and Planetary Science Letters, v. 244, p. 270–284. doi:10.1016/j.epsl.2006.01.049
Yamamoto, Y., Nidaira, M., Ohta, Y., and Ogawa, Y., 2009, Formation of chaotic rock units during primary accretion processes: Examples from the Miura-Boso accretionary complex, central Japan: Island Arc, v. 18, p. 496–512. doi:10.1111/j.1440-1738.2009.00676.x
Yuasa, M., 1985, Sofugan Tectonic Line, a new tectonic boundary separating northern and southern parts of the Ogasawara (Bonin) arc, northwest Pacific, *in* Nasu, N., Kobayashi, K., Uyeda, S., Kushiro, I., and Kagami, H., eds., Formation of active ocean margins: Tokyo, Terra Scientific Publishing, p. 483–496.