Unmetamorphosed sedimentary mélange with high-pressure metamorphic blocks in a nascent forearc basin setting

Brian Hitz, John Wakabayashi *

Department of Earth and Environmental Sciences, California State University, Fresno, 2576 E. San Ramon Avenue, Fresno, CA 93740, USA

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**A B S T R A C T**

Mélanges crop out within unmetamorphosed basal Great Valley Group (GVG) forearc basin strata and between GVG and the underlying Coast Range Ophiolite (CRO) in the San Francisco Bay region of coastal California. These mélanges include high-pressure (HP) metamorphic blocks of the Franciscan subduction complex that structurally underlies the unmetamorphosed CRO as well as blocks of GVG and CRO. The matrix consists of foliated shale and serpentinite, locally interleaved at centimeter scale. The mélanges strike and dip parallel to bounding GVG sandstones and conglomerates. The matrix locally consists of sedimentary breccia and conglomerate made up of clasts of serpentinite and shale. GVG sandstones within and bounding the mélanges have detrital serpentinite clasts. The field relationships indicate a sedimentary origin of the mélanges as olistostromal deposits within latest Jurassic to earliest Cretaceous basal GVG. The mélanges correlate to units along the eastern margin of the northern Coast Ranges, about 250 km to the north with restoration of post-subduction dextral faulting, and differ from the latter in the higher proportion of shale, stronger matrix foliation, and common occurrence of HP blocks. Similar units may have mistakenly been assigned to the Franciscan owing to the foliated nature of the matrix and occurrence of HP blocks. This and the broad distribution of localities indicate that these deposits are more widespread than previously believed. Exhumation rates of coarse-grained HP mélange blocks may have been 2 to 10 mm/yr or higher based on the ages of similar blocks in the Coast Ranges, burial depth of the blocks, and depositional age of the enclosing strata. Exhumation and deposition of Franciscan blocks in these GVG mélanges predate preserved accretion of similar materials in the adjacent Franciscan by at least 30 m.y., suggesting subduction erosion of previously accreted material, or exhumation of the blocks in forearc serpentinite–shale diapirs.

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1. Introduction

Mélanges consist of blocks in finer-grained (than the block size) matrix (e.g., Cowan, 1985; Hsiü, 1968; Hsiü and Ohrbom, 1969; Lash, 1987; Raymond, 1984). Mélages tend to be associated with convergent plate margins, and apparently form in a variety of tectonic settings within such plate boundary zones, so understanding their origin and the history of the blocks within them gives insight into large-scale material movements along such plate boundaries (e.g., Alonso, et al., 2006; Cloos, 1985; Cowan, 1985; Cowan and Page, 1975; Festa, 2011; Festa et al., 2010; Fryer et al., 2000; Phipps, 1984; Wakabayashi, 2011; this volume).

Although mélages may form by tectonic, diapiric, and sedimentary (olistostromal) processes (e.g., Dela Pierre et al., 2007; Festa, 2011; Raymond, 1984), ascertaining mélange origins has proven consistently challenging, because (1) later tectonic strain and recrystallization may obscure earlier sedimentary or diapiric origins (Aalto, 1989; Cowan, 1978; Cowan and Page, 1975; Osozawa et al., 2009, 2011; Raymond, 1984; Wakabayashi, 2011, this volume), and (2) because matrix exposures are seldom adequate to evaluate the presence of opposing sense-of-shear on opposite boundaries of a mélange, the diagnostic criteria for diapiric mélages (Dela Pierre et al., 2007; Festa, 2011; Orange, 1990). These difficulties have spawned contrasting hypotheses of mélange origin, and even contrasting definitions of mélanges themselves (Cowan, 1985; Raymond, 1984; Sengor, 2003). This has led many to adopt a descriptive definition of mélange similar to that we employ above, which does not include genetic criteria (e.g., Silver and Beutner, 1980; Wakabayashi, 2011) in contrast to a genetic definition such as that of Sengor (2003) who argued that the term “mélange” should be reserved for units whose block-in-matrix fabric originated by tectonic strain.

Whereas late deformation and recrystallization make it difficult to distinguish tectonic, sedimentary, or diapiric origins of some mélanges, the tectonic/structural setting of a mélange, commonly a key to interpreting the connection between mélanges and large-scale processes (e.g., Festa et al., 2010; Wakabayashi, 2011), may also be obscured by geologic complexity. In this paper we present new data from mélanges, in the Hayward Hills of the eastern San Francisco Bay area of the California Coast Ranges (Figs. 1, 2), whose combination of structures and lithologies has previously defied assignment to a simple tectonic setting (Wakabayashi, 2004; 2011). From these field relationships we will...
propose that the mélanges are sedimentary deposits within basal forearc basin strata. This allows estimation of exhumation rates for high-pressure metamorphic rocks included in the unmetamorphosed mélanges as well as an assessment on the extent of serpentinite-rich olistostromal deposition in the former forearc basin.

2. Regional tectonic setting

Major rock units of the California Coast Ranges include the Franciscan subduction complex, Coast Range Ophiolite (CRO), and Great Valley Group (GVG) forearc basin strata, with some regional overlap of these three units by Cenozoic sedimentary deposits. Before presenting the detailed field relationships of the study area, we will briefly review the three main rock units that make up the mélanges and bounding units, with emphasis on the distinction between these units.

The Franciscan Complex, regarded by many as the world’s type subduction complex, comprises both mélange units and coherent thrust sheets, with at least one fourth of the exposed units exhibiting high-pressure/low-temperature (HP–LT) blueschist facies metamorphism or higher grades (Wakabayashi, 1992, 1999a). The Franciscan Complex formed from materials offscraped or underplated from the downgoing plate during 140 m.y. or more of continuous east-dipping subduction starting at about 165–170 Ma, with subduction persisting to approximately 15 Ma at the latitude of the study area (Ernst, 1984; Wakabayashi, 1992, 1999b; Wakabayashi and Dumitru, 2007). The particular Franciscan rocks in this part of the San Francisco Bay region were likely accreted between about 165 Ma and 85 Ma (Ernst et al., 2009; Snow et al., 2010; Wakabayashi and Dumitru, 2007).

The Coast Range Ophiolite (CRO) structurally overlies the Franciscan, and comprises serpentinitized ultramafic rocks, gabbro, quartz diorite, basalt, intermediate to felsic volcaniclastic rocks and more rarely sheeted intrusives (Hopson et al., 1981; 2008). Most of the Coast Range Ophiolite formed at about 165–172 Ma (Hopson et al., 2008; Shervais et al., 2005). The Great Valley Group (GVG) depositionally overlies the CRO and consists of well-bedded clastic sedimentary rocks, mainly sandstone (commonly called graywacke) and shale (Dickinson, 1970; Ingersoll, 1978).

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The CRO and GVG lack burial metamorphism, in contrast to the Franciscan (Platt, 1986), although the CRO exhibits variable sea-floor metamorphism from zeolite and prehnite–pumpellylite grade in the volcanic units to amphibolite grade in some of the gabbros (Evarts and Schiffman, 1983). Unlike the Franciscan, mélanges do not occur within the CRO and are rare in the GVG. The mélanges identified in the GVG prior to this study occur at or near the base of the unit and comprise mostly serpentinite-matrix sedimentary units with various blocks, most of which appear to be derived from the Coast Range Ophiolite, although high-pressure (HP) metamorphic blocks occur locally (Carlson, 1981). The unmetamorphosed matrix of these mélanges exhibits little foliation, and locally displays sedimentary structures (Lockwood, 1972; Moiseyev, 1970; Phipps, 1984). These mélanges depoositionally overlie CRO (Phipps, 1984), and at one locality GVG shale (Wakabayashi, 2011).

3. Geology in the Hayward Hills

Geologic units in the Hayward Hills region consist of GVG (sandstones, shales, and conglomerates), CRO (Leona Rhyolite, basalt, gabbro, and serpentinite) (Dibblee, 1980; Robinson, 1956) and Franciscan lithologies that exist entirely as blocks in mélangé, and make up a small fraction of the total outcrop area in this region (Fig. 3). The Franciscan blocks consist of blueschist facies metagraywacke and metashale, chert, fine-grained blueschists, and various coarsely crystalline metamorphic rocks commonly referred to as “high-grade blocks” in Franciscan literature (e.g., Wakabayashi, 1992). The high-grade blocks consist primarily of blueschist with HP (rutile-bearing) amphibolite relics. In many cases blueschist facies minerals have almost completely replaced earlier amphibolite facies minerals and the classification of many of the blocks in Fig. 3 as “blueschist” instead of “amphibolite” reflects this. Some high-grade metacherts, distinguishable from the lower grade metacherts because of their macroscopic metamorphic minerals, and rare garnet amphibolite/eclogite blocks occur.

The GVG rocks have been assigned to the Knoxville Formation, the basal subunit of the GVG based on the presence of Tithonian bivalve Buchia piochii (Robinson, 1956). The Knoxville Formation, now considered latest Jurassic to earliest Cretaceous on the basis of detrital zircon chronology (Surpless et al., 2006; Wright and Wyld, 2007) is

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shale-dominated in the type exposures along the western margin of the Sacramento Valley, several hundred km from this field area, but in the Hayward area has a much higher proportion of sandstone and conglomerate, in addition to subordinate siltstone and shale. The sandstone is lithic rich (>50% lithics) and lacks flattening strain and significant pressure solution (Fig. 4A). Volcanic lithics, including a significant proportion of felsic volcanic lithics, comprise the largest fraction of the lithic grains, followed by siltstone/mudstone, and chert. Many grains of chlorite, with variable degrees of alteration to clay minerals, are present. As discussed in Section 4, at least some of these grains are likely derived from serpentinite. The sandstone is well-bedded with average bedding thickness ranging from 3 cm to >1 m. GVG shale, sandstone, and conglomerate occur both as coherent units and as mélange blocks.

The CRO lithologies comprise gabbro, a quartz-keratophyre unit known as the Leona Rhyolite, and basalt (Bailey et al., 1970; Hopson et al., 2008). These rocks crop out as coherent units and blocks-in-mélange. Serpentinite is present in the area, but it is unclear as to whether this represents serpentinite associated with the CRO. Franciscan, or deeply exhumed mantle hanging wall of the paleo subduction zone (Wakabayashi, 2004); we describe the serpentinite in detail in descriptions on the mélange matrix (especially Section 4.2) below. The Leona Rhyolite has a distinctive light brown weathered color, lighter colored than weathered basalt in the area and it is distinguished from the latter in thin section by common occurrence of quartz. Similarly in fresh exposures, the Leona Rhyolite tends to be medium green versus the very dark green of basalt. Neither the basalt nor the Leona Rhyolite exhibits any penetrative fabric, so igneous textures are well preserved. Metamorphic minerals consist of fine-grained pumpellyite and chlorite. Basalt crops out in the area and it is difficult to determine whether it is CRO or low-grade (prehnite–pumpellyite facies) Franciscan. The lack of associated Franciscan lithologies (including chert and prehnite–pumpellyite facies greywacke) and the fact that this unit is found in contact with Leona Rhyolite or GVG lead us to conclude that it is CRO basalt. The gabbro consists of plagioclase with ortho- and clinopyroxene and ranges from remarkably fresh, with pristine plagioclase (transparent gray-colorless in hand specimen instead of the weathered milky white) and pyroxenes to altered with plagioclase replaced by various phyllosilicates and Ca-silicates such as prehnite, and pyroxenes replaced by secondary amphibole (hornblende and actinolite)
and chlorite. Cumulus textures are locally present. The gabbro tends to lack a penetrative fabric but it is locally cut by brittle and brittle-plastic shear zones that range up to at least a meter in thickness. These shear zones locally contain syntectonic actinolite and hornblende, demonstrating that they formed in a spreading center environment, because of the lack of post-formational burial metamorphism, as shown by the complete lack of burial metamorphic minerals in the GVG that depositionally rests on the CRO.

4. Mélanges of the Hayward Hills

Below we describe the mélange exposures or areas of mélange exposures in the study area (Fig. 3). To facilitate descriptions we have divided the mélange exposures on a geographic basis. This division does not necessarily mean that these mélange exposures represent distinct geologic units, let alone different sorts of mélanges. The description that follows, however, documents the variation in characteristics of these mélanges within the field area.

Mélanges are observable on both the centimeter and meter scales, as noted in earlier reconnaissance work (Wakabayashi, 2004). Only the largest and most distinctive blocks are shown in Fig. 3 and these are small enough that they cannot be shown to scale (depicted by symbol) except for one gabbro block. Where visible, the mélange matrix consists of both foliated serpentinite and interleaved shale-serpentinite (Fig. 5) (see also borehole core photos in Wakabayashi, 2004). The matrix exhibits sedimentary features in nearly all of its exposures, and these features include sedimentary breccia and conglomerate consisting of serpentinite and shale clasts (Fig. 5B,C,D,E).

A sandstone block from one of the mélange zones appears similar to the GVG sandstones bounding the zone, except for the incipient development of cleavage and much greater abundance of chlorite grains (Fig. 6; compare to Fig. 4A). Some of the chlorite grains either preserve serpentinite mineralogy, or pseudomorph serpentinite mineral fabric. The preservation of serpentinite mineralogy and/or textures in the grains of this sample indicates that some, and likely most, of the detrital chlorite grains in other GVG sandstones in this area are derived from detrital serpentinite. This is similar to the observations made for Franciscan sedimentary breccia and sandstones in the Panoche Pass area, where the full gradation between serpentinite clasts and chlorite clasts is observed (Wakabayashi, this volume). Most of the GVG sandstones flanking the mélanges have detrital serpentinite grains but detrital serpentinite is most abundant in the sandstone blocks in the mélanges.

A reconnaissance study, that included now-reclaimed (and covered) quarry exposures, geotechnical borehole core samples and temporary test pit exposures, had a greater opportunity to closely examine the matrix (Wakabayashi, 2004 and unpublished) given the scarcity of present exposures. Our detailed characterization of matrix and block-matrix relationships derives both from presently accessible outcrop and from the previous study of temporary exposures. We have arranged our descriptions of localities below in approximate north to south order keyed to outcrops shown in Fig. 3.

There are some significant gaps in the map as a result of property access and there is an additional problem of significant topographic modification due to quarrying in the west-central mélange area in Fig. 3, as well as the development of a large landslide (that removed some previously-mapped exposures) that postdates the topography on the base map. Because of these problems, the topography beneath west-central mélange and the southern part of the central mélange will not match the current topography.
4.1. North mélange

This mélange exposure is about 400 m long by up to 50 m wide with an average north–northeast trend (Fig. 3). Matrix is not exposed. The blocks in the mélange consist primarily of Franciscan high-grade blocks, mostly blueschists, and amphibolite with variable blueschist overprints, with some blueschist facies metacherts, as well as Knoxville sandstones. These blocks range in size up to 8 m in maximum exposed diameter.

The boundaries of the mélange define contacts striking ENE and dipping south in the northern part of the exposure, whereas the same contacts strike NW and dip SW in the southern part of the exposure. The contact between GVG and Leona Rhyolite of the CRO directly west of the mélange exposures is sub parallel to the western mélange contact.

4.2. Central mélange

This mélange extends for about 1 km with a map width up to about 100 m (Fig. 3). It strikes northwest and its contact relationships indicate a general southwest dip, parallel to the GVG–Leona Rhyolite contact east.
of the body. The matrix exposed along the southeastern portion of the mélange consists of a foliated shale and serpentinite interleaved at cm scales (Fig. 5A,C; also Wakabayashi, 2004). The matrix appears to consist of sedimentary breccia and conglomerate that has been subsequently deformed. The natural exposures of the matrix, including the headscarp of a recent (post-2004) landslide (Fig. 5A) indicate that shale predominates in the matrix. Serpentinite is lizardite dominated with angular and rounded clasts (to about 30 cm) that are antigorite rich. Relict peridotite textures occur only in small blocks less than 50 cm in size. Hard outcrops of the serpentinite or shale are rare and large temporary (landslide headscars or excavations) exposures show that much of the shale and serpentinite matrix has a soft, crumbly, disaggregated character. Shale is unmetamorphosed. The largest amount of serpentinite is exposed in the above-mentioned headscarp and the multiple serpentinite bodies separated by shale there may extend for over 200 m in long dimension with a collective thickness of up to 100 m. Matrix foliation exhibits orientations subparallel to parallel to the unit boundaries. Both the north and south boundaries of the mélange pinch out along strike. Blocks include blueschist facies metavolcanics and metacherts, actinolite schist, Knoxville sandstone, and CRO gabbro.

4.3. West-central mélange

This mélange or mélange zones were exposed in the walls of a now inactive quarry that has been reclaimed, unfortunately resulting in the covering of the quarry wall exposures that were viewed by the second author in 1999. Geology of this area in Fig. 3 is generalized from a geotechnical investigation (Frank Groffle, unpublished mapping) and the second author’s reconnaissance in 1999. The mélanges have subzones with abundant gabbro blocks in foliated serpentinite matrix and subzones of foliated shale matrix. Overall, shale predominates over serpentinite as the matrix lithology and the largest serpentinite body reaches about 100 m in long dimension. Blocks consist of sandstone (GVG and Franciscan affinity), gabbro, clinopyroxenite, serpentinite (in shale matrix zones), actinolite schist, and blueschist. One small (30 cm) block of eclogite, retrograded to garnet blueschist was found embedded in shale matrix (Fig. 4C). Much of the serpentinite occurs as antigorite schist with growth of talc, and tremolite, whereas other samples show extensive growth of lizardite rather than antigorite (Wakabayashi, 2004). The antigorite, talc, and tremolite bearing assemblages indicate metamorphism at temperatures up to amphibolite grade (Evans, 1977). One sample of shale matrix was examined and this sample features growth of lawsonite (Fig. 4B) indicating high-pressure, low-temperature metamorphism, in contrast to most of the unmetamorphosed shale matrix in this area.

The mélange zones strike subparallel to bounding GVG but because of the quality of the quarry exposures discordance in between the mélange boundaries and the GVG bedding was observed. Although subparallel to general GVG strike, these mélanges locally cut across the bedding of the bounding units. Unfortunately detailed observation of these exposures was conducted in the context of an engineering geology investigation so critical structural data, such as shear sense along the mélange borders was not recorded. One zone pinches out northward, whereas the mélanges merge with the central mélange to the south. To the west, GVG strata strike northwest and dip and moderate angles to the northeast, but folds at scales of up to a few hundred meters in wavelength result in local northeast-striking domains. In contrast, the mélange unit contacts, as well as the Leona–GVG contact to the east, dip southwestward so a regional-scale synclinal axis directly west of this mélange zone. This results in structural repetition of the southern part of the central mélange as the southwest mélanges. The large recent landslide (Fig. 5A) has removed the GVG bedrock to the west of the southern end of the central mélange, so that the present mélanges exposure is continuous with the eastern branch of the southwest mélanges (Fig. 3). The GVG overlies basalt of likely CRO affinity to the west (base of slope). The GVG appears more complexly folded in the areas directly adjacent to the mélange zones.

4.4. Southwest mélange(s)

This is actually a series of mélanges that extend for a strike length of at least 600 m (probably more than 1 km), and their collective structural thickness exceeds 100 m (Wakabayashi, 2004; 2011). Similar to the west-central mélange, temporary exposures, in this case geotechnical borings and test pits, allowed for close examination of the matrix that is otherwise poorly exposed.

The matrix consists of foliated serpentinite and shale intermixed with serpentinite at scales as small as centimeters (see photos in Wakabayashi, 2004). Serpentinite with relict peridotite textures is limited to small blocks of meter size or smaller. The serpentinite mineralogy includes antigorite, talc, and locally tremolite-bearing assemblages, indicating high-grade metamorphism as noted for the west-central mélange, although lizardite appears to predominate, as in the central mélange. Some narrow bedding-parallel zones (as thin as centimeters) of intermixed shale and serpentinite are present throughout the Knoxville sandstone in this area (too small to map). Their presence was revealed in borehole cores and test pit excavations (Wakabayashi, 2004). No blocks were observed in these cm-scale zones.

Franciscan blocks in the mélanges range in size up to about 8 m in long exposed dimension, lithologies include chert, prehnite–pumpellyite facies and fine-grained blueschist facies metabasalt (greenstone with incipient blueschist facies metamorphism), amphibolite, and one block of Skaggs Spring schist (a distinctive quartz-rich glaucophane–lawsonite
schist that is probably a completely recrystallized metagraywacke; Snow et al., 2010; Wakabayashi, 2011). Blocks of Knoxville sandstone (to at least 5 m in size) are common in the mélanges in addition to some large blocks (up to at least 100 m in size) of Coast Range Ophiolite gabbro. GVG sandstone appears petrographically identical in all of the various domains between and flanking the mélange zones (see photomicrographs in Wakabayashi, 2004 as well as representative photomicrograph Fig. 4A). As noted above, these sandstones include detrital serpentinite grains.

In the northern part of this area, the mélange bounding contacts and internal foliation strike northwest and dip northeast parallel to bedding in bounding units of identical Knoxville sandstone (Wakabayashi, 2004). In the southeastern part of this area mélange contacts may truncate Knoxville bedding (the contacts were traced beneath fill and landslide deposits on the basis of borehole cores and test pits). Alternatively the outcrop pattern may result from the folding of mélanges and enclosing GVG strata. As noted in the section on the central mélange the post-2004 landslide (Fig. 5A) appears to confirm the large-scale folds in these units because this has resulted in the merging of the southern part of the central mélange and the eastern branch of the southwest mélanges.

4.5. Southeast mélange

This mélange forms a somewhat circular map pattern of exposure with a map diameter of about 500 m. The foliated serpentinite and shale matrix constitute the best of the natural matrix exposures in this area; matrix crops out in the northern, eastern, and southern parts of the inferred body. This matrix exhibits sedimentary features, including sedimentary breccia and conglomerate (Fig. 5). Blocks include blueschist metavolcanics with amphibolite relics, mafic breccia, and Knoxville sandstone (Fig. 3).

The western margin of the mélange abuts steeply-dipping GVG conglomerate. Although we have shown this contact as faulted, the contact may in fact be depositional. The contact location in the northwestern and southwestern margin of this mélange is poorly defined owing to surficial cover, whereas it is well constrained in other places by GVG exposures. Whereas the northern and eastern contacts are subparallel to the foliation orientations in the matrix (i.e. northerly strike and northeasterly dip), the southern contact may truncate matrix foliation and represent a late fault.

5. Discussion: origin and emplacement of mélanges

5.1. Metamorphic contrasts, field relationships, and mélange origins

Identical rocks on both sides of the mélanges described indicate minimal displacement across them as noted by Wakabayashi (2004). In contrast, the high-pressure and high-temperature metamorphism (blueschist facies, eclogite facies, high-pressure amphibolite) of many of the blocks, demands considerable exhumation of blocks before incorporation into the mélanges, which also includes...

Fig. 7. Schematic cartoons illustrating a model for development of sedimentary mélanges in the nascent Great Valley forearc basin as a consequence of mud volcano deposition. After initiation of subduction and metamorphism of Franciscan high-grade rocks at ca. 165 Ma (A), a period of subduction erosion/non accretion ensued (B). During this time serpentinite/shale diapirs may have exhumed high grade blocks, some early lower grade blueschist facies rocks, shale, and serpentinite and deposited them on the sea floor as mud volcano deposits in the nascent forearc basin, coeval with the earliest siliciclastic deposits of the forearc basin. Collectively, this represents the basal part of the Great Valley Group. Some of westernmost forearc region may have been removed by subduction erosion (Wakabayashi, this volume). The Skaggs Spring schist presently exposed in coherent outcrops lay at depths of > 20 km in the subduction zone at this time, but serpentinite–shale diapirs may have exhumed blocks of this unit to the surface. One such rock is found in the mélange described in this study.

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unmetamorphosed blocks of CRO gabbro and GVG sandstone. Some of the serpentinite appears to reflect higher temperature or higher pressure history that is more compatible with the high-grade blocks (talc–tremolite locally present in serpentinite) than the serpentinites of the CRO that tend to be dominated by lizardite (Hopson et al., 1981, but see Shervais et al., 2011 for antigorite associated with CRO serpentinite), but the antigorite/tremolite-bearing serpentinite crop out as blocks within unmetamorphosed shale and the more common lizardite-rich serpentinite. Similarly the lawsonite-bearing shale matrix sample of the west-central mélangé represents a block of metashale within otherwise unmetamorphosed matrix.

The sedimentary textures within the matrix, lack of significant displacement across the mélanges, the parallelism of most of the mélangé contacts with bounding GVG strata, and presence of detrital serpentinite in GVG sandstones within and bounding mélanges, indicate a sedimentary origin for most, if not all, of the mélanges in the area. The contacts of the west-central locally cross cut GVG stratigraphy so it is possible that this mélangé represents a minor (in displacement) diapiric remobilization (still within lower part of GVG) of similar sedimentary mélangé material as proposed by Moiseyev (1970) for similar deposits in the northern Coast Ranges. The somewhat circular form of the southeast also suggests that this body represents a diapiric feature remobilizing sedimentary mélangé. However, the contacts of this body may be a consequence of folding of stratigraphic contacts and the late faulting of the southern margin of the body, and sedimentary features are ubiquitous in the matrix (Fig. 5B,D,E).

5.2. Regional correlations and extent of olistostromes in paleo forearc basin

Serpentinite-bearing sedimentary mélangé deposits have been identified in similar stratigraphic position in the basal GVG of the northern Coast Ranges (Lockwood, 1972; Moiseyev, 1970; Phipps, 1984; Wakabayashi, 2011). The latter deposits differ from those described here in having a less deformed matrix, larger proportion of serpentinite, scarcity of metamorphic blocks, and finer grained associated GVG strata (shale with thin sandstone interbeds) (e.g., Phipps, 1984). The Hayward Hills locality is some 100 km south of the southernmost GVG mélangé deposits identified in the northern Coast Ranges. This distance increases to about 250 km by restoring post-subduction dextral faulting passing between the Hayward locality and northern localities (Wakabayashi, 1999b). This suggests a much greater spatial extent of these forearc basin olistostrome deposits than previously realized. Moreover, it is likely that correlatable deposits in the Coast Ranges have been mistakenly classified as Franciscan instead of GVG because of the intensity of the matrix foliation and the occurrence of HP blocks, as well as the common occurrence of Franciscan serpentinite-bearing mélanges at the structurally highest level of the Franciscan (Wakabayashi, 2011; this volume). This points out the potential difficulty of what seems to be simple unit/tectonic environment assignments (in this case subduction complex versus forearc basin) for mélangés along paleo convergent margins.

5.3. Exhumation rate of metamorphic blocks and tectonic significance

Here we speculate on the sedimentary–tectonic history of these mélangés and their context the trench–forearc system. The CRO and protoliths for the Franciscan high-grade metamorphic blocks formed in a supra subduction zone environment at about 165–170 Ma, based on the geochemistry of both units, as well as geochemical and regional geologic relationships (Wakabayashi et al., 2010) (Fig. 7A). The high-temperature metamorphism of the high-grade Franciscan rocks, their anticklywice PT paths, their oceanic lithologies (mostly metabasites with minor metachert), structurally high position of rare coherent equivalents of these rocks, and metamorphic ages (oldest in the Franciscan), suggest that they formed at the inception of subduction (Wakabayashi et al., 2010). The higher temperature ages (Lu–Hf garnet, Ar–Ar hornblende) approximate the peak metamorphic conditions in those rocks and span a range of about 155–168 Ma, whereas cooling ages (Ar–Ar white mica) range as young as 139 Ma (Anzcziwicz et al., 2004; Shervais et al., 2011; Wakabayashi and Dumitru, 2007).

Although coherent sheets of these high-grade rocks are preserved (Wakabayashi and Dumitru, 2007) much of this material was broken into blocks and surrounded by serpentinite at elevated temperatures, as indicated by actinolite–chlorite–phengite rims found encasing the blocks (e.g., Wakabayashi, this volume; Coleman and Lanphere, 1971; Moore, 1984), as well as the tremolite-bearing serpentinite found in some Franciscan serpentinite-matrix mélanges (Wakabayashi, this volume) and in the mélanges described herein. The highest grade of the blocks in the Hayward Hills mélanges was exhumed from depths of up to about 65–80 km (based on P estimates of eclogites and high-pressure amphibolites of Tsujimori et al., 2006; Page et al., 2007), and deposited on the floor of the nascent forearc basin between ca. 147 and 135 Ma based on both fossil and detrital zircon ages of the basal GVG (Surpless et al., 2006; Wright and Wyld, 2007) (Fig. 7B).

Pairing the minimum time difference between high-grade metamorphism and deposition paired with the higher limit of burial depth yields an exhumation rate of about 10 mm/yr, whereas the maximum difference in metamorphic and deposition age paired with the lower burial depth estimate yields an exhumation rate of about 2 mm/yr. Exhumation rates of higher than 10 mm/yr are possible if the younger cooling ages (cooling through Ar closure in phengite, possibly at considerable depth) are paired with older permissible ages of deposition.

The block of Skaggs Spring schist found in the southwest mélangés also requires extremely rapid exhumation. This unit has yielded phengite Ar–Ar ages of 132 Ma (Wakabayashi and Dumitru, 2007) and a maximum depositional age from U–Pb detrital zircon chronology of 144 Ma (both from the type locality where it occurs as a 70-km-long coherent unit), which is very similar to the 144–147 Ma detrital zircon ages obtained from the basal GVG (Surpless et al., 2006; Wright and Wyld, 2007). The exhumation of this block and depositional in the basal GVG clearly requires exceptionally rapid exhumation from ca 20–30 km (glaucophane, lawsonite, jadeite, aragonite-bearing assemblage; Ernst, 1993 for detailed PT estimates on similar assemblages in the Franciscan). Only the youngest possible range of basal GVG ages from fossils paired with the Skaggs Spring schist detrital zircon age as depositional age allows for a finite exhumation rate, which is >2.2 mm/yr for 20 km of exhumation in 9 m.y. (does not take into account time to reach to metamorphic depth). The metamorphic age of the Skaggs Spring schist from the type locality is too young for the age constraints noted above and suggests that parts of coherent exposures of this schist from which the dates were obtained were above the closure temperature for Ar in phengite (i.e., likely at depths >20 km) at the time a few pieces of this unit were exhumed and deposited in the young forearc basin (Fig. 7B).

The occurrence of fine-grained blueschist (not high-grade blocks) and blueschist facies metashale blocks also places constraints on large-scale material movements along the paleo convergent margin. In the Franciscan, such rocks have yielded metamorphic or formation ages younger than about 123 Ma (Dumitru et al., 2010; Ernst et al., 2009; Snow et al., 2010) significantly younger than the youngest permissible depositional age of the basal GVG in which they occur as blocks in the Hayward Hills. This may suggest accretion and exhumation of these units in the Franciscan, followed by their removal in the accretionary complex by surface and tectonic erosion. Alternatively, some of this material may have been exhumed from the subduction zone in serpentinite and shale diapirs that cut the ooof the nascent forearc basin but not the subduction complex (Fig. 7B).

Fryer et al. (2000) proposed that the sedimentary serpentinite deposits in the GVG represent serpentinite mud volcano deposits.
similar to those found in the modern Marianas forearc. The field relationships observed in the Hayward Hills and elsewhere in the GVG appear consistent with such a model, with a higher proportion of shale in the hypothetical diapirs for the former. The recent finding of high-grade metamorphic blocks up to 10 m (near or slightly more than the maximum size of high-grade blocks in the Hayward Hills locality) in Marianas forearc sea floor deposits makes this model more plausible (Maekawa et al., 2008) given that earlier studies had only recovered blocks of less than 1 m in size (e.g., Maekawa et al., 1992). Field relationships, however, demonstrating the presence of deep-seated diapirs, have not been found in the Coast Ranges, including in the Hayward Hills, so we can only evaluate the model of original diapirc extrusion of source material for the sedimentary mélanges based on indirect criteria.

The mélanges include unmetamorphosed blocks with upper plate affinity, CRO and GVG. Whereas this is compatible with a source diapir or diapirs that included blocks of near-surface material, the occurrence of Franciscan blocks of a range of metamorphic grades and burial depths may be more problematic. These may require removal points along the subduction zone at different positions down dip, and fluids evolved from the downgoing plate in the Marianas forearc apparently reflect a progressive down-dip increase in metamorphic grade rather than mixing of rocks of different metamorphic grade (by exhumation) along the subduction interface (Mott et al., 2004). If diapirs emplaced the subducted blocks tapped from different depths of the subduction zone, they may have been spread over a long trench-perpendicular distance (say 50 km or more); this is compatible with the rounding of many of the clasts in the mélanges that suggests some degree of subarne transport. On the other hand, age relationships for the Skaggs Spring schist suggest that some of the first-accreted high-grade material may have cooled and have been partly exhumed at the time of the accretion of the Skaggs Springs schist block that was “harvested” from its accretionary horizon by a diapir (Fig. 7B).

An alternative to diapirc exhumation of blocks is exhumation of coherent fault-bounded terranes, followed by sea floor erosion and deposition (see Wakabayashi, this volume). The characteristics of the mélanges are equally compatible with diapirc, exhumed coherent, or a combination of both sources.

The deposition of exhumed serpentinite, and HP metamorphic blocks in the Great Valley forearc appears to have been short-lived as these deposits appear to be limited to the basal part of the GVG. This exhumation and deposition predates that start of significant accretion in the Franciscan that began ca. 123 Ma and coincided with initiation of significant accretion of clastic sediment (Dumitru et al., 2010). Accretion began even later in other parts of the Franciscan, perhaps as late as 100 Ma in the San Francisco Bay area and much of the Diablo Range (Wakabayashi, this volume).

Sedimentary serpentinite deposits with high-grade blocks have recently been identified in the Franciscan (Wakabayashi, 2011; this volume) and preliminary analysis suggests that they were not accreted in the subduction complex until about 100 Ma. This suggests that serpentinite emplaced on the sea floor in this arc-trench system was exposed for a limited time (at ca. 135–147 Ma) in a position to shed detritus into the forearc basin, but for longer (until at least 100 Ma) in a position to shed detritus into the trench. Alternatively, after initial deposition of olistostromes into the forearc basin, subduction erosion and collapse of the hanging wall allowed periodic reposition of forearc basin mélangé deposits into the trench (Wakabayashi, this volume). Whereas the serpentinite making up Great Valley Group and Franciscan sedimentary serpentinite mélanges appears to have been derived from the mantle wedge above the subduction zone (Wakabayashi, this volume; Fryer et al., 2000; Phipps, 1984), minor amounts of serpentinite detritus were apparently shed into the trench as a result of exposure of ultramafic rocks scraped off the downgoing plate (Prohoroff and Wakabayashi, this volume).

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