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Sandstone-matrix mélanges, architectural subdivision, and geologic history of accretionary complexes: A sedimentological and structural perspective from the Franciscan Complex of Sonoma and Marin counties, California, USA

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ABSTRACT

Understanding details of accretionary complex architecture is essential to understanding construction of oceanic "outer" sides of orogens. The architecture of the Franciscan Complex (California), considered by many to be the "type" accretionary complex, is widely viewed in the context of terranes or belts delimited by reconnaissance mapping that reveals neither regional variations within terranes nor critical details of stratigraphy and structure. The architectural importance of Franciscan mélanges is recognized, but the importance of sandstone-matrix mélanges and olistostromal sandstones is not. Large-scale mapping in Sonoma and Marin counties, California, shows that Franciscan rocks are deformed, submarine-fan units of Facies A–E, plus Facies F olistolith-bearing submarine channel sandstones and olistostromal sandstone- and shale-matrix mélanges. Some mélanges are polygenetic with a sedimentary origin and a tectonic overprint. Glaucophane schists were recycled into conglomerates and olistostromes. Mappable units constitute members, broken and dismembered formations, and mélanges. Considering the stratigraphy and structure evident at the 1:24,000 scale, accretion via a subduction channel mechanism is impossible. The Sonoma-Marin Central belt or Central terrane (mélange) is not a monolithic shale-matrix mélange and lacks this characteristic of rocks assigned the same name to the north. Franciscan rocks here structurally underlie thrust-faulted fragments of a regional ultramafic sheet and, locally, an underlying exotic block-bearing serpentinite-matrix mélange. The detailed mapping shows that regional relations among and within Franciscan terranes and belts are poorly understood and suggests that such mapping is needed to clarify accretionary complex architecture and history. The implication for accretionary complex studies, in general, is that, while terrane or belt designations provide a general picture of the collage nature of accretionary complexes and clarification of regional relationships, only large-scale structural and stratigraphic studies can elucidate the architectural details of these orogenic complexes.

INTRODUCTION

Plate tectonic theory brought a new focus to the study of outer orogenic belts, leading to the view that these belts reflect a history of plate convergence, subduction, and accretion (e.g., Dewey and Bird, 1970; Ernst, 1970; Dietz and Holden, 1974). Orogenic belts in general and outer belts in particular were recognized as mega-collages of tectonostratigraphic elements accreted and assembled via tectonic processes (Helwig, 1974; Seely et al., 1974; Coney et al., 1980; Pessagno et al., 2000). The general history of the accretionary complex elements, formed by sedimentation in seafloor and trench environments on drifting plates and in the associated trenches, followed by accretion to the continents during subduction, is now well known (e.g., Dickinson, 1970; Ernst, 1970; Chipping, 1971; McLaughlin and Pessagno, 1978; Pessagno et al., 2000; Moore et al., 2007). Each major segment or element of an accretionary complex is commonly designated as a tectonostratigraphic terrane—a fault-bounded regional block of rocks that has a geologic history different from those of adjoining blocks—and delineation of terranes may yield an understanding of broad-scale accretionary complex architecture (Irwin, 1972; Coney et al., 1980; Howell, 1985; Zhang, 1985; Raymond et al., 1989). The architectural details, however, are commonly much less well understood.

The Franciscan Complex of western California was recognized during the development of plate tectonic theory as a subduction accretionary complex. For many it became the archetypical accretionary complex (e.g., Ernst, 1970, 2015; Wakabayashi, 2015). The Complex was initially divided into three (possibly fault-bounded) geographic belts—the Eastern, Central, and Western belts—with each belt characterized by particular rock types, rock ages, and a low-temperature metamorphic facies (blueschist, prehnite-pumpellyite, and zeolite facies—from east to west; Fig. 1; Berkland et al., 1972). The belts, and parts of them, were later designated as terranes, and these, together, comprise the strike-slip–faulted, NNW-SSE–trending Franciscan accretionary

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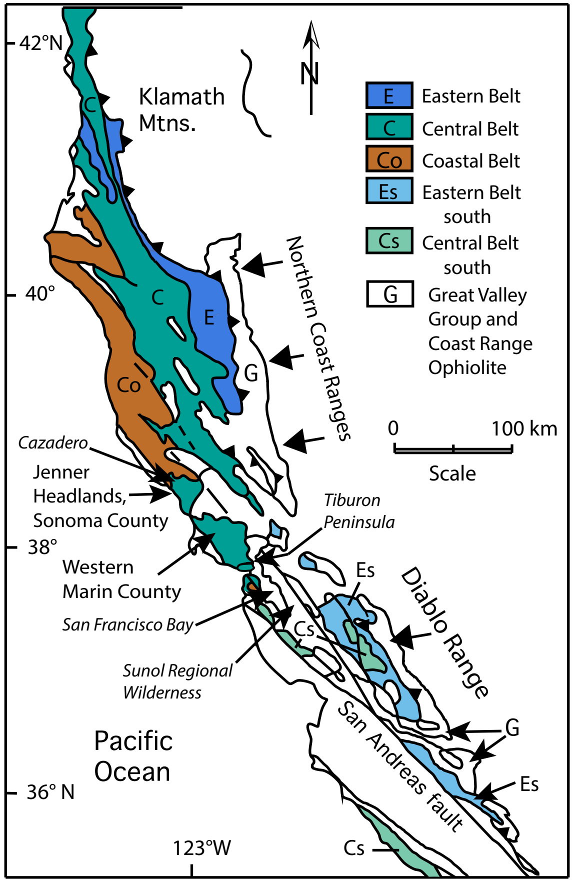

Figure 1. Generalized geologic map of western California, showing distribution of large areas of the three traditional "belts" of the Franciscan Complex. The Eastern belt (E), the Central belt (C), and the Coastal belt (Co) are distinguished from belts south of Marin County and the San Francisco Peninsula (Eastern South—Es; Central South—Cs), which are less well defined and controversial (e.g., see Raymond, 2014). Locations of western Marin County, site of the Liberty Gulch–Azalea Hill study area; Jenner Headlands, site of the Russian Gulch–Hill 572/905 study area; and other important sites mentioned in the text are identified.

Complex (Blake et al., 1982, 1984; Wakabayashi, 1990, 1999, 2015; McLaughlin et al., 1996).

Although terrane names are commonly used, various workers also use belt, nappe, and other types of units (and names) to designate architectural elements of the Franciscan accretionary complex, creating both controversy and confusion (cf. Wakabayashi, 1990, 2015; Ernst, 2011; Dumitru et al., 2015). Different terminologies partly reflect divergent views of the details of accretionary complex construction (e.g., Blake et al., 1982, 1988; Cloos, 1982; Ernst, 2011, 2015; Ukar and Cloos, 2013; Dumitru et al., 2015; Wakabayashi, 2015). For example, the original geographically based belt terminology is still used to delineate three major architectural elements considered to have accreted to form the Complex (e.g., Ernst, 2011). In contrast, some workers assign Franciscan rocks to numerous, thin to thick (<2–10+ km), structurally complex tectonostratigraphic terranes, each representing one of many accretion events (e.g., Blake et al., 1982; Blake et al., 1984; McLaughlin and Ohlin, 1984; Blake and Wentworth, 1999; McLaughlin et al., 2000; Blake et al., 2002; Bero, 2014). Alternatively, the Franciscan Complex is considered by Wakabayashi (1990, 2013, 2015) to consist of a stack of accreted, refolded, thin to thick (<0.5–>5 km) nappes. The nappes are composed of coherent and mélange units, including sandstone-matrix sedimentary mélanges, and are separated by relatively thin shear zones or tectonic mélange zones. Detrital zircon dating of sedimentation history supports a model of nappe stacking and seaward younging (e.g., Prohoroff et al., 2012; Wakabayashi, 2015). Other workers have mapped regionally extensive, tectonostratigraphic sheets and mappable (nappe-like) thrust layers consisting of, and locally subdivided into, lithostratigraphic units, but did not designate these as nappes or terranes (Raymond, 1973a, 2014; Crawford, 1976; Ernst, 1993; Bero, 2010; this report). The larger units locally display stacking sequences like the nappes. Assessment of mélange rocks has led some to envision accretion of thick (1–10+ km), regionally extensive mélange units after formation of the mélange in a subduction channel (Cloos, 1982; Ukar, 2012; cf. Hsü, 1974). These thick mélange units are designated as major belts within the accretionary complex. Some authors add confusion to this array of terms, architectural units, and accretion concepts, by using a mix of terms—for example, both "belt" and "terrane" (Ernst and McLaughlin, 2012; Dumitru et al., 2015). All contemporary workers envision accretion of various units, but the dimensions, character, and accretion history of the units, and the envisioned and resulting architecture of the Complex, differ.

Around the Pacific basin and elsewhere, outer orogenic belts are similarly recognized as consisting of terranes (e.g., Howell, 1985; Leitch and Scheibner, 1989). Because general analogies are commonly drawn with the elements of the Franciscan accretionary Complex, clarity is elusive due to the differing perspectives on Franciscan Complex architecture and history.

Another major accretionary complex issue that remains unresolved and overlaps the terminology and associated architectural issues is that of mélange genesis and accretion within and between Franciscan architectural units (e.g., Crawford, 1976 versus Page, 2000; Blake and Wentworth, 2000; Wakabayashi, 2011, 2015; Ukar, 2012 versus Ogawa et al., 2014). Whether most mélanges are primarily of tectonic, diapiric, or sedimentary origin confounds interpretations of Franciscan accretionary complex history. The importance and abundance of primary tectonic versus primary olistostromal mélanges are issues raised by the works of Hsü (1974), Cloos (1982), Cloos and Shreve (1988a, 1988b), MacPherson et al. (1990, 2006), Erickson (2011), Wakabayashi (2011, 2012, 2013, 2015), Prohoroff et al. (2012), and Ukar (2012). In addition, the term mélange is

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closely linked to the Franciscan Central belt name, and the belt is considered by many to be predominantly a shale-matrix mélange, with or without intermixed additional rock types (e.g., Berkland et al., 1972; Cloos, 1983; Blake et al., 1988, 2000; Dumitru et al., 2015). Yet, the work reported here and by Prohoroff et al. (2012) reveals that large tracts of the Central belt north of San Francisco are dominated by sandstone and sandstone-matrix mélange (sandstone bodies containing exotic clasts, notably of chert and mafic metavolcanic rock), rather than shale-matrix mélange. Where large shale-matrix mélanges are present in accretionary complexes, they provide a basis for the subduction channel model of mélange formation and accretionary complex construction (Cloos, 1982, 1984; Cloos and Shreve, 1988a, 1988b). The presence of sandstone-matrix mélange, rather than shale-matrix mélange that we show here, challenges the view that the subduction channel model is applicable to all of the Central belt or alternatively requires redefinition of that belt. Furthermore, if the sandstone matrix mélanges are widely distributed in accretionary complexes (reducing the applicability of the subduction channel model of accretionary complex construction), a reassessment of transfer mechanisms and quantities of materials from the overriding plate to the subducting plate is required. Thus, the mélange issues are linked to controversies of terrane character, architecture, and history.

The issues of what constitutes an architectural element of an accretionary complex, what such architectural elements should be called, and what compositional and tectonic history implications the various types of mélanges and other units have for accretionary complex architecture are the underlying issues of this paper. The purpose of the paper is to address aspects of these issues through the perspective of detailed sedimentological and structural mapping in two areas of the Central belt of the Franciscan Complex—the Russian Gulch–Hill 572/905 area of Jenner Headlands in Sonoma County and the Liberty Gulch–Azalea Hill area of Marin County, California. These studies reveal some details of the fine-scale architecture of the accretionary complex and raise a number of specific questions. First, with regard to mélange distribution, are sandstone-matrix mélanges a dominant component of the Franciscan Complex (at least in this region) and are these mélanges and the coherent sandstone units interfingered or interbedded? We find that they are both dominant and interbedded. Second, does the Central belt of Sonoma and Marin counties differ from the Central belt to the north, or are the two regions underlain by different major units? Clearly, as we show, the rocks of the two regions differ, suggesting the need for reassessment of the use of the Central belt and Central terrane names in the Sonoma-Marin region. Inasmuch as sandstone-matrix mélanges that we, Erickson (2011), and Prohoroff et al. (2012) show to exist in the region are underappreciated, there are ramifications for accretion models and, specifically, the subduction channel model (Cloos and Shreve, 1988a, 1988b). The subduction channel model is linked to plastic flow of weak shale- and serpentinite-matrix mélange. As such, it is neither a viable model for (1) mixing of metamorphic rocks of various grades within sandstone-matrix mélanges of this region and elsewhere nor for (2) forming an independent accretionary complex architectural element, where sandstone-matrix mélanges are predominant.

We show that large-scale mapping reveals important details of accretionary complex architecture, such as the existence of mappable stratigraphic units and interbedded mélanges of decimeter scale. Such units are not accounted for in typical subdivisions of accretionary complexes into terranes. The details constrain both sedimentological history and the deformational history of the complex. A hierarchy of accretionary complex units is beneficial to describing both the character and history of accretionary complexes, and we argue here that members, formations, broken formations, mélanges, and units of similar level in stratigraphic codes provide the first and second levels of subunit that comprise larger units, such as belts.

FRANCISCAN NOMENCLATURE ISSUES

Of the three Franciscan belts originally designated, the Eastern belt is perhaps the most clearly defined. The original designation was based on its geographic position plus its petrologic description and age (Bailey and Irwin, 1959; Blake, 1965; Berkland et al., 1972). That age was thought to be Jurassic. This belt is composed of schistose-textured, blueschist-facies metasandstones and associated metachert and basic metavolcanic rocks. The dominant metasandstones are now known to be predominantly of Early to Middle Cretaceous depositional age; whereas some cherts are of Jurassic to Early Cretaceous age (Isozaki and Blake, 1994; Dumitru et al., 2015). The Central belt was defined by its geographic position between the Eastern and Coastal belts and was characterized as consisting of widely distributed shale-matrix mélange, prehnite-pumpellyite–facies metasedimentary rocks, and a Jurassic to Middle Cretaceous age (e.g., Bailey and Irwin, 1959; Berkland et al., 1972; Cloos, 1982). The detrital zircon depositional age of this belt is now known to be predominantly Late Cretaceous but may extend from latest Jurassic to Eocene age (Dumitru et al., 2015). The Coastal belt, which is younger than the Central and Eastern belts, lies to the northwest and west of the Central belt and has a combined depositional and microfossil age of Late Cretaceous to Miocene (Bailey and Irwin, 1959; Evitt and Pierce, 1975; Kramer, 1976; Bachman, 1978; Damassa, 1979a, 1979b; Dumitru et al., 2015). Generally, it contains the least metamorphosed rocks of the Franciscan Complex, rocks of zeolite-facies to unmetamorphosed character.

Following development of the terrane concept (Coney et al., 1980; Howell et al., 1985), the belts or parts of each belt were assigned a terrane name, and in particular, separate terranes—smaller than the belts—were eventually mapped or designated within each of what had been the three belts (e.g., Blake et al., 1982, 1984; McLaughlin et al., 1994). The Pickett Peak and Yolla Bolly terranes were subdivisions of the former Eastern belt (Blake et al., 1982). The Marin Headlands terrane, north of San Francisco, was carved out of the former Central belt, as were the Alcatraz terrane to the east and other terranes (Blake et al., 1982, 1984). In the north, the Coastal belt was subdivided into several terranes (e.g., McLaughlin et al., 1994; Ernst and McLaughlin, 2012). In some areas, however, large tracts of rocks were given generalized terrane names such as

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Central "terrane" (mélange) (Blake et al., 2000, 2002). All the terranes assumed the role of major architectural elements within the accretionary complex.

Many Franciscan Complex rocks in the San Francisco Bay region, including those of northwestern Marin County, California, were assigned first to the Central belt and subsequently to the Central terrane (Berkland et al., 1972; Blake et al., 1982, 1984, 2000) (Fig. 1). Some former Central belt rocks, however, were assigned to the Nicasio Reservoir terrane by Wright (1984). Many of these were redesignated later by Blake et al. (2000, map and p. 5) as Franciscan "Central 'terrane' (mélange)." Other rocks were assigned to other terranes. In Marin County and the northern San Francisco Bay region, some units were also given nappe names (e.g., Angel Island nappe, Wakabayashi, 1990) or were designated as interterrane mélanges or shear zones (Wakabayashi, 1990, 2015; Prohoroff et al., 2012). Thus, there is a confusing and conflicting application of terrane and nonterrane names to the same rocks in Marin County and in most cases, new names were assigned without regard to historical precedence and with little or no written justification for the change.

In westernmost Sonoma County, similar problems exist. Some former Central belt rocks there were assigned to the "Central 'terrane' (mélange)" (Blake et al., 2002). Subsequently, that terrane was subdivided locally into new units. Near Jenner, California, the "Central 'terrane' (mélange)" was remapped in reconnaissance and provisionally divided into three tectonostratigraphic units named only by the rock type (sandstone, schist, and mélange) (Bero, 2010, in Edwards and Chestnut, 2012). Nearby, to the northeast, near Cazadero, Erickson (2011) combined Central belt sandstone and Central belt mélange units (of Blake et al., 2002) into a new sandstone-matrix mélange unit he named the King Ridge Road mélange. On the regional scale, Erickson (2011) depicts the King Ridge Road mélange as extending across extensive areas to the southwest, formerly designated by Blake et al. (2002) both as undifferentiated Central belt sandstone and mélange and as Central "terrane" (mélange). As a result, the King Ridge Road mélange would include the rocks north of Jenner formerly assigned in reconnaissance mapping by Blake et al. (2002) to two units of the Central belt and assigned, in reconnaissance mapping by Bero (2010), to three smaller units of the Jenner Headlands area. The lumping of all the rocks near the coast into Erickson's single mélange unit is considered by Wakabayashi (2015) to be reasonable, based on his assessment of matrix, block, and structural character of rocks in a small area he mapped south of Jenner.

The descriptions above emphasize the conflicting interpretations and revisions of unit designations in just two of the many areas of Franciscan Complex exposures. Additional examples are provided by Raymond (2014) for an area east of San Francisco Bay. These architectural unit revisions were based largely on reconnaissance but in some cases informed by limited amounts of large-scale mapping (in Marin County, Blake et al., 2000; Prohoroff et al., 2012 versus Wright, 1984; in Sonoma County, Erickson, 2011; Blake et al., 2002; Wakabayashi, 2015, fig. 14, versus Bero, 2010). Some correlations and changes in unit assignment in the region, made by Wakabayashi (2015), are based on correlations linked primarily to accretion ages derived from detrital zircon analyses and supported by interpreted structural position, metamorphic grade, and anecdotal petrographic observations. As noted, in none of the cases where the designations were changed, was the change made considering historical precedence, and none of the changes was supported by detailed, data-based justification for the change. In terms of historical precedence, for large tracts in the accretionary complex, the belt terminology has precedence. It is reasonable to consider that the new knowledge gained in the past four decades might demand reevaluation and possible replacement of the belt terminology; but in our view, changes should be defended in the literature by data and a rationale rather than simply being presented as a new reality.

OLISTOSTROMES AND SANDSTONE-MATRIX MÉLANGES

Olistostromes, representing submarine debris flows, have been described in many studies, and modern submarine landslides are well known (e.g., Flores, 1955; Abbate et al., 1970; Embley, 1976; Ballance, 1991; Steen and Andreson, 1997; Pini, 1999; Cowan and Pini, 2001). Among the features important to recognizing olistostromes in a subsequently deformed rock body are (1) the diversity of block types, (2) the contact relationships of the blocks in the matrix, (3) the contact structure of the olistostrome relative to adjoining units, and (4) petrochemical or petrologic indications that some blocks are derived from the hanging wall of a subducting plate (e.g., Aalto, 1981; Aalto and Murphy, 1984; MacPherson et al., 1990; Pini, 1999; Prohoroff et al., 2012). The block-matrix contacts should show relatively little or no deformation or at least locally display an undeformed surface of contact. If large blocks occur in a thin submarine olistostrome, the overlying sediments should drape over the block and locally abut its edges. With regard to the relationship to underlying and overlying beds, an olistostromal unit should be generally concordant and locally display an undeformed contact surface with the underlying unit. We searched for relationships (1) to (3) in examining the Franciscan Complex units in both the Jenner Headlands and Liberty Gulch–Azalea Hill areas of Sonoma and Marin counties.

In the context of sand-dominated, submarine-fan sequences, like those present in the Franciscan Complex and Great Valley Group of California, olistostromes typically represent debris flows and liquefied flows of slope and inner- to mid-fan channels (cf. Ingersoll, 1978; Shanmugam and Moila, 1985). Sand bodies containing exotic blocks that were eroded from older units exposed upslope, however, may be either (1) exotic block-richer olistostromes formed from debris flows and liquefied flows or (2) block-poor, olistolith-bearing sandstones produced where a flow-formed sediment layer now contains blocks emplaced by subsequent falling or sliding into the previously deposited layer (cf. well known limestone olistoliths, the "Cipit boulders" in the basinal St. Cassian Formation of the Dolomiti of Italy; e.g., Russo et al., 1997; Brandner and Keim, 2011) (Fig. 2). In some Marin and Sonoma County units, exotic blocks are abundant, whereas in others, they seem to be relatively sparse. In both cases, the exotic block-bearing units are associated with submarine-fan lithofacies.

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Figure 2. Photograph of a "Cipit Boulder" of white limestone enclosed in volcanic turbidites of the St. Cassian Formation in the Sella Massif of the Dolomiti of northeastern Italy. The late Professor F.K. McKinney (approximately 2 m in height) provides scale.

The submarine-fan facies descriptors used here follow the designations of Mutti and Ricci-Lucchi (1972 [1978]) as employed by Ingersoll (1978) and Shanmugam and Moila (1985). While we recognize that turbidites are diverse in their character (Bouma et al., 1985; Bouma and Stone, 2000; Lomas and Joseph, 2004), the sandstone-shale units of the Central belt fit the general descriptions of submarine-fan facies used by Ingersoll (1978) and Shanmugam and Moila (1985). Under this facies scheme: (1) inner-fan to mid-fan channel deposits include conglomerates and massive, pebbly, and graded sandstones with thick beds that are commonly amalgamated and are assigned to Facies A and B; (2) channel and slope slump and slide deposits, plus debris flows (the olistostromes), are assigned to Facies F; (3) mid- to outer-fan channels are marked by thick- to medium-bedded sandstones composed of Bouma turbidites (Facies C) with Tabcde beds and sand-dominated Tc-e and Tde turbidites with interbedded mudrocks (Facies E); (4) overbank, inter-channel, and fan lobe deposits consist of mudrock-dominated turbidites of Facies D with thin-bedded sandstones containing Tde intervals (and to a lesser extent Facies E sandstone-shale sequences) plus interlayered mudrocks of Facies G; and (5) pelagic and hemipelagic deposits, particularly of the basin plain, but also formed by temporally inter-turbidite deposition elsewhere on the fan, are mudrock-dominated, generally sandstone-free sections, also designated as Facies G.

Inasmuch as olistostromes that are formed from submarine landslide-induced debris flows have a block-in-matrix structure, they are essentially a type of mélange (Raymond, 1984). Both Erickson (1995, 2011) and Prohoroff et al. (2012) offer evidence that sandstone-matrix mélange rocks formerly assigned to the Central belt of the Franciscan Complex display evidence of an olistostromal character. The evidence includes (1) one block of deformed chert in contact with massive sandstone (Erickson, 1995, 2011, p. 173 and Fig. 2); (2) one block of metavolcanic rock in contact with sandstone that is reported to be little deformed regionally, displaying *only* a weak, locally developed pressure solution cleavage (Prohoroff et al., 2012, esp. fig. 6); (3) the general absence of mudrocks—typically the matrix precursor in shale-matrix mélange—in exotic block-bearing rocks of western Sonoma and Marin counties (Erickson, 1995; Prohoroff et al., 2012); and (4) the presence of exotic blocks

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scattered across the parts of the western Marin landscape apparently underlain by sandstone (Prohoroff et al., 2012).

Block-matrix contacts in the Franciscan Complex are rarely exposed. Therefore, two examples of blocks in a matrix of little deformed sandstone is crucial evidence that (1) the blocks occur in the sandstones of the units underlying the surrounding terrain; and (2) the blocks were not tectonically introduced at a postdepositional time. We have examined block-matrix contacts where possible and have mapped the surrounding rocks in detail at the two locales in western Sonoma and western Marin counties. Our mapping and observations only partially support the recently proposed hypotheses regarding these rocks, and they argue for a more complex view of the sedimentology of Franciscan rocks in landscapes decorated at the surface by exotic blocks of various rock types.

GEOLOGY OF THE RUSSIAN GULCH–HILL 572/905 AREA, JENNER HEADLANDS, AND THE NORTHERN SONOMA COAST STATE PARK

The Russian Gulch–Hill 572/905 area lies at the northwest edge of a group of hills called the Jenner Headlands. We selected an area of ~3 km^2 for our study north of Jenner between the shoreline and associated coastal cliffs of Russian Gulch and surrounding the unnamed hilltop and ridge labeled with the elevations 572 and 905 on the Arched Rock 7.5′ quadrangle (Fig. 3A). This area partly overlaps the existing Jenner Headlands reconnaissance map of Bero (2010), and much of it is covered by more detailed mapping reported here; but it includes areas along the coast and to the north not previously included in the Jenner Headlands map. Cliff exposures along the coast exhibit structural detail not available in typical, soil-covered hillside areas underlain by Franciscan Complex rocks to the east. Rock units mapped in the Russian Gulch–Hill 572/905 area not only include the prominent “sandstone” unit of Bero’s (2010) map, but also include a previously undescribed mélange unit recognized in the sea cliff exposures.

The geologic map of the Russian Gulch–Hill 572/905 area (Fig. 3A) is divided into two geographic zones that are separated geologically by a NW-trending fault, here designated the Headlands Front fault. The Headlands Front fault is traced along the line of a topographic lineament and passes through a zone of sheared rock exposed along Highway 1. It is unlikely that the sheared rock marks only the fault zone, because the fault contact separates sheared sandstone-shale mélange on the west from sheared sandstone-shale broken formation on the east. Much of the fault trace is concealed by soil, landslide debris, and Quaternary marine terrace sediments, but the trace does separate a zone to the northeast in which most exposures exhibit sandstone-shale turbidites from one to the southwest containing abundant exposures of mélange matrix with exotic blocks. The mélange rocks southwest of the Headlands Front fault are exposed in sea cliffs below wave-cut terraces that are typically capped with shoreface sediment. To the northeast, the hills are underlain by two poorly exposed (meta)sandstone units characterized by grassy slopes with local and scattered, prominent blocks of exposed, unmetamorphosed to weakly metamorphosed, unfoliated sandstone. The eastern unit, in particular, contains scattered erosionally-exposed blocks of bedded to massive radiolarian chert, basic metavolcanic rock, and metasandstone, and at least one exposure of conglomerate containing cobbly mudstone (Fig. 4). To the east and structurally overlying the sandstones is a schistose blueschist-facies metasandstone unit overlain by serpentinite-matrix mélange (Bero, 2010; Figs. 3A and 3B).

The mélange exposed along the coastal cliffs and beneath the terraces is here designated the Heaven’s Beach mélange of the Franciscan Complex (KTfhb). The type locality is located along the north end of Heaven’s Beach, between Hammerhead Point on the north and Heaven’s Point to the south (Figs. 3A and 5). Large, mappable megablocks (20 m–>200 m), as well as smaller mesoscopic blocks of rock that characterize the mélange, are enclosed in a sheared matrix of mixed metasandstone and metashale. Sheared shale does not dominate the matrix, which is generally sparse. Rather, the sheared shale, with equally abundant associated sheared metasandstone, seems to consist of thin masses that commonly form rims on, grade into, and separate blocks, rather than forming an extensive matrix in which enclosed, but dispersed blocks, “float.”

At Heaven’s Beach, multimeter- to centimeter-scale blocks of basic metavolcanic rock (“greenstone”), metachert, sandstone, and glaucophane schist occur in wave-cut exposures and on the beach (Fig. 5). In a cliff at the north end of the beach, there is a sheared megablock of submarine-fan Facies A and B, massive, amalgamated sandstone with some mudrock layers (Fig. 6A). Topographically above the sandstone is a thin lens of serpentinite associated with some sheared metasandstone and sheared shale that strikes into a sheared contact between clastic rock bodies. Hammerhead Point, a large megablock located west of the massive sandstone megablock, consists of highly fractured and faulted Facies A sandstone and conglomerate. A block of Facies E medium-bedded sandstone and shale lies along the eastern edge of Hammerhead Point and is visible at low tide (Fig. 6B). Note that the strike of the Facies E beds is N0°W, and the dip is steeply east. The tombolo that is Hammerhead Point has a connector with the mainland composed of sheared Facies D mudrocks with sandstones (Figs. 5 and 6C). This block of Facies D rocks, with some minor channel Facies B sandstones, abuts the rocks of Hammerhead Point along a cm-scale shear zone with no obvious, intervening mélange matrix. To the north, at Russian Gulch, a large, mappable megablock of Facies A (±B) sandstone and conglomerate (Fig. 3A) consists of beds that strike northeast and dip northwest. To the south, Fishhead Point is composed of a sheared, overturned turbidite sequence. Between Hammerhead Point and Fishhead Point, Heaven’s Point is a tombolo with a megablock of glaucophane schist constituting the headland (Figs. 3A and 7). On the intervening beach, the scattered blocks of chert, mafic metavolcanic rock, sandstone-shale, and glaucophane schist (some with brecciated margins) for the most part lack exposed contacts with matrix materials.

Northeast of Heaven’s Point, the cliffs behind the beach expose a megablock with steeply east-dipping, submarine-fan–facies beds, including an over-

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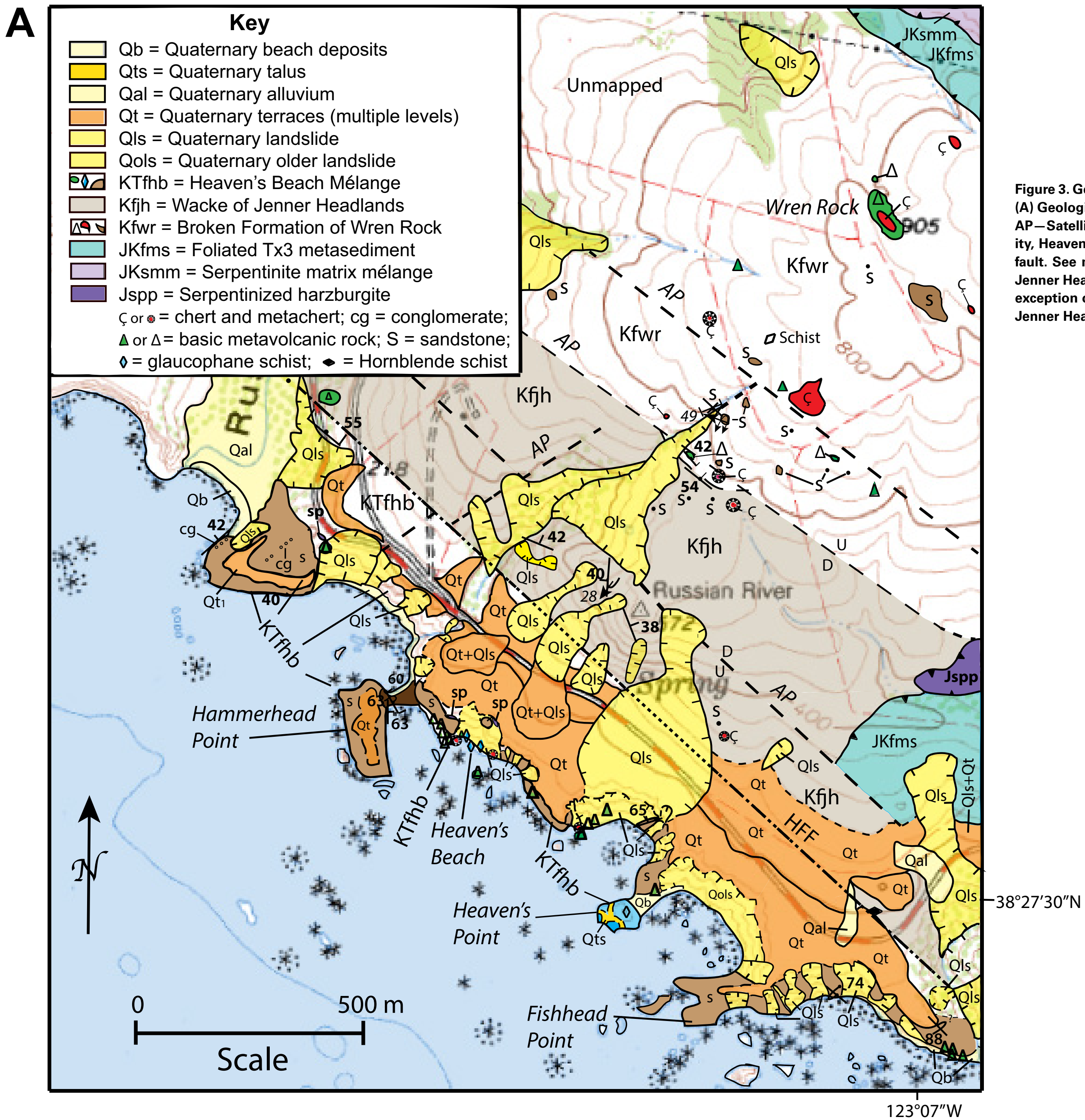

Figure 3. Geologic map and tectonostratigraphic column of the Russian Gulch–Hill 572/905 area. (A) Geologic map. Contacts along the eastern edge are based on reconnaissance by Bero (2010). AP—Satellite photo lineaments, some of which are recognized as small faults. The type locality, Heaven's Beach, of the Heaven's Beach mélange (KTfhb) is labeled. HFF—Headlands Front fault. See map key for additional labels. (B) Tectonostratigraphic column of the northwestern Jenner Headlands area, showing unit thicknesses. All units are fault bounded, with the possible exception of a local depositional contact of Broken Formation of Wren Rock (Kfwr) on Wacke of Jenner Headlands (Kfjh).

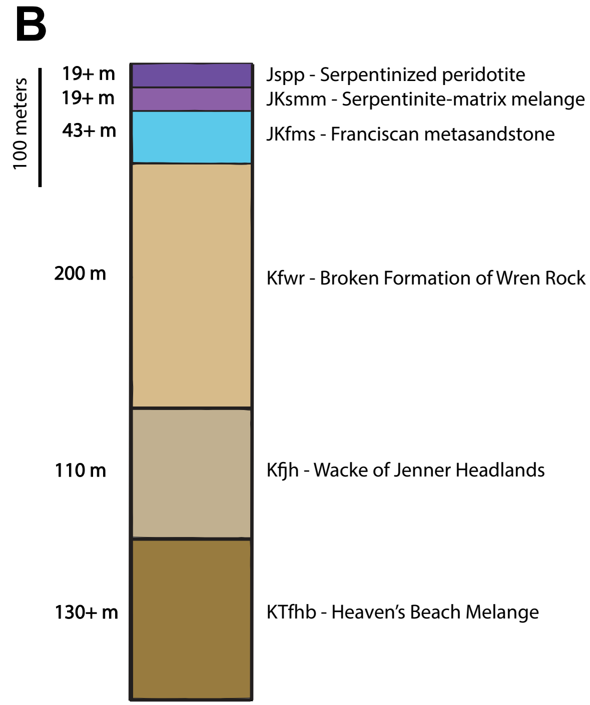

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Figure 4. View of "Wren Rock," facing north at Sonoma Headlands, showing a typical exposure of an exotic block—greenstone capped with chert in this case—surrounded by soil and lacking exposure of the contacts with surrounding rocks of the Broken Formation of Wren Rock (Kfwr). This body is shown as a red and green colored mass in the NE part of Figure 3A. The visible width of the base of the body is ~40 m.

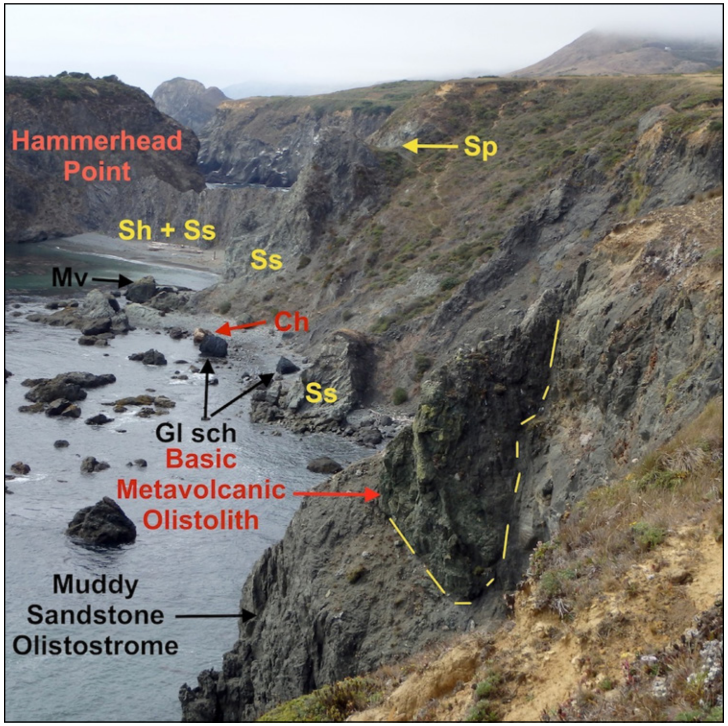

Figure 5. View of Heaven's Beach, the type locality of the Heaven's Beach mélange, facing northwest. The mélange consists of (1) various megablocks of submarine-fan–facies sedimentary rocks, including a block with bouldery-muddy-sandy-matrix olistostromal mélange beds with small to large blocks of chert and mafic metavolcanic rocks (e.g., lower right foreground); (2) blocks of mafic metavolcanic rock, chert and/or metachert, glaucophane schist and serpentinite; and (3) a superimposed, sheared sandstone-mudrock matrix with a shear-fracture tectonite fabric. On the upper left edge of the photo, a block of sheared, submarine-fan (SF) Facies A sandstone (Ss) and conglomerate making up Hammerhead Point is in contact to its east (right) with SF Facies D mudrock with minor sandstone. A small lens of serpentinite (Sp) is exposed to the east (right) near the saddle upslope from the SF Facies D rock and a large block of SF Facies A, amalgamated, coarse-grained, locally conglomeratic sandstone forming a promontory sticking up above the beach. The mélange was transformed into a landslide in the right middle ground (the landslide is decorated with a trail, above the glaucophane schist blocks). Ch—chert; Gl sch—glaucophane schist; Sh—shale.

turned boulder conglomerate and a stratigraphically underlying (structurally overlying) boulder, muddy, sandstone-matrix olistostromal mélange (Figs. 8A and 8B). Clasts in the olistostromal mélange include small to large clasts of red, green, and black chert, green basic metavolcanic rock, glaucophane schist, and gray to brown sandstone, some well-rounded and spherical and others angular and irregular. The largest, visible in situ olistolith within the olistostrome is a multimeter metabasite block exposed on a cliff face between Heaven's Point and Hammerhead Point (outlined in Fig. 5). We did not observe blocks of serpentinite in contact with olistostromal matrix; although exposures of serpentinite are in contact with sheared matrix in less well exposed settings along the cliff face.

The olistostrome-bearing megablock, like the other megablocks, is a megaclast in what is now a tectonic mélange, as evidenced by sheared matrix along megablock boundaries (e.g., Fig. 9A). Hence, there is a sedimentary (olistostromal) mélange precursor to a tectonic mélange. Clearly the former has contributed some blocks to the latter. A few exposures, some in landslides, reveal that some blocks of all sizes are bounded by sheared sandstone and shale mixtures (Figs. 9A and 9B). Inasmuch as the tectonic mélange contains serpentinite and large, breccia-rimmed glaucophane schist blocks not yet observed in the olistostrome, the latter blocks may have been introduced during tectonic mélange formation and associated mixing. Some glaucophane schist blocks have brecciated margins mantling inner gneissose Tx4 glaucophane rock, indicating that the glaucophane schist blocks had a

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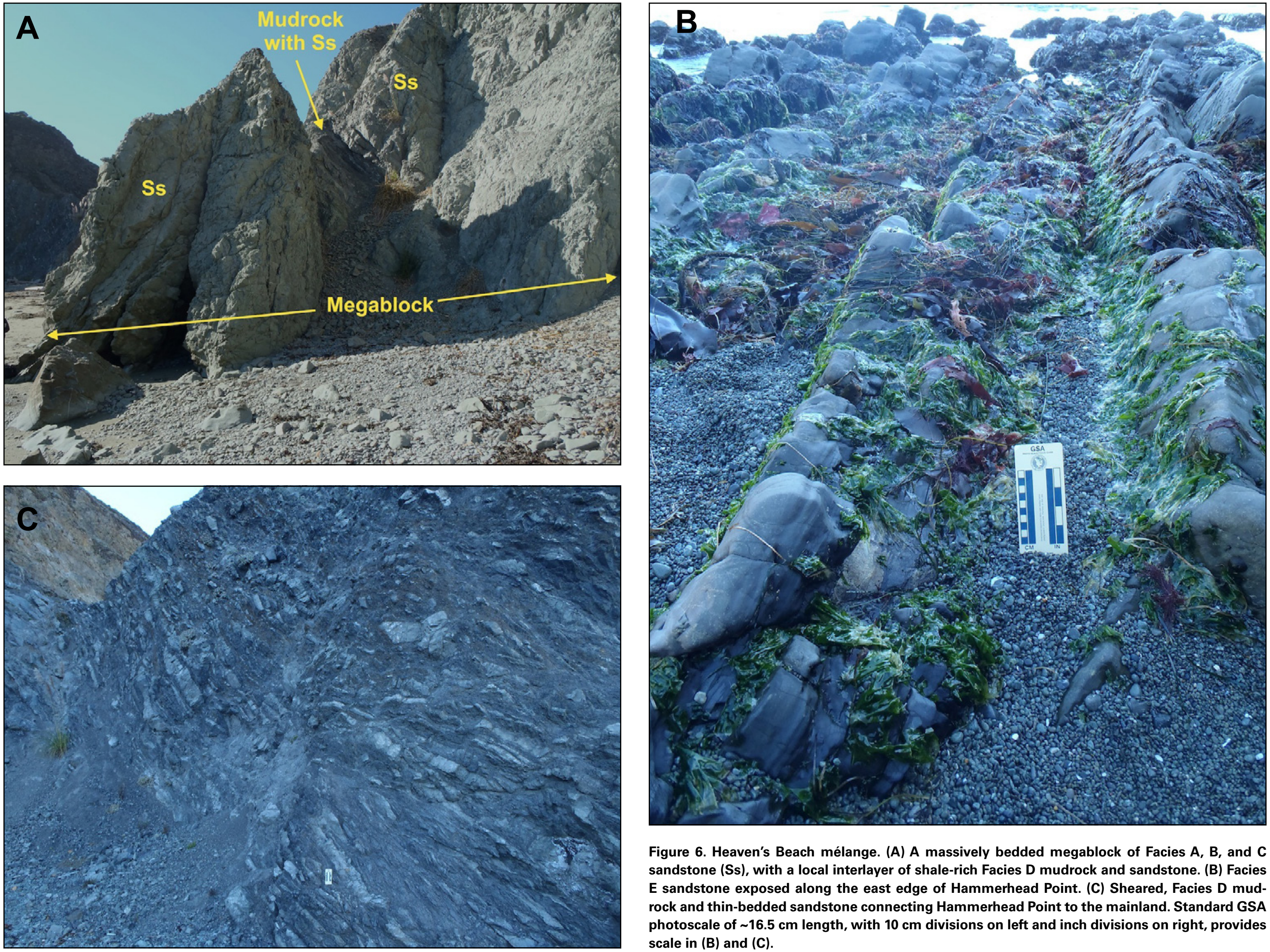

Figure 6. Heaven's Beach mélange. (A) A massively bedded megablock of Facies A, B, and C sandstone (Ss), with a local interlayer of shale-rich Facies D mudrock and sandstone. (B) Facies E sandstone exposed along the east edge of Hammerhead Point. (C) Sheared, Facies D mudrock and thin-bedded sandstone connecting Hammerhead Point to the mainland. Standard GSA photoscale of ~16.5 cm length, with 10 cm divisions on left and inch divisions on right, provides scale in (B) and (C).

multi-deformational history (see Raymond, 2014 for texture definitions). We interpret the megablocks of metaclastic rock and some glaucophane schist, plus additional similar, but smaller blocks of various types, to be megaclasts and clasts within a polygenetic mélange.

In summary, block-matrix contacts in the Heaven's Beach mélange commonly consist of a deformed, sheared sandstone-shale matrix juxtaposed against enclosed blocks and megablocks (Figs. 9A and 9B), but locally, within one layered megablock, an olistostrome contains blocks of chert, mafic metavolcanic rock, and glaucophane schist that are clearly enclosed as clasts within sediment and lack deformed contacts (Figs. 5 and 8C). These large clasts within the muddy sandy matrix of the olistostrome are interpreted to be olistoliths within the fluidized flow deposits of the inner-fan channels. One block

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Figure 7. View south over Heaven's Beach showing large block of glaucophane schist (Gl schist) forming tombolo in middle ground and Fishhead Point in the background.

of coarse-grained glaucophane schist is present in the conglomerate stratigraphically overlying (structurally underlying) the overturned olistostrome (Fig. 8D). Considering that the olistostrome is partially dismembered, blocks in the tectonic mélange may have come from the olistostrome or overlying conglomerate. Our present view is that some blocks of sheared serpentinite that form clasts, and some glaucophane schist blocks, are tectonic clasts, perhaps introduced during deformation. We do not know the source of the blocks. The glaucophane schist blocks observed on the beach do not contain the rounded erosional margins of the glaucophane schist clast in the conglomerate (Fig. 8D) (but neither do some olistoliths in the olistostrome), and the existing shear-fracture fabric of the serpentinite likely could not have survived transport as a clast in the olistostrome. Yet, it is possible that the fabric was imposed during later deformation. Some metabasite and metachert blocks are now tectonic blocks, but such blocks are common in the olistostrome; so that it is likely that fragmentation of the olistostrome unit yielded various blocks of these types to the developing tectonic mélange. Thus, exotic blocks in the mélange include both some tectonic blocks of unknown provenance and former olistoliths. There is little doubt that some clasts were eroded blocks that first became olistoliths and were later incorporated into the tectonic mélange.

The second geographic zone of the Russian Gulch–Hill 572/905 area is located northeast of the Headlands Front fault and is underlain just east of the fault by the Wacke of Jenner Headlands (Kfjh). No well-exposed stratigraphic section exists for this unit; so we have given it an informal name. Only a few exotic blocks exist on the slopes on the west edge of the unit, none are known in the middle, and a few are present near the top (on the east). The western blocks are either isolated olistoliths in inner-fan liquidized flow deposits or turbidites, or they are blocks that were introduced along the Headlands Front fault (a possibility, if the fault is a wider zone than we have mapped). No olistoliths were observed in the best exposures of clastic rocks in the Kfjh on the north side of Hill 572. One easily observed block of metabasite, however, is present near Russian Gulch, a few feet above Highway 1. That block lies just east of or within the Headlands Front fault zone. The contacts of the metabasite block are obscure here, but the block appears to be surrounded by metasandstone of the Kfjh. Exposures in road cuts of Highway 1 immediately to the south are marked by sheared metasandstone and scaly shale. Thus, the exotic blocks of metabasite (and similar blocks of chert) are either sparse blocks that are a part of the Kfjh, or they are blocks within the fault zone.

Clastic rocks of the Wacke of Jenner Headlands are almost entirely unmetamorphosed submarine-fan–facies rocks. On the north slope of Hill 572, locally folded exposures consist of submarine-fan Facies B, C, and E with beds of 2.5 cm to 50 cm thick likely deposited in inner-, mid-, to outer-fan channels, plus some Facies A of the inner-fan channels and basinal Facies G mudrocks (Fig. 10). Most of the rocks are medium- to coarse-grained lithic and quartz wackes with minor red and green chert grains, some biotite, and numerous black lithic clasts. No potassium feldspar is evident in studied thin sections. Two grains observed in thin section contain minute and unidentifiable internal needles that could be pumpellyite, but no other evidence of neoblastic metamorphic minerals was observed. A few conglomerates, but no olistostromes, occur in this unit.

East of the Kfjh, overlying it, and largely faulted against it along a high-angle fault, is a second wacke unit, the Broken Formation of Wren Rock (Kfwr). As is the case with the Kfjh, the Kfwr is rarely well exposed. Unlike the Kfjh, the Kfwr underlies a landscape locally decorated with clusters of large to small exotic blocks of metaigneous rocks, cherts, and wackes. Exposed rock adjacent to and between the prominent outcrops of the Kfwr is nearly nonexistent. The exposed clastic rocks that exist are generally nearly structureless, fine- to coarse-grained, Tx1 biotite- and chlorite-bearing, weakly metamorphosed lithic arenites, lithic wackes, and quartz wackes. Bedding is present locally. No alkali feldspar was observed in any thin sections studied. A few Tx2 rocks occur, notably near the eastern edge of the unit, where the unit underlies a thrust fault. Weak metamorphism is indicated throughout by minute pumpellyite (?) needles nucleated within grains and from grain margins. Calcite, chlorite, and white mica also occur as intragranular replacements in plagioclase feldspar.

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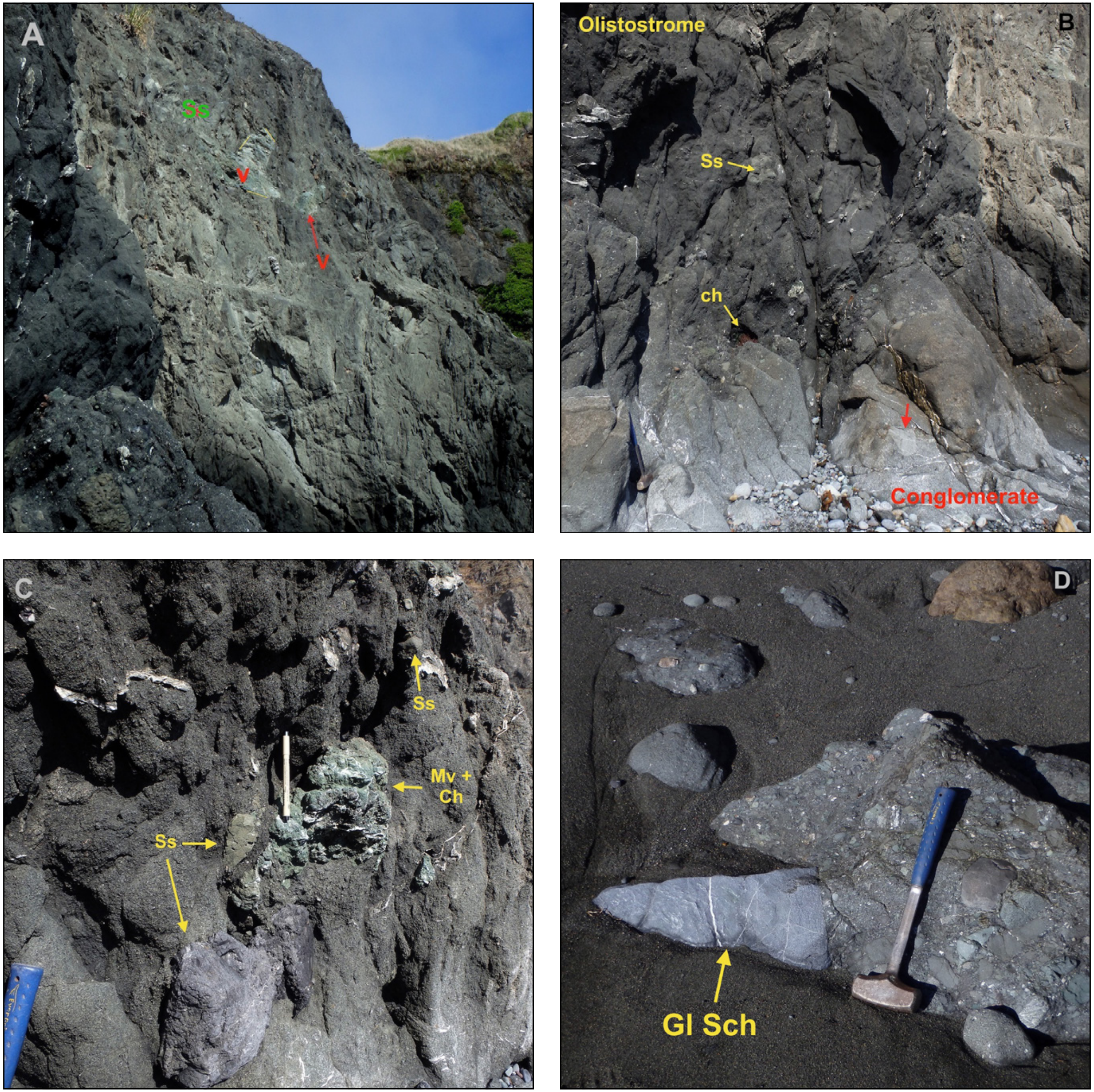

Figure 8. Olistostromal mélange comprising part of a clastic rock megablock in the Heaven's Beach mélange. (A) Olistostromal mélange (dark gray) with blocks of chert, mafic metavolcanic rock (i.e., v—light green in cliff face), and sandstone (i.e., Ss—gray in cliff face) in a muddy sandstone matrix. (B) Olistostromal mélange (dark gray) structurally overlying a boulder conglomerate (medium to light gray). At lower left, the hammer handle of ~32 cm in length provides scale. Note the generally structureless olistostrome matrix containing a variety of clasts and the rounded boulder in the conglomerate at the lower right (indicated by the red arrow). The irregular contact between olistostrome and conglomerate is noticeably offset by small faults. (C) Small blocks (clasts) of various rock types in muddy sandstone-matrix olistostromal mélange. Note the total lack of deformation on clast contacts, indicating their sedimentary history, and the range of rounding from well-rounded (Ss—sandstone in the upper right) to irregular and subrounded in the center to lower right. Mv—metavolcanic; Ch—chert. Pen (13.5 cm) at center provides scale. (D) Beach exposure of conglomerate with large, coarse-grained glaucophane schist clast (Gl Sch on left; blue colored).

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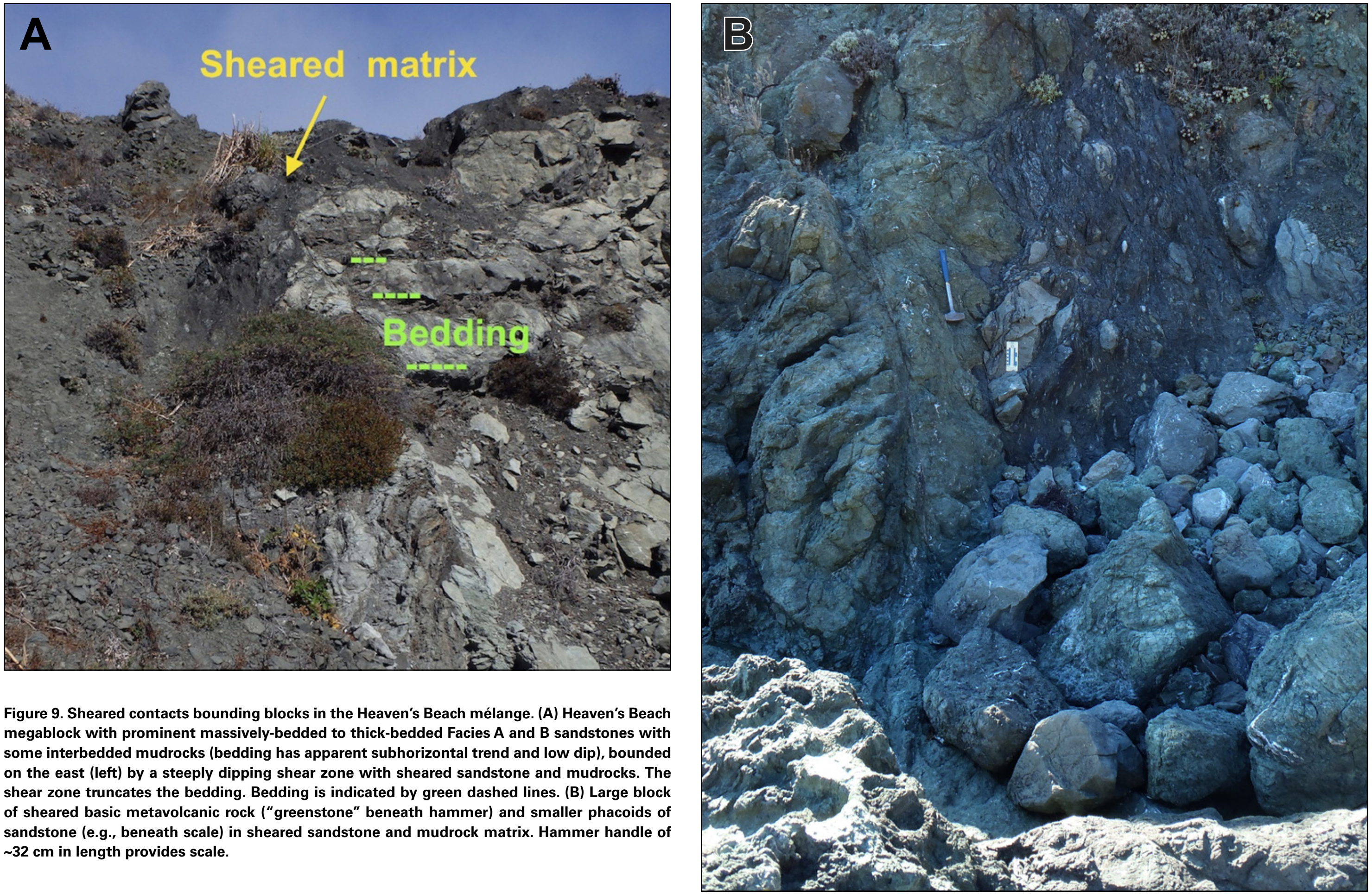

Figure 9. Sheared contacts bounding blocks in the Heaven's Beach mélange. (A) Heaven's Beach megablock with prominent massively-bedded to thick-bedded Facies A and B sandstones with some interbedded mudrocks (bedding has apparent subhorizontal trend and low dip), bounded on the east (left) by a steeply dipping shear zone with sheared sandstone and mudrocks. The shear zone truncates the bedding. Bedding is indicated by green dashed lines. (B) Large block of sheared basic metavolcanic rock ("greenstone" beneath hammer) and smaller phacoids of sandstone (e.g., beneath scale) in sheared sandstone and mudrock matrix. Hammer handle of ~32 cm in length provides scale.

In general, the rocks appear to represent submarine-fan Facies A or B sandstones. One shale-matrix, sandstone clast-bearing olistostromal rock occurs as a block (less than a meter in diameter), suggesting that some of the underlying rock is possibly olistostromal mélange. The only obviously exposed contact between block and matrix was observed in an exposure of a metasandstone block in a gully ~250 m west of the large chert mass on the ridge crest (see Fig. 3A). The block lies generally along the line of a small NE-trending fault. The matrix is sheared shale, and it contains green chert and basic metavolcanic rock clasts. The matrix, while apparently wrapping the block, has a strike that falls within a few degrees of the trend of the fault. As a result, the origin of the sheared shale matrix is moot. Wren Rock, in the northern part of the area, is a large, locally pillowed, mafic metavolcanic block with a cap of red, bedded radiolarian chert (Figs. 3A and 4). The contact between the block and the enveloping rocks is nowhere exposed. Also among the blocks at the surface level of exposure is a block of Tx3 (schistose) jadeitic metawacke with folded layers that define a mesoscopic, overturned anticline.

Considering (1) the olistolith-bearing units observed in the coastal exposures of submarine-fan complex rocks of the Heaven's Beach mélange, both

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Figure 10. Turbidites of the Wacke of Jenner Headlands (Kfjh). Beds include a small channel fill of Ta (basal turbidite) conglomerate at the middle right (above arrow) with well-rounded sandstone clasts to 2 cm in diameter, and overlying Tce and Tde turbidite beds (see Raymond, 2007, p. 262–265 for explanation). Beds face east with tops to the left.

at Heaven's Beach and to the south at Blind Beach near Goat Rock (this report; Wakabayashi, 2015) and (2) the presence of at least one block on the Kfwr landscape that has an olistostromal character, it is a reasonable possibility that the blocks scattered about the landscape above the Kfwr similarly represent olistoliths in olistostromal layers. What the nature of the matrix enclosing the blocks might be is unresolved because metasandstone dominates in blocks and soil chips, but muddy matrix is present on the margins of a few blocks. In short, whether or not this is a sandstone-matrix mélange, a sandstone-shale-matrix mélange, or a shale-matrix mélange is, at present, not clear. It is clear that submarine-fan–facies metasandstone and sandstone are the dominant rock types, respectively, of this unit and the Kfjh to the west.

An alternative hypothesis that we have considered for the exotic blocks is that, in the Kfwr terrain, the blocks resting on the surface have migrated downhill via landsliding and creep over the millennia of exposure from an uphill source. There is, however, no uphill source for abundant low-grade mafic metavolcanic rocks and chert, and these rock types plus sandstone are the most abundant. Hence, this possibility seems unlikely. We do know of two small blocks of blue amphibole-bearing rock present in a gully and on the slope, and these rocks may have been derived from the serpentinite-matrix mélange exposed at the hilltop, a mélange that contains blueschist- and eclogite-facies rocks, but relatively little chert and mafic metavolcanic rock. Because we have not observed glaucophane-rich rock in situ in the Kfwr unit, we simply do not know whether or not the blue amphibole-bearing blocks are foreign to the Kfwr or native to its possible olistostromal units.

The landscape mapped here and assigned to the Broken Formation of Wren Rock resembles many rock belts north of San Francisco Bay. These belts have been mapped in reconnaissance and are considered to be underlain by mélange (e.g., Blake et al., 2000; Blake et al., 2002). The terrain also resembles that in western Marin County, in part described below, reportedly underlain by thick, exotic block-bearing, olistostromal sandstone-matrix mélange (Prohoroff et al., 2012). Like those at other locales, the Hill 572/905 outcrops are inadequate to reveal all of the relationships between blocks and matrix.

Approximately 1–1.5 km southeast of Hill 572, along the general strike of Kfwr and Kfjh, blocks of glaucophane schist, hornblende schist, and eclogite occur locally on the slope and at the base of the wave-cut cliff below. These blocks, especially those exposed along Highway 1 and Jenner Beach to the south, are well known to geologists in California and elsewhere (e.g., Krogh et al., 1994; Anczkiewicz et al., 2004). We currently interpret these blocks to be "float" and landslide blocks derived from the "high-grade" block-bearing, serpentine-matrix mélange (SMM) exposed at the top of the ridge to their northeast (Bero, 2010).

FRANCISCAN GEOLOGY OF THE LIBERTY GULCH–AZALEA HILL AREA, WESTERN MARIN COUNTY

Northwestern Marin County has been the site of multiple studies of Franciscan regional geology. Both large- and small-scale published maps depict the geology in conflicting ways, and general agreement about the Franciscan Complex structure does not exist (Gluskoter, 1969; Wright, 1984; Blake et al., 2000; Prohoroff et al., 2012) The area is underlain entirely by rocks designated initially as Central belt Franciscan (Berkland et al., 1972). Because northwestern Marin County includes the Pine Mountain–Alpine Lake area used by Prohoroff et al. (2012) for a study that calls attention to sandstone-matrix mélanges and because the area includes rocks designated as both Central belt and Central terrane Franciscan, it is one of particular importance for examination of critical questions of mélange origins and architectural character and terminology within the Franciscan Complex. Within the Alpine Lake–Pine Mountain region, we have chosen a small but relatively well exposed area, the Liberty Gulch–Azalea Hill area, for a detailed examination of structural and sedimentological characteristics of Franciscan architecture.

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Geologic Perspectives of the Liberty Gulch–Azalea Hill Area

The general geology surrounding the Liberty Gulch–Azalea Hill area was mapped previously by Gluskoter (1969), Wright (1984), and Prohoroff et al. (2012), and is presently being mapped by one of the coauthors (Bero), providing the background for this report (Fig. 11). An overview of the geology in the larger region is presented by Blake et al. (2000). A number of significant differences exist among the various published maps (Table 1).

In the Pine Mountain region, Wright (1984) recognized a metaigneous rock unit dominated by serpentinite, plus three sandstone units, and he also mapped a chert unit, locally, in the Liberty Gulch area. The three sandstone units were arbitrarily subdivided, on the basis of geographic position, from what Wright considered to be a single sandstone body. He suggested that all the sandstones of the area are very similar petrographically, a view he supported with modal point-count data. The metaigneous rocks, mapped as a separate unit, are ultramafic. These ultramafic/ultrabasic rocks were considered by Wright (1984) to be both ophiolitic and intrusive. The major structural features of Wright's map are the igneous intrusions, major NW-SE–trending faults, and a large number of small ENE-trending faults (Fig. 11).

Interpretations distinctly different from those of Wright (1984) are presented by Gluskoter (1969) and Prohoroff et al. (2012). Gluskoter (1969) depicted the general region containing the Liberty Gulch–Azalea Hill locale, as containing a syncline-anticline pair, and although he did not discuss the specific relationship between serpentinite (and gabbro) and the metaclastic rocks, he showed the serpentinite as a layer within the stratigraphic section, with sandstones above and below. Based on petrography, Gluskoter (1969) lumped all the sandstones of the Liberty Gulch–Azalea Hill area together as a single lithic wacke and arkose "zone" of the "Franciscan Formation." In broad terms, the map and cross section of Prohoroff et al. (2012) are similar to those of Gluskoter (1969), but the structural and stratigraphic interpretations are more complex. Prohoroff et al.

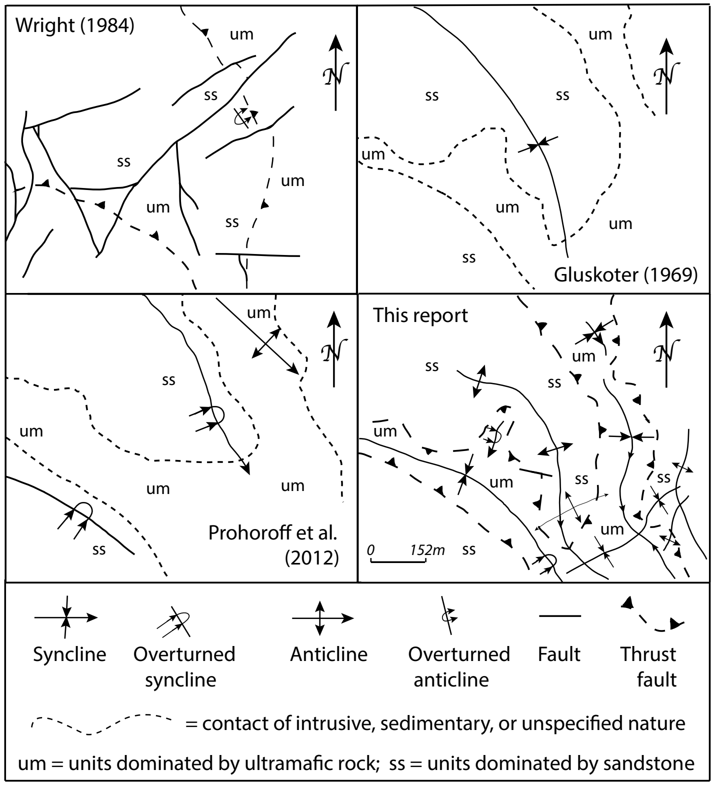

Figure 11. Comparison of major and some minor structures on various maps of the Liberty Gulch–Azalea Hill area.

TABLE 1. COMPARISON OF MAPPED DETAILS IN THE LIBERTY GULCH AREA

Feature (below)	Gluskoter (1969)	Wright (1984)	Blake et al. (2000)	Prohoroff et al. (2012)	This study
Mappable formational units	2	4	2	2	2 (with 4 mappable members in one)
Mappable Franciscan clastic units	1	2	0	1	4
Mélanges	0	0	1	1	2*
Structures	One tight, nearly symmetrical syncline.	NW-trending thrust faults; Several NE-trending faults; some minor folds, including one local west-vergent overturned antiform; NW-trending intrusive contacts.	NW-trending thrust and high-angle faults.	2 west-vergent, overturned NW-trending synclines with 2 adjoining anticlines; ultramafic rocks with fault at base and depositional contact above.	2 major NW-trending open to overturned synforms and 1 intervening antiform; thrust fault beneath metaigneous rocks; minor NE-trending folds; small mesoscopic folds and faults; shear-fracture fabric.

*The serpentinite matrix mélange may not be mappable at the 1:24,000 scale but is locally mappable at the 1:6000 scale.

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(1) mapped foliated serpentinite bodies with massive serpentinized peridotite capping several ridges; (2) considered the serpentinites to mark the cores of anticlines; and (3) described the serpentinites as interleaved within the tectonostratigraphic sequence between structurally underlying and stratigraphically overlying olistostromal sandstone-matrix mélanges. The serpentinite is considered by Prohoroff et al. (2012) to be a nappe emplaced structurally and derived from the underlying subducting plate, rather than an intrusion.

In the broader region, Prohoroff et al. (2012) mapped a somewhat coherent sandstone unit and three thick sandstone-matrix mélanges as a tectonostratigraphic stack with some internal sedimentary contacts. From the top down, the sequence described by them consists of a thick olistostromal sandstone-matrix mélange deposited on an underlying serpentinite that is faulted against the underlying sequence of sandstone-matrix mélanges and other rocks. Between two lower mélanges, Prohoroff et al. (2012) mapped a large metabasite unit—designated as Nicasio Reservoir terrane—structurally underlying some mélange and a coherent sandstone unit. Various olistostromal sandstone-matrix mélanges were distinguished by block content rather than statistically-based petrography; although Prohoroff et al. (2012) do suggest that there are differences in the lithic content of the different sandstone units. They also provide detrital zircon data from four sandstone-bearing units that reveal two dated rocks to be 120–122 Ma in age, one to be 100 Ma in age (their Kfm1w unit exposed in the Liberty Gulch–Azalea Hill area), and one with a 90 Ma age, indicating that although the rocks of the region may be petrographically similar, they are of significantly different ages. Blocks of metachert and metabasite are mapped as particularly abundant near the structural base of their structurally highest Kfm1w unit that they consider to overlie the serpentinite above a depositional contact. The matrix of the olistostromal mélanges is said to exhibit “minimal strain.” The major structural features depicted by Prohoroff et al. (2012) are regional west-vergent thrust faults, folded thrust faults, and overturned folds (Fig. 11). None of the local ENE-trending faults mapped by Wright (1984) are depicted on the Prohoroff et al. (2012) map. The area of study of this report includes a single (meta)sandstone-metashale unit previously assigned to an eastern “zone” by Gluskoter (1969), to both western and central (meta)sandstone units by Wright (1984), and to a sandstone-matrix, olistostromal mélange unit (Kfm1w) by Prohoroff et al. (2012).

All of the maps, including ours, show the serpentinite bodies to be NW-SE–trending bodies. In contrast to the maps of others, we find that the serpentinites are commonly synformally folded, generally ridge-capping, and structurally overlying the sandstone-dominated tectonostratigraphy (Fig. 12). A few small faults like those depicted by Wright (1984) are present, but regional folds highlighted by the serpentinites and the thrust faults underlying the serpentinites are the dominant structural features of the regional map (Fig. 12A).

The Liberty Gulch–Azalea Hill area encompasses a NW-trending, SE-plunging, synform-antiform-synform structure (Figs. 11 and 12). This area is shown on the Gluskoter (1969) map as a single NW-trending syncline, with an anticline to the east of the Azalea Hill–Liberty Gulch area and the synclinal axis in sandstone approximately following an unnamed drainage between Pine Mountain Road and Liberty Gulch (Figs. 11 and 12B). As noted, the Prohoroff et al. (2012) map of the area also depicts the area as a structurally folded domain, but with the dominant folds shown as overturned, west-vergent synclines, with anticlines within the serpentinites on the limbs of the synclines and with axial traces of the synclines within the sandstone unit. Thus, the Prohoroff et al. (2012) map, like that of Gluskoter (1969), has a metasedimentary unit in the axial region of the major synclinal fold; but rather than the somewhat symmetrical syncline depicted by Gluskoter (1969) as generally centered along the unnamed drainage, Prohoroff et al. (2012) show the fold axis as overturned toward the southwest, with the axial trace located northeast of the drainage line and near the west edge of the serpentinite body exposed along Pine Mountain Road (Fig. 11). Where Gluskoter (1969) depicts an anticline northeast of the Liberty Gulch–Azalea Hill area, Prohoroff et al. (2012) show a syncline.

Our detailed map of the geology of the Azalea Hill–Liberty Gulch area (Fig. 12B) is grossly similar in rock distribution to those of previous workers (Figs. 11 and 12), but the details differ. As we show, the mesoscopic details reveal a much more complex structural and sedimentological picture than has been presented previously. In contrast to all previous maps, our map depicts the serpentinite-rich rocks as constituting a locally ridge-capping, synformally folded unit that is thrust over the tectonostratigraphic pile of Franciscan rocks (Figs. 12A and 12B). Syncline axial traces are centered on ultramafic bodies, and anticlinal axes generally fall within the areas underlain by sedimentary and metasedimentary rocks.

Detailed Geology of the Liberty Gulch–Azalea Hill Area

The area of detailed study is in the Liberty Gulch–Azalea Hill area of the Pine Mountain–Alpine Lake region of western Marin County and covers ~0.85 km^2 (Fig. 12B). It stretches from the northwest slope of Azalea Hill west to the drainage of Liberty Gulch. Although the area is small, it includes excellent exposures along Fairfax-Bolinas Road, and it contains two of the major units mapped by Prohoroff et al. (2012), as well as major units previously mapped by Gluskoter (1969), Wright (1984), and Blake et al. (2000). The major units here, as described by Prohoroff et al. (2012), are a Cretaceous, structurally highest olistostromal sandstone-matrix mélange (their Kfm1w) and the serpentinite (sp) of eastern Pine Mountain Road (and its correlative to the south).

Several important questions can be addressed by a detailed study at this locality. Of particular interest are issues of mélange character, including “exotic” block distributions, the block-matrix relationships, and the general nature of mélange units. In addition, inasmuch as Prohoroff et al. (2012) suggest that Kfm1w rests depositionally on the serpentinite, we reassessed the sedimentary lithofacies of the Kfm1w, the nature of the contact between the Kfm1w and the sp, and the structural position of the sp within the tectonostratigraphy. Many serpentinite and serpentinized peridotite bodies in the broader region, notably at Tiburon Peninsula to the southeast and at Jenner Headlands to the northwest (Fig. 1), are structurally high units (Bero, 2010, 2014) rather than

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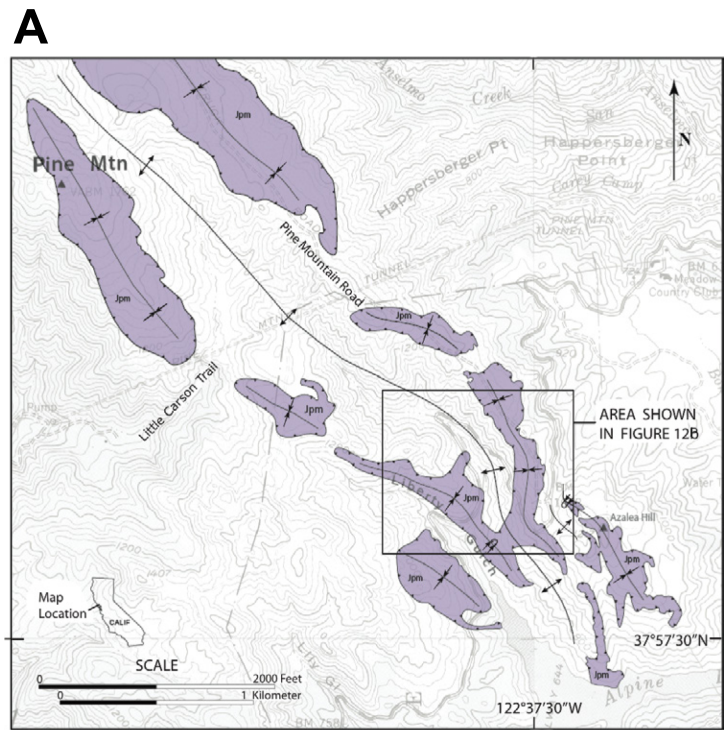

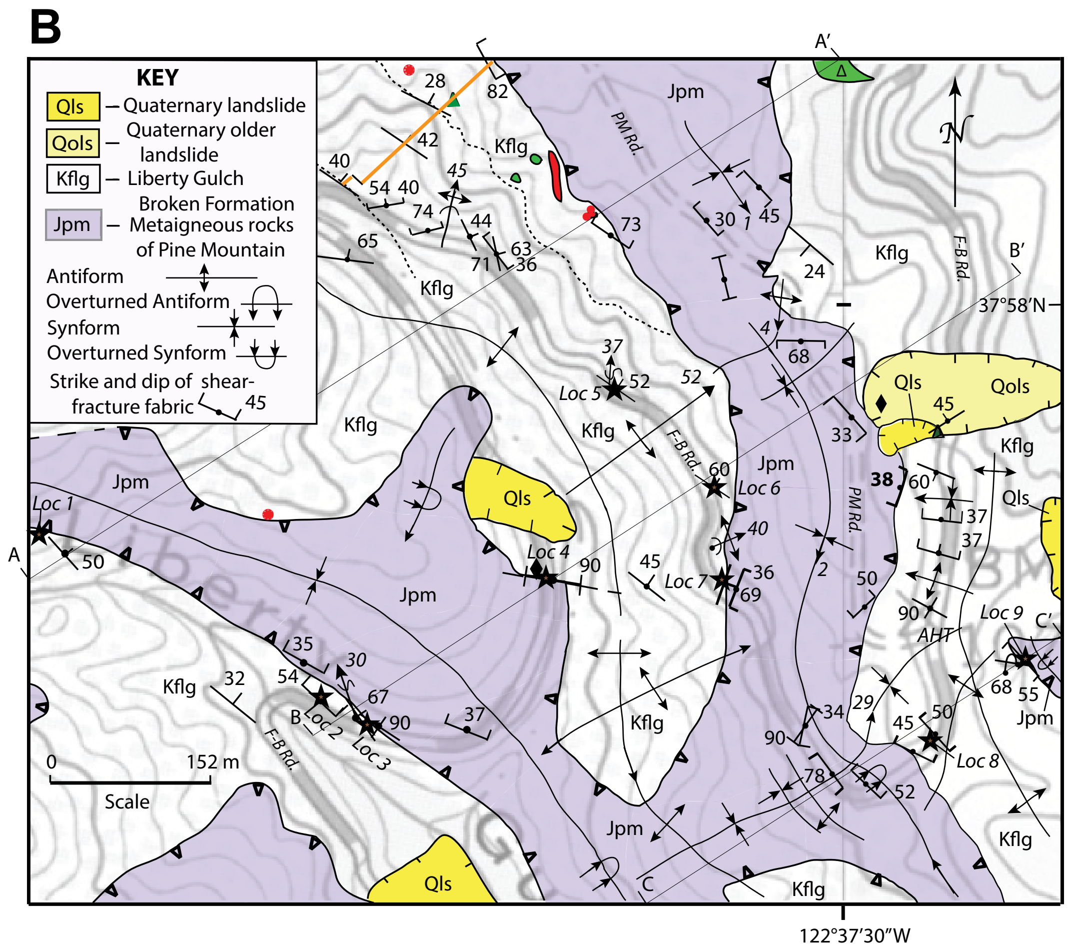

Figure 12. Geologic maps of the Liberty Gulch–Azalea Hill area and region. (A) Reconnaissance map of ultramafic rock distribution of the Pine Mountain region, showing ultramafic rocks exposed within the axes of synclinal folds and distinguished from underlying units. Structure symbols same as in Figure 11. (B) Detailed geologic map of the Liberty Gulch–Azalea Hill area. Red areas are chert blocks, and green bodies are basic metavolcanic rock, with other symbols as on Figure 3. The orange line is the line of the measured type section. Other symbols are standard geologic symbols for strike and dip of bedding and thrust faults (faults with barbs). AHT—Azalea Hill trailhead and parking area; PM Rd.—Pine Mountain Road; F-B Rd.—Fairfax-Bolinas Road. Dotted lines in NW are stratigraphic trend lines for members of the Liberty Gulch Broken Formation.

interlayers within a Franciscan sequence, as reported for the Pine Mountain Road serpentinite by Gluskoter (1969) and Prohoroff et al. (2012); so we sought evidence to confirm the structurally different position of the serpentinite in western Marin County. The structural character of the Kfm1w is also of interest, because reconnaissance observations revealed numerous mesoscopic folds, faults, and sheared rock zones within the unit, in contrast to Prohoroff et al.'s (2012) description of the unit as relatively undeformed. Finally, we were interested in the relationship between the larger structures in the serpentinite, with its internal shear-fracture structure, and those within the Kfm1w. The structural details provide a view of accretionary complex architecture.

Map Units and Contacts

Other than surficial Quaternary alluvium and landslide deposits, the Liberty Gulch–Azalea Hill area contains two units. These units we here designate as the Metaigneous Complex of Pine Mountain (Jpm) and the Liberty Gulch Broken Formation (Kflg). Our mapping reveals that both units are structurally complex and that the Jpm structurally overlies the Kflg along a thrust fault contact.

Within the map area, the Metaigneous Complex of Pine Mountain (Jpm) consists predominantly of serpentinite, including some blocky serpentinized peridotite. Three structural forms of serpentinized metaultrabasic rock are

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present. The dominant rock is scaly, shear-fractured serpentinite (SFS) (Fig. 13A). The rock consists of slickensided flakes or lenses of serpentinite that commonly can be further subdivided easily into smaller, similar fragments. Large bodies dominated by this rock type theoretically could be mapped as shear-fractured serpentinite dismembered formation (SF-SDF). The second structural form is that of blocky serpentinized peridotite (BSP) (Figs. 13B and 14A). The rock is characterized both by block-shaped fragments of serpentinized peridotite with bastite grains reflecting a probable harzburgite protolith and by some cross-fracture structure (cf. O'Hanley, 1996, p. 52). The blocks are enclosed in a SFS matrix. The blocks with cross-fracture structure exhibit veinlets of serpentine subdividing larger blocks into submeter-scale polygons of less altered rock. On the edges of the blocks, spheroidal weathering and exfoliation tend to render the blocks into more rounded shapes (Fig. 14A). The progression from more cubic to rounded forms is revealed by various blocks in different stages of tectonic deformation and weathering. Between these blocks there are generally open spaces at the surface and more scaly forms of serpentinite at depth. The appearance of the BSP ranges from nearly block supported to matrix supported.

The third form of serpentinite is serpentinite-matrix mélange-like rock (SMM). It is presently unclear whether or not bodies of this rock are mappable in the broader Liberty Gulch–Pine Mountain area, and if not, since mappability is part of the definition of mélange (Raymond, 1984), the SMM cannot be formally designated as a mélange. Unlike the SMM at localities such as Ring Mountain on the Tiburon Peninsula, where numerous and varied exotic blocks are present in the mappable SMM (Wakabayashi, 2013; Bero, 2014), at the Liberty Gulch–Azalea Hill locality, the only blocks recognized in the scaly serpentine-matrix mélange are blocks of coherent, schistose serpentine tectonite (Figs. 13C and 14B). At Sunol Regional Wilderness in the Diablo Range to the southeast and at Ring Mountain, on Tiburon Peninsula (Fig. 1), similar blocks composed of antigorite serpentine tectonite occur in a matrix of shear-fractured lizardite (Wakabayashi, 2011; Bero, 2014). Although we observed no types of tectonic inclusions other than serpentinite tectonite in our small map area, at least one large glaucophane schist block surrounded by serpentinite crops out on the flank of Pine Mountain to the north of our study area. That block is a "high-grade" block that is closely associated with the SMM-type rocks. Blake et al. (2000) depict two high-grade blocks at serpentinite-metaclastic rock contacts south of the Liberty Gulch–Azalea Hill area, but Prohoroff et al. (2012) show no exotic blocks within the serpentinite. We observed two relatively small glaucophane schist blocks, one in the northeastern part of the study area (also mapped by Prohoroff et al., 2012), in a small landslide just below the Jpm-Kflg contact, and the other surrounded by sheared metaclastic rock adjacent to the contact at locality 4 along the Fairfax-Bolinas Road (Fig. 12B). Clearly, the high-grade blocks are sparse, rather than abundant and seem to occur near the Jpm-Kflg contact. In most cases, the exotic blocks are not clearly within the SMM-like rocks. The two glaucophane schist blocks we mapped may be exotic blocks within a shale-matrix mélange that locally, directly underlies the Jpm serpentinite, but present exposures preclude resolution of this matter.

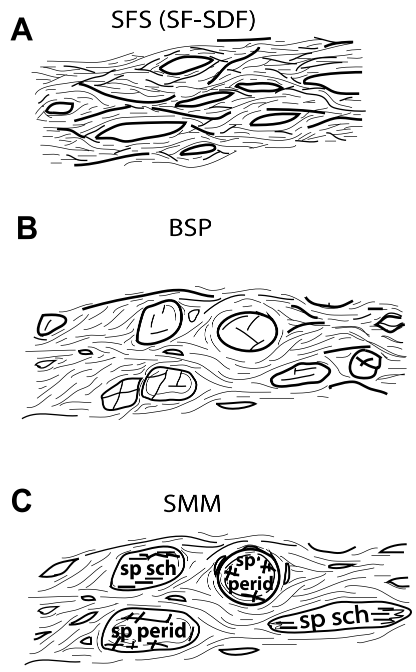

Figure 13. Sketches of structural types of serpentinite in the Pine Mountain Metaigneous Complex. (A) Shear-fractured serpentinite (SFS) and shear-fractured serpentinite dismembered formation (SF-SDF). (B) Blocky serpentinized peridotite (BSP). (C) Serpentinite-matrix mélange (SMM). Sp sch—serpentine schist; sp perid—serpentinized peridotite.

The Liberty Gulch Broken Formation is a broken to dismembered, submarine-fan unit. The rocks are slightly metamorphosed, but the protoliths were dominantly inner-fan channel sandstone turbidites and fluidized flow deposits, locally separated by a few shale interbeds, with some sections dominated by mid- to outer-fan mudrocks cut by local channel sandstones (Fig. 15). The section presented here in Figure 15 was measured in the northwestern part of the map area along a gully tributary to a major unnamed gulch eroded by a tributary to the Liberty Gulch stream (Fig. 12B). The measured section is considered to be the type section of the Liberty Gulch Broken Formation. We acknowledge at the outset that the unit contains many beds and subsections that lack lateral continuity across the region, but this is a function of complex mesoscopic sedimentation patterns overprinted by extensive, similar scale shearing, faulting, and folding of the unit. In addition, we note that the stratigraphic base of the unit was not observed within the map area. Its structural base may lie a short distance down section in soil-covered areas or to the west in Lily Gulch, where Prohoroff et al. (2012) suggest a possible fault.

Most submarine-fan facies types are present within the Kflg section. In good exposures along Fairfax-Bolinas Road, submarine-fan facies A, B, D, E, and F are clearly present (Fig. 16). Facies F is represented locally in the Kflg section by olistostromes, rocks of particular interest to this study. Some

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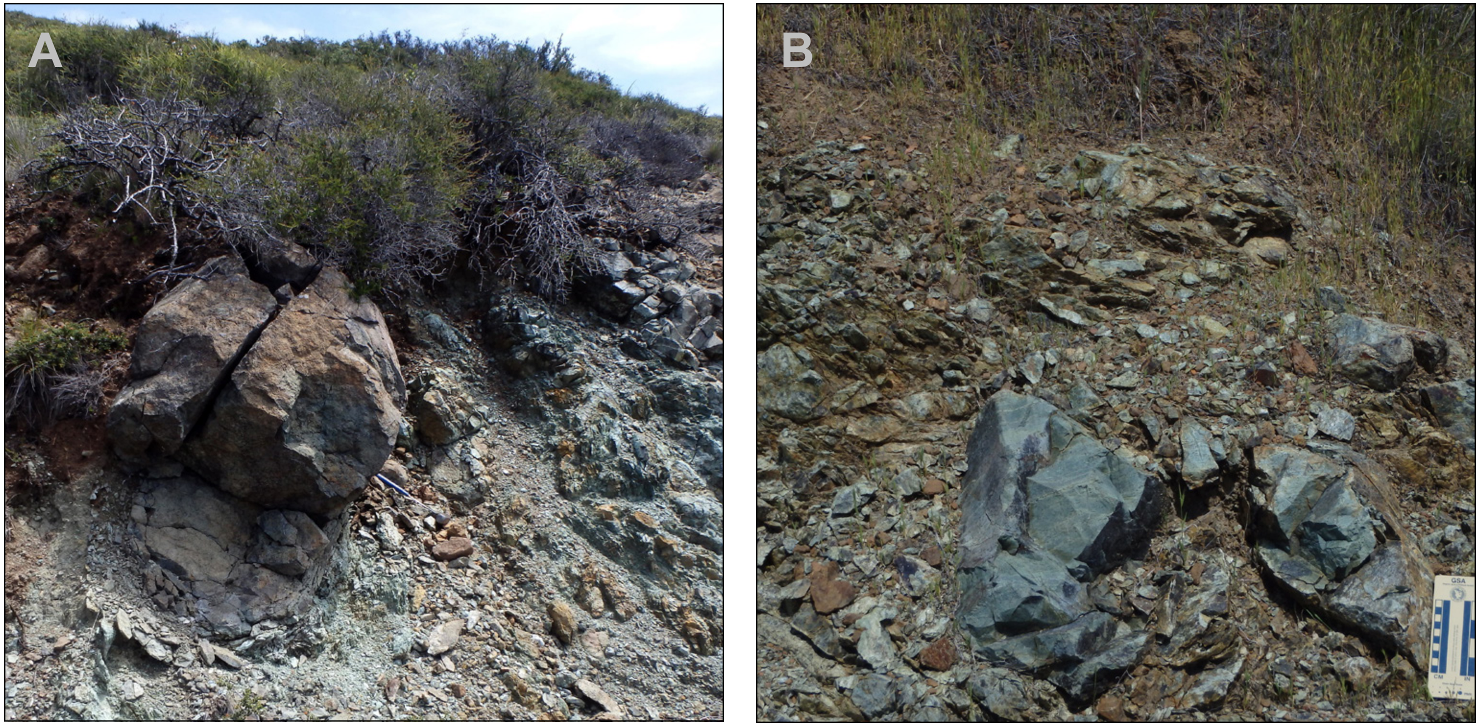

Figure 14. Photographs of structural types of serpentinites in the Pine Mountain Metaigneous Complex. Compare to Fig. 13. (A) Blocky serpentinized peridotite (BSP) along the Fairfax-Bolinas Road WNW of Azalea Hill. Note the rounding resulting from serpentinization and weathering in situ at the lower left on the base of the large serpentinized peridotite block. (B) Serpentinite-matrix mélange (SMM) containing a block of unfractured coherent serpentinite tectonite exposed along the Fairfax-Bolinas Road WNW of Azalea Hill. Note that foliation in the block of serpentinite tectonite (lower left) dips away and to the left. In contrast, the dominant foliation in surrounding shear-fractured serpentinite matrix dips to the right.

olistostromes containing a few well-rounded pebbles and cobbles of igneous rocks and cherts, occur as relatively thin (<2-m-thick) muddy sandstone-matrix layers—notably at localities 2 and 6 (Figs. 12B, 16B, and 16C). In addition to the thinner olistostromes, a 35-m-thick, tectonized, shale-matrix olistostromal mélange caps the stratigraphic section southwest of Pine Mountain Road (Figs. 12B, 15, and 17D). We observe that Facies F olistostromes occur primarily as multiple smaller beds rather than as the single, extremely thick olistostromal unit reported by Prohoroff et al. (2012). We also note that the olistostromes of the Kflg have a range of matrix compositions from mudrock to muddy sandstone.

In addition to Facies F olistostromes, both the type section and road exposures contain other fan facies. The parts of the section representing inner-fan channels include, in addition to the Facies F olistostromes, abundant Facies A and B thick-bedded to massive sandstones with little internal structure, plus some beds that arguably can be assigned to Facies C. The latter consist of archetypical Bouma sequences with interbedded mudrocks. In some sections, fan lobe and mid- to outer-fan lobe channel deposits of interbedded shale and thin-bedded sandstone dominate (Facies D with some Facies C and E).

The type section of the Liberty Gulch Broken Formation can be divided into four members (Fig. 15). These are unnamed and are designated as members 1, 2, 3, and 4. The uppermost member (member 1), which commonly, structurally underlies the serpentinite body, is a 35.2-m-thick, shale-matrix mélange. Empirically, we observe that the mélange contains meter-scale exotic blocks of subrounded to rounded red, green, and white chert and metachert, basic metavolcanic rock, plus exotic or native blocks of (meta)sandstone (Fig. 16D). Locally, some blocks of metasandstone contain centimeter- to decimeter-scale layers and clasts of green chert and other rocks that have relatively undeformed clast-matrix boundaries (Fig. 16E). Some large blocks of red chert also appear to occur with undeformed contacts within sandstone, but the contacts range from poorly exposed to locally sheared and are equivocal. The undeformed block-matrix contacts clearly indicate that clasts were incorporated in sandstone hosts via a sedimentary depositional process.

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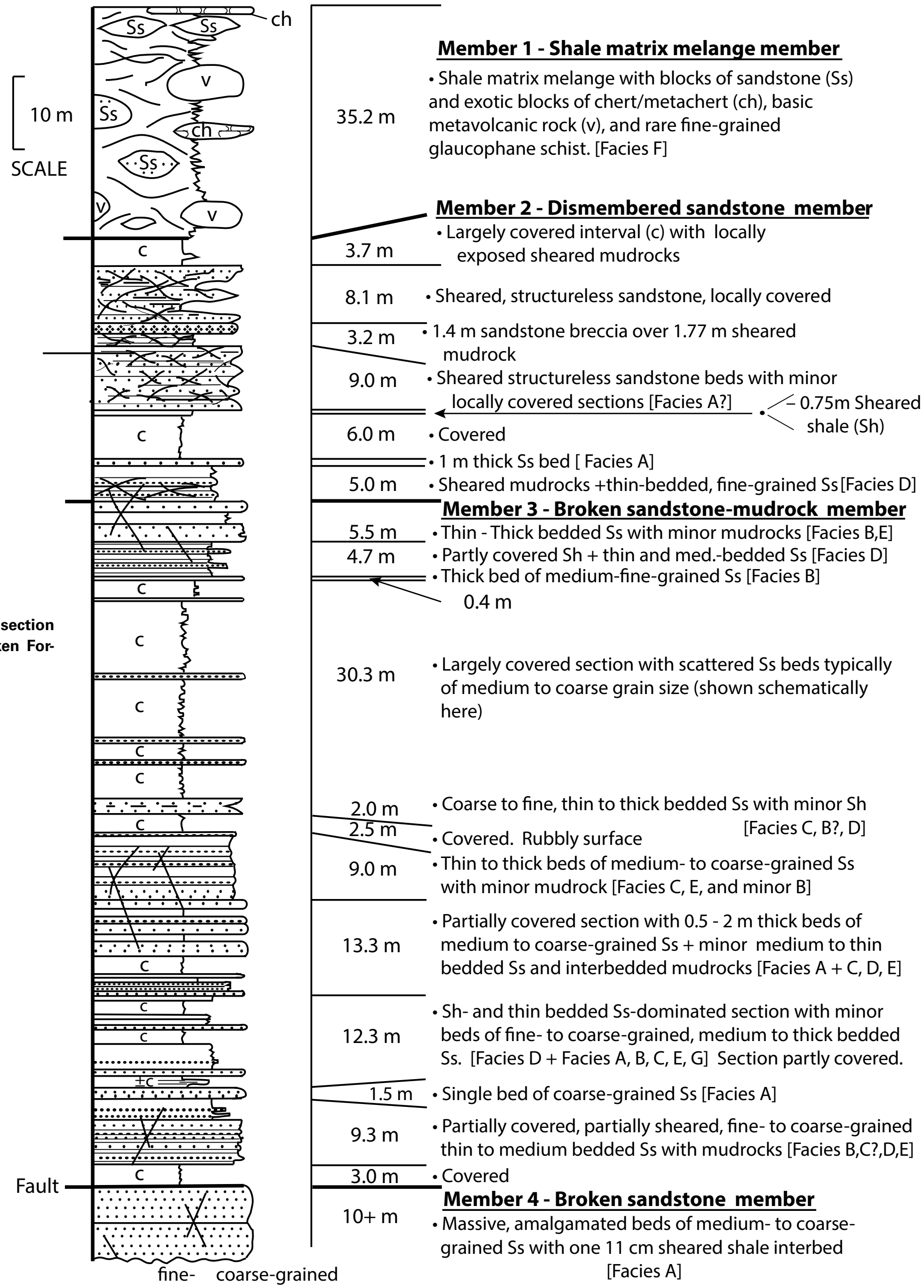

Figure 15. Measured, type section of the Liberty Gulch Broken Formation; c—covered.

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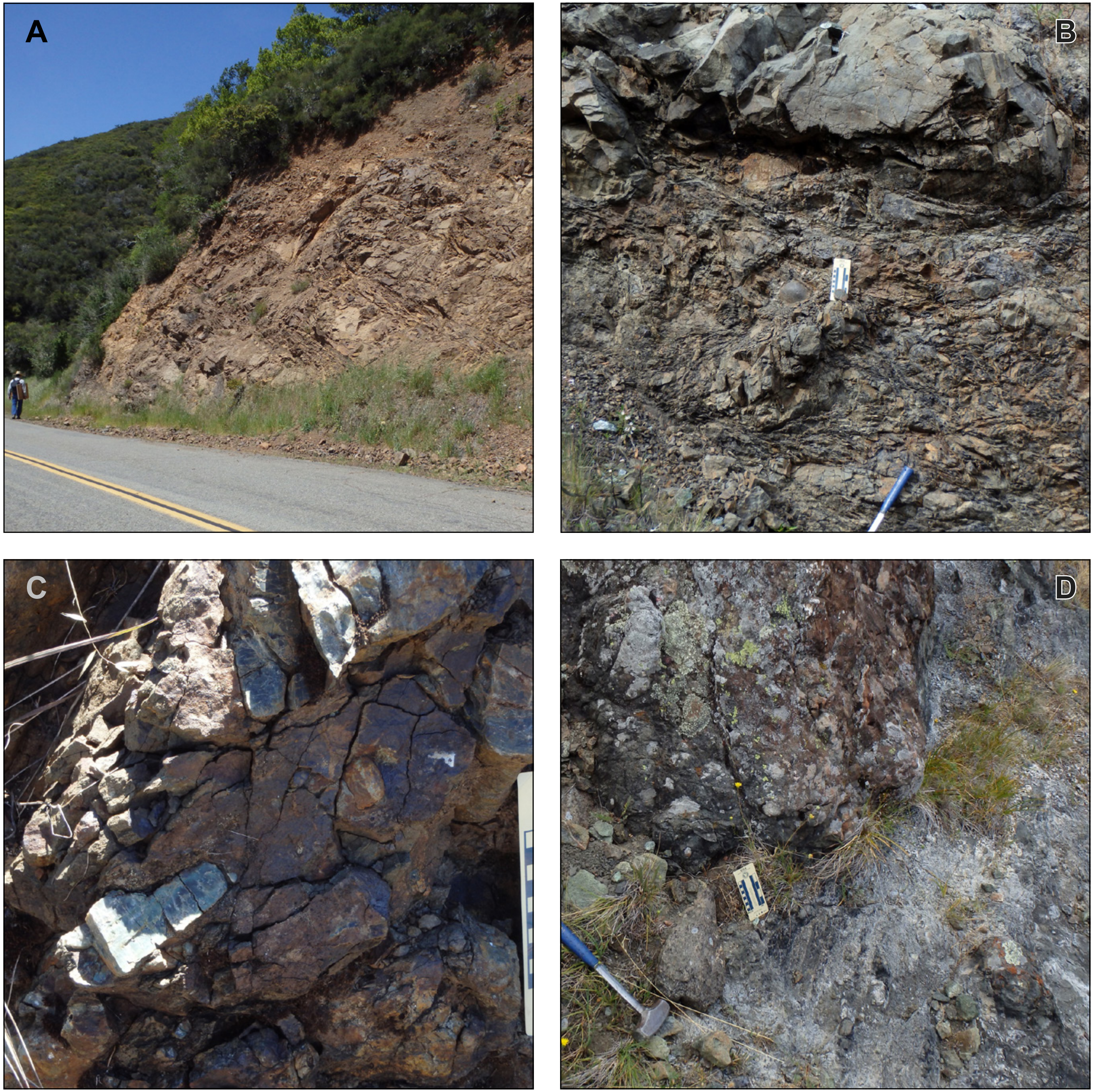

Figure 16 (*on this and following page*). Photographs of submarine-fan rocks of the Liberty Gulch Broken Formation along Fairfax-Bolinas Road and the type section. (A) Thick to massive submarine-fan Facies A and B beds with interbedded thin Facies D and E beds along Fairfax-Bolinas Road. Note second author at left on road for scale. (B) Rounded clast (directly left of scale) in sheared, muddy sandstone-matrix olistostrome containing well rounded clasts and blocks of Facies B, thick-bedded sandstone, locality 2, Fairfax-Bolinas Road. (C) Rounded green chert clasts in thick bed of muddy sandstone-matrix olistostrome, locality 6, Fairfax-Bolinas Road. (D) Large block of metasandstone surrounded by sheared black shale in shale-matrix mélange, member 1 of the Liberty Gulch Broken Formation. Block is one of several that form a prominent line of exposures, just below the contact between the Liberty Gulch Broken Formation (Kflg) and the Metaigneous Complex of Pine Mountain (Jpm), at the top of the measured section.

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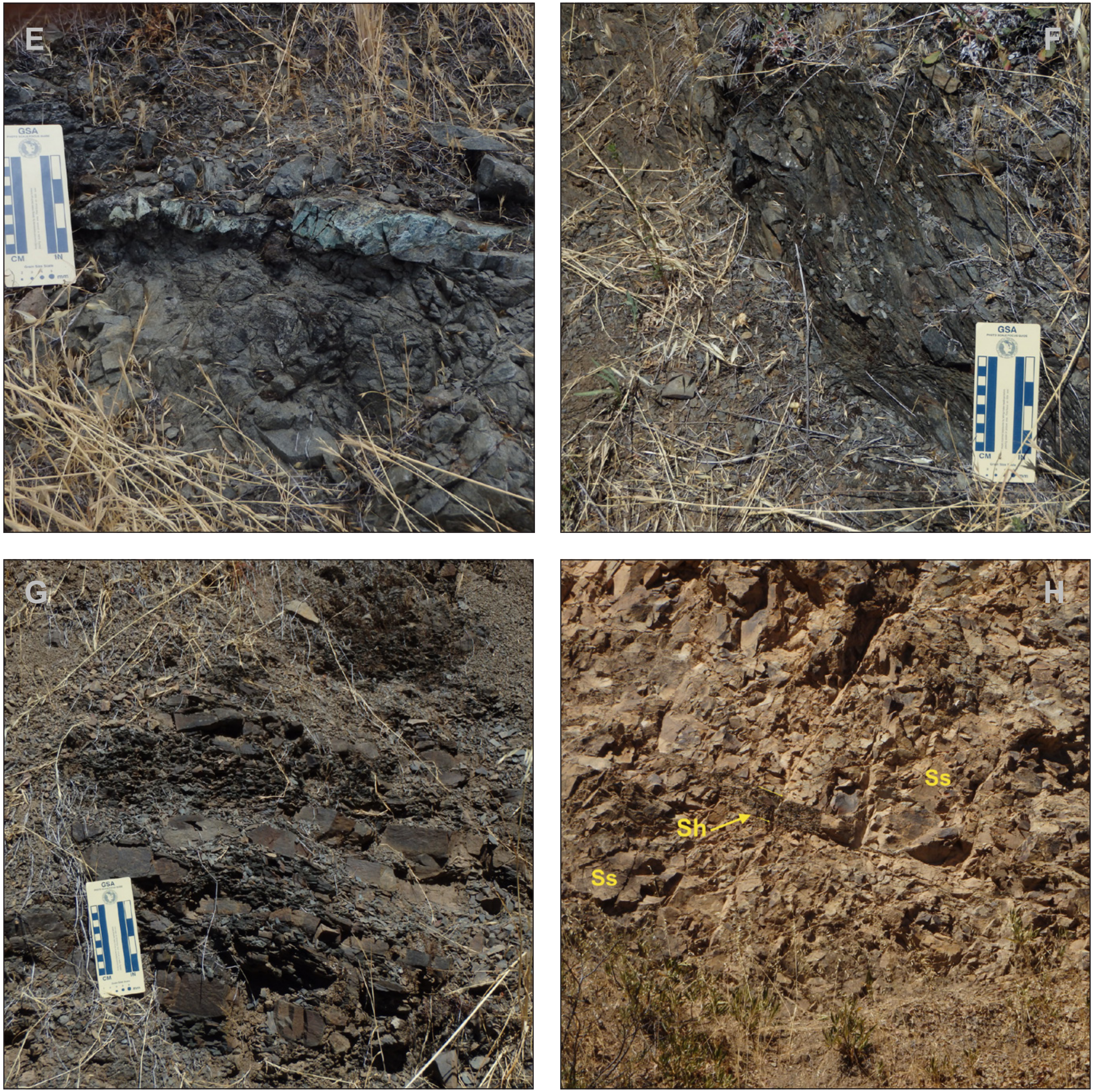

Figure 16 (*continued*). (E) Slab of green chert that forms a clast within a sheared sandstone block in shale-matrix mélange of member 1 of the Kflg. (F) Sheared sandstone and mudrocks of indeterminate facies in member 2 of the Liberty Gulch Broken Formation, exposed just above the base in the measured section. (G) Member 3, Facies D mudrocks with thin-bedded sandstones, exposed at the gully confluence just NE of the Fairfax-Bolinas Road along the line of the measured section. (H) Two massively bedded (amalgamated?) and fractured sandstone (Ss) beds of Facies A separated by a 10-cm-thick bed of fractured and faulted mudrocks (above arrow) in member 4 of the Liberty Gulch Broken Formation. Exposures are located along the Fairfax-Bolinas Road at the SW end of the measured section line. Sh—shale.

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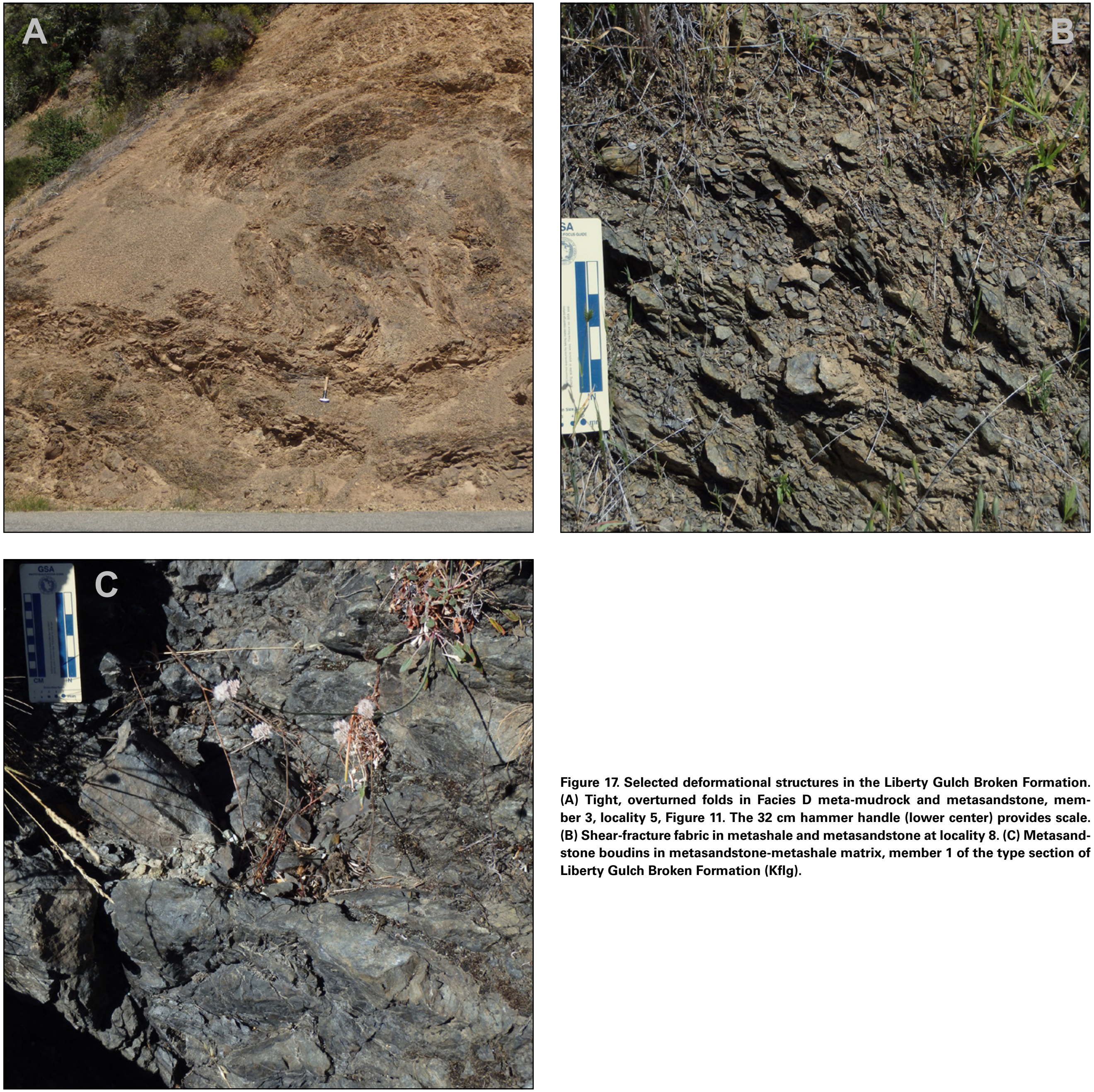

Figure 17. Selected deformational structures in the Liberty Gulch Broken Formation. (A) Tight, overturned folds in Facies D meta-mudrock and metasandstone, member 3, locality 5, Figure 11. The 32 cm hammer handle (lower center) provides scale. (B) Shear-fracture fabric in metashale and metasandstone at locality 8. (C) Metasandstone boudins in metasandstone-metashale matrix, member 1 of the type section of Liberty Gulch Broken Formation (Kflg).

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In contrast, the larger host sandstone blocks have sheared margins and are clasts within the shale-matrix mélange that is member 1 (cf. block in Fig. 16D). The sheared margins that encircle well-exposed blocks plus the almost pervasively sheared matrix indicate that the shale-matrix mélange has undergone tectonic deformation. The structural and sedimentological features are reminiscent of those of the Heaven's Beach mélange (described above), in which unequivocally olistostromal bouldery beds are parts of a stratigraphic section that has been disrupted by subsequent tectonic deformation. If the sedimentology and structure are similar, the pre-deformation section of member 1 initially had more mudrock than did that of the Heaven's Beach mélange, but like the Heaven's Beach mélange, the member 1 shale-matrix mélange is polygenetic. Thus, considering its structural position, internal sedimentological features, and tabular nature, we interpret member 1 to be a part of the stratigraphic section, likely representing one or more submarine-fan channel debris flow(s) yielding one or more olistostromes. This member and some of the underlying member 2 were subsequently sheared, in part at least, during thrust fault emplacement of the rocks of the Metaigneous Complex of Pine Mountain over the Liberty Gulch Broken Formation. Recalling that (1) the only unequivocal exotic elements of the mélanges are mafic metavolcanic and chert/metachert blocks observed as clasts and blocks in the less deformed parts of the olistostromes and (2) excepting folding in chert, the clasts in undeformed olistostromal rocks exhibit little deformation, it is reasonable to consider that early fragmentation of protolithic units yielding exotic blocks was an erosional and sedimentary process. Yet, it is also possible that tectonism played a role. Clearly, mixing was both sedimentary and tectonic. Hence, in summary, the shale-matrix mélange is polygenetic, because it, like other olistolith-bearing units within the section, at least in part, had an olistostromal sand- and mud-matrix mélange protolith.

Member 2 of Kflg, stratigraphically underlying the shale-matrix mélange member, is a sheared sandstone-shale unit (Fig. 16F). Examination of the rocks to the west suggests that this unit may not have lateral continuity for any great distance, but at the site of the measured section, the member consists of 32.3 m of sheared sandstone and subordinate sheared mudrocks. Where visible, most sandstone beds are amalgamated Facies A or B sandstones, but thinner bedded sandstones are also present. Pervasive fracturing of the rocks obscures evidence of primary sedimentary structures. At the base of this member, five meters of sheared, Facies D mudrock with thin-bedded sandstone underlie a single Facies A sandstone and a section concealed by soil.

Member 3 of the stratigraphic section is the thickest at 96 m. It consists of a mix of beds but is dominated by fan lobe and interchannel submarine-fan Facies D and E sandstones (Fig. 16G), with interspersed, commonly individual beds of Facies A, B, and C channel sandstone. Because more easily weathered mudrocks are more abundant in this part of the section, some parts of the section are concealed by soil and rock rubble. The base of member 3 is faulted.

Member 4, interpreted to underlie member 3, is juxtaposed against member 3 along a high-angle fault present in a road cut along Fairfax-Bolinas Road. The road cut lies west of the gully in which the section was measured. Member 4 consists of amalgamated channel sandstone beds of Facies A (Fig. 16H). In the road outcrop, two 5-m-thick beds are separated by a thin, truncated and sheared shale layer. To the west, additional sandstones occur along the gulch, and these may underlie the two amalgamated sandstone layers, which would make member 4 much thicker than shown in Figure 15; however, the relationships are unclear.

In summary, the Liberty Gulch Broken Formation (Kflg), as a whole, is not a single olistostrome, but is a submarine-fan section that does contain thinner, now sheared, olistostromes that are commonly interbedded with fan channel sandstones of Facies A and B and it contains thick, polygenetic shale-matrix olistostromal mélange at the top of the section. Examples of rounded clasts in the olistostromes are present at several localities. For example, at locality 2, as noted, a sheared olistostromal bed containing sparse, well-rounded clasts of igneous rock, is interbedded with fan channel deposits. A similar olistostromal bed with a 20 cm cobble of hypabyssal igneous rock occurs at locality 6, where the olistostrome also contains chert and small to large metasandstone blocks. At the northern edge of the map area, some chert blocks greater than 3 m in diameter and a large metabasite block occur west and east, respectively, of the Jpm unit, and their size suggests that in this area, the enclosing olistostrome is member 1. We noted no overturning or repetition of members, observations in direct conflict with the suggestion of Prohoroff et al. (2012) that overturning exists between the bottom of Liberty Gulch and the base of the serpentinite along Pine Mountain Road.

Our petrographic observations are consistent with the point counts presented by Gluskoter (1969) and Wright (1984), whose data plot in the lithic wacke field of the modified Dott classification (Dott, 1964; Raymond, 2007, p. 282). Substantially higher quartz and generally higher lithic fragment content are reported by Gluskoter (1969) than by Wright (1984) and our observations are more consistent with those of Gluskoter. In addition, we note the distinctive and common presence of biotite in these rocks. Biotite, as well as chlorite, was reported by Prohoroff et al. (2012). These authors also call attention to the presence of serpentinite grains in some sandstones, an observation consistent with our own. Serpentinite grains are not abundant, but were observed in members 1 and 3. In member 1, pebbly glauconitic sandstones form a few distinctive blocks. The rocks are dominantly Tx1 (epiclastic-textured rocks), but locally Tx2 to Tx3 (semi-schistose to schistose) metasandstones are present in the more deformed parts of the unit. Rare neoblastic pumpellyite, reported by Prohoroff et al. (2012), is visible in thin section on some grain margins and within quartz and feldspar grains.

Discussion of Metachert and Metabasite Blocks and the Olistostromes

Several metachert and volcanic metabasite blocks within the geographic areas of Kflg exposure were mapped by Prohoroff et al. (2012) and by us (this report). On the Prohoroff et al. map, the blocks are decidedly more common near the Jsp-Kflg contact. The blocks are considered by Prohoroff et al. to be olistoliths within a relatively undeformed, relatively thick, sandstone-matrix

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mélange. Our mapping indicates, however, that most large blocks are confined to the relatively thin, deformed stratigraphic unit, member1, of the Kflg. Our reconnaissance suggests that the latter observation is characteristic on the regional scale.

We searched for block-matrix contacts and examined contacts where we could find them in order to better understand the block-matrix relationships. Most blocks, like the large metabasite at the northeast edge of the map (Fig. 12B), are surrounded by soil that conceals the contact (as was the case at Jenner Headlands within the Broken Formation of Wren Rock). A large metabasite block in the second western mélange of Prohoroff et al. (2012) and at some distance from our study area is cited by them as having minimal strain in the surrounding (meta)sandstone matrix, indicating its olistolithic character. In contrast, in the type section (at the north edge of our map; Fig. 12B), large elliptical sandstone phacoids are clearly enveloped by sheared shale (Fig. 16D). Nearby, chert masses and basic metavolcanic blocks seem to be entrained in the sheared shale matrix below the Jpm-Kflg contact. A metachert body exposed north of the study area along Pine Mountain Road, similarly occurs below the contact and similarly exhibits a well-exposed and clearly sheared contact in a roadside ditch. Member 1 does contain metasandstones containing small to large blocks of red chert that appear to have undeformed contacts and lack significant sheared shale at their boundaries, and although these exhibit some fractures, they appear to be olistoliths deposited as clasts rather than blocks inserted tectonically. Yet, poor exposures render the blocks inconclusively sedimentary. In contrast, small chert blocks in members 1 and 3 that are unequivocally enclosed in sandstone matrix with absolutely no deformation at the contacts, are undisputedly sedimentary clasts, as are the well-rounded clasts associated with them.

In a general sense, our observations support the view of Prohoroff et al. (2012) that blocks of exotic rocks (cherts, metabasite ["greenstone"], and perhaps some glaucophane schist) are enclosed within olistostromal beds of the Franciscan Complex—here specifically, olistostromes of the Liberty Gulch Broken Formation. The matrix of these mélanges, however, ranges from mudrock to sandstone. Although some exotic blocks are clearly encased, without deformed contacts, in sandstone of perhaps fluidized flow origin, others clearly occur in sheared sandstone, sheared mudrocks, or both.

The abundance of exotic blocks near the Kflg-Jpm contact may be explained by one of two possibilities. First, olistostrome beds may be more abundant near the top of the section, as is the case in the measured section (Fig. 15), and the top of the section may be commonly associated with the Jpm-Kflg contact. Alternatively, numerous exotic blocks may be derived from a tectonically thinned, SMM or shale-matrix mélange that is not widely or well exposed, but occurs at the base of the Jpm unit (like the mélange underlying the metaultrabasic rocks on Tiburon Peninsula; Bero, 2014). To date, we have found no exotic blocks in SMM-like rocks other than exotic serpentinite tectonite, which suggests little support for the second of these hypotheses. While we do note that one glaucophane schist body on Pine Mountain to the north of Figure 12B is partially surrounded by Jpm rocks, we currently favor the first of these hypotheses.

Structural Geology of the Liberty Gulch–Azalea Hill Area

Structurally, the Liberty Gulch Broken Formation (Kflg) is highly deformed. Deformational features include regional folds to mesoscopic (outcrop, multi-meter-scale) folds, local minor mesoscopic faults to larger faults that may have a more regional dimension, and mesoscopic shear-fracture fabric (S_1) at the outcrop and hand specimen level. Folds with wavelengths of meter to decimeter scale are notable locally (e.g., locality 5, Fig. 12B; Fig. 17A). Some are closed to tight and overturned, whereas others are open, upright structures. Faults and shear zones of microscopic to mesoscopic scale are widely distributed. Shear-fracture fabric is notable in the matrix of some deformed, shale-matrix olistostromal beds, but is also evident in local parts of exposed sections of sandstone and mudrock (Fig. 17B). Many typical outcrops contain (meta)sandstone beds, as well as masses of interbedded (meta)sandstone and shale that have shear-fracture fabric and exhibit boudinage or pinching of bed ends (Fig. 17C). These deformed rocks structurally underlie a regional thrust fault that separates the Jpm from the Kflg.

The thrust fault contacts between Kflg metasedimentary bodies and Jpm metaultrabasic rocks are well exposed at several locations. We have selected six localities to highlight the structural relations, and these are marked on Figure 12B as localities 1, 3, 4, 7, 8, and 9. The westernmost locality is locality 1 in Liberty Gulch. Here, Jpm serpentinite lies uphill from exposures of Kflg metasedimentary rocks. The strike of the contact is roughly parallel with that of the gulch and the dip is low, but variable, so that the contact appears in two-dimensional view to be nearly horizontal (a similar relationship exists in western parts of the exposures at locality 3, Fig. 18A). The strike of the underlying (meta)sandstone-(meta)shale beds is more northerly, the dip is ~50° NE, and the beds trend into the sheared, but relatively sharp contact, where they are truncated against serpentinite. The contact at locality 3 is located along the road east of the location where Bolinas-Fairfax Road crosses the stream channel of Liberty Gulch. The contact at this locality is clearly a folded or curviplanar shear zone that truncates bedding in the underlying metaclastic units (Fig. 18A). A one-third to 2-m-wide zone of brecciation, mixing, folding, and shear-fracture deformation occurs at the Jpm-Kflg contact. Shear-fractured serpentinite dominates the Jpm serpentinite body structurally up section. Locality 4 is ~200 m northeast of locality 3 along Bolinas-Fairfax Road on the northeastern contact between Jpm and Kflg. At this locality, the contact is a sharp vertical line between sheared serpentinite and sheared metaclastic rocks. The contact is interpreted to be one of the small, high-angle faults that trend generally E-W across the area. Alternatively, the contact may simply be folded into a vertical position. Shearing at the contact is also evident at locality 7 on the lower contact of Jpm due west of the Azalea Trailhead parking area (AHT on Fig. 12B; Fig. 18B). At this locality, a 0.7-m-long block of sheared, but locally well bedded and laminated (meta) sandstone with interbedded (meta)shale (Ss-Sh), plus several other blocks of rock, mark a 1- to 2-m-wide, serpentinite-rich shear zone separating metasedimentary rocks below from serpentinite above. The long dimension of the Ss-Sh block parallels the contact zone, as does the general shear-fracture fabric in both overlying Jpm and underlying Kflg.

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Figure 18. Exposures of the thrust fault contact between the Metaigneous Complex of Pine Mountain (Jpm) and Liberty Gulch Broken Formation (Kflg). (A) View of the serpentinite-sedimentary rock contact near locality 3 east of Liberty Gulch. Sedimentary beds below the contact trend into the contact and are truncated. Sheared serpentinite occurs above. (B) The Jpm-Kflg contact at locality 7. Here a 0.7 m block of sheared metasandstone and metashale occurs within the sheared contact zone. Note the elliptical shape of the dark brownish-gray Sandstone-shale (Ss-Sh) block. The 32 cm handle of the hammer on the block provides scale. (C) Sheared serpentinite, meta-mudrock, and metasandstone (Mss) at the Jpm-Kflg contact along the trail east of the Azalea Hill Trailhead (locality 9, Fig. 11). The contact zone dips to the right (west), but local shear fractures dip east within this broader zone. Note the lenticular phacoid of serpentinized peridotite (Spp) in the upper left.

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At two locations, anomalous contact relations were observed. Like the contact exposures described above, the contacts are shear zones. The exposure at locality 8, due south of the Azalea Hill Trailhead along the Fairfax-Bolinas Road, at a drain pipe excavation, shows east-dipping sheared sandstone and shale that structurally overlies (rather than underlies) Jpm serpentinite to the southwest. The structural relations here are unusual, in that the dip of shear-fracture fabric in both serpentinite and Kflg sandstone and shale is to the northeast, placing the serpentinite structurally beneath the clastic rocks. Similar relationships occur at the easternmost site, locality 9, located in the fire road/trail east of the Azalea Hill Trailhead. Here, a 1- to 2-m-wide shear zone with blocks and boudins of serpentinite and metawacke separates the Jpm and Kflg (Fig. 18C). Foliation at this locality locally dips southwest, putting the serpentinite, exposed to the east, structurally beneath the sedimentary rocks of Kflg, a relationship that Prohoroff et al. (2012) suggest is typical and depositional. The shear zone exhibits considerable variation in the strike of the sheared serpentinite fabric, but the contact in the road exposure has an attitude of approximately N63°W 70°SW; whereas a block of overturned Facies C sandstone with an attitude of N81°W 68°SW strikes into the contact. Considering the local relationships described above (supported by the overturned sandstone), the contact is overturned at this locale. Hence, prior to overturning, the serpentinite was structurally above the sedimentary rocks. Localities 8 and 9 are the only exposures we have found in the region with serpentinite structurally below the clastic rocks. This unusual structural situation yields an unusual cross section that must result from local refolding or faulting. We depict the former in cross section C of Figure 19.

Clearly, the contact between Jpm and Kflg is everywhere a sheared (faulted) contact, and its commonly low dip and configuration suggest that it is a thrust fault. At all but localities 8 and 9, the serpentinites structurally overlie the metasedimentary rocks. Even at locality 9, the distribution of serpentinite in the surrounding area suggests that the reverse relationship in the fire road is a very local dip reversal, perhaps associated with the nearby superimposed NE-trending fold or easterly-trending small fault. Across the region, the details of the structure above and below the contact indicate that a discordance exists, so that structures such as tight to overturned mesoscopic folds below the con-

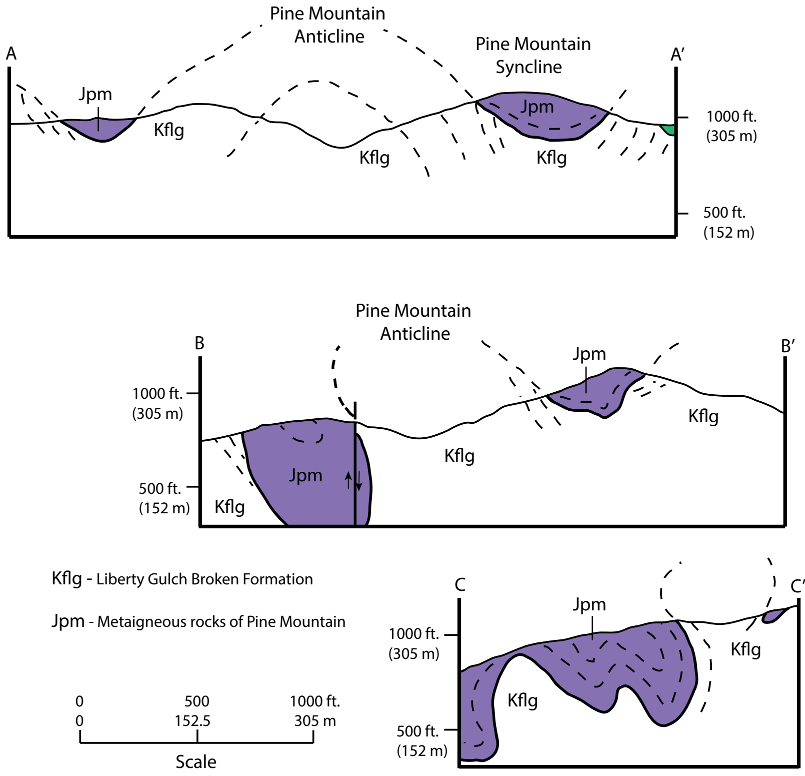

Figure 19. Cross sections A–A′, B–B′, and C–C′ across the Liberty Gulch–Azalea Hill area (see Fig. 12B for section lines). Note the discordance between the Metaigneous Complex of Pine Mountain (Jpm) and the Liberty Gulch Broken Formation (Kflg).

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tact within the Kflg are not present above the contact in the Jpm serpentinites. Furthermore, in the northern part of our map, the members of the Kflg (the trend of which is indicated by dotted lines on Fig. 12B) strike more westerly than the Jpm and appear to pass beneath the Jpm, reappearing to the east.

In examining the structure of the area, we walked and mapped nearly all parts of the contacts of all mappable units, and we measured attitudes on bedding (S_0) and shear-fracture fabrics (S_1)—both S_0 and S_1 in the Liberty Gulch Broken Formation and S_1 in the metaigneous rocks of Pine Mountain (the serpentinite). Our mapping shows that the Jpm metaultrabasic rocks nearly everywhere structurally overlie the Kflg metasedimentary rocks (Fig. 19). We note that Wright (1984), Blake et al. (2000), and Prohoroff et al. (2012) all show the serpentinite-rich unit commonly capping ridges, as do we. If the metaigneous rocks either intruded or were folded up from below, erosion should cut more deeply into the Jpm unit; yet we note that to the northwest of the Azalea Hill–Liberty Gulch study area and southeast of Pine Mountain, the ultramafic body appears to be breached, where deep erosion by a tributary to Kent Lake in the vicinity of the Little Carson Trail cuts through the Jpm (Fig. 12A, cf. fig. 3 of Prohoroff et al., 2012). This structural relationship indicates that the serpentinite is not only ridge capping, but is not rooted beneath the ridges.

We used stereographic analyses of bedding (S_0) and shear-fracture fabrics (S_1) of Liberty Gulch Broken Formation and S_1 of the serpentinites to evaluate some structures in the area. Figure 20 provides two stereograms. Orientations of minor folds and faults within individual outcrops, such as locality 5, reveal the diversity and complexity of the structures and suggest some relationships between minor folds and some of the larger folds of the area (Figs. 12B, 19, and 20).

As noted above, both Prohoroff et al. (2012) and we consider the Metaigneous Complex of Pine Mountain to be folded by major regional, NW-trending folds. The stereogram in Figure 20A reveals the folded pattern within the serpentinite SF-fabric (S_1) in the eastern part of the area. Field relations and average foliations here locally reveal a very symmetrical, open synform striking N25°–26°E and plunging at a low angle to the south, with limbs dipping 36°–38°. Our data conflict with some data on the map of Prohoroff et al. (2012), and the fold we depict conflicts with their interpretation that the rocks of this area represent the steeply overturned limb of adjoining major west-verging syncline-anticline pair. Our measured section (Fig. 15) beneath the Jpm reveals no major overturning or repetition of units that would be required by the structure shown by Prohoroff et al. (2012). Locally, our data reveal that the major fold is refolded by minor NE-trending folds. In contrast to the rocks along Pine Mountain Road, that part of the metaultrabasic body exposed ENE of the intersection of Fairfax-Bolinas Road and Liberty Gulch is asymmetrically folded, with a moderately dipping southwest limb (30°–40°NE) and a locally vertical to overturned northeastern limb. Here, the vertical NE contact exposed adjacent to the road (locality 4) is likely deformed by a local high-angle fault, and while exposures of the northeast limb overall are quite limited by soil and vegetation, they generally seem to be steeply dipping. As was the case to the north, there is local evidence, in the form of the configuration of the contact, that the

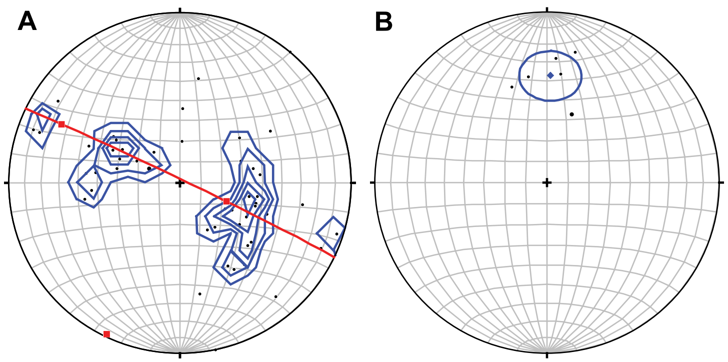

Figure 20. Selected stereograms of structures in the Liberty Gulch–Azalea Hill area. (A) Stereogram of attitudes of shear fracture foliations in serpentinite, measured in the east-central map area, northeast of locality 7. The fold defined by the foliations plunges 2°S25°W (represented by red dot in lower left of stereogram). N = 51. Contours are 2%/1% area. Field relations show that the fold is an open synform with interlimb angle of ~112°. (B) Mean orientation of six mesoscopic folds in outcrop at locality 5 on Fairfax-Bolinas Road (Fig. 17A). Mean fold orientation (blue dot in circle) is 37°N2°E. Note that folds such as these do not occur in overlying serpentinites of the Metaigneous Complex of Pine Mountain (Jpm). Stereograms were constructed using R. Almendinger's Stereonet for Macintosh Program version 6.3.3.

major NW-trending fold in the Jpm is refolded by a minor NE-trending fold. Overall, the exposures do not reveal a symmetrical fold like that along Pine Mountain Road but rather show an asymmetrical SW-vergent fold somewhat consistent with the structural concept of Prohoroff et al. (2012) but differing from it in detail. In the larger region, the folds in the serpentinite are generally open structures, as reflected by their ridge-capping positions and broadly contour-subparallel contacts (Fig. 12A).

The more open, large-scale folding of the serpentinite of Jpm contrasts with much of the mesoscopic folding observed in the Liberty Gulch Broken Formation. Mesoscopic folding in the Kflg is commonly tight to isoclinal, although open folds are present. At locality 5 (Fig. 20B) and ~200 m to the northwest along the road, folding in the Kflg does not seem to significantly affect the trace of the Kflg-Jpm contact above, as would be expected if the folding was post-thrust faulting in age. Furthermore, as noted, the more northerly trend of the serpentinite folds and bodies appears to truncate the generally N50°–60°W trend of the members of the Kflg exposed in the area of the measured section (Fig. 12B).

The relationships we describe here indicate that the Jpm was thrust over the Kflg. Clearly, there is a structural discordance between overlying Jpm and underlying Kflg. Thrusting likely caused tectonic deformation of the Kflg melange (member 1) and at least some of the Kflg folding, but the discordance between structures below and above the thrust suggest that the Jpm was transported over the underlying folded rocks by continued movement along the thrust fault. Nowhere did we observe a depositional relationship between Jpm and Kflg.

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DISCUSSION AND CONCLUSIONS

Reviewing all of the data from the detailed analysis of the Liberty Gulch–Azalea Hill area and the northwest Jenner Headlands, Russian Gulch–Hill 572/905 area, we reach a number of conclusions of importance to Franciscan architectural studies in particular and accretionary complex architecture in general. First, our observations support the hypothesis of Prohoroff et al. (2012) that olistolith-bearing sandstone-matrix mélanges and (we add) other sandstone units, comprise a large part of the Central belt in the Sonoma-Marin region of the Northern Coast Ranges, as it is currently defined. Where exotic blocks are abundant, the units bearing the blocks may represent sandstone-matrix olistostromal mélanges like those described by Aalto and Murphy (1984) and suggested by Erickson (1995, 2011) and Prohoroff et al. (2012). Where the blocks are sparse and relatively widely distributed, as seems to be the case in the Wacke of Jenner Headlands, they may represent olistolith slide blocks within fluidized grain-flow deposits and turbidites, like some Cipit Boulders of Italy. Second, we note that the sandstone-rich units at both locales studied are parts of turbidite-bearing inner- to mid-fan sequences, common in accretionary complexes.

Several areas between San Francisco Bay and the general latitude of Jenner, California, are underlain by Franciscan rock units assigned to the Central belt or Central terrane. These appear in reconnaissance to be dominated, at least in part, by sandstone and/or metasandstone and decorated at the surface by scattered blocks of metabasite and metachert, just as was the case in the two small areas we studied. Determination of whether or not these blocks represent olistoliths deposited in submarine canyons and inner fans, are olistoliths within sandstone-matrix mélanges, or are fault blocks incorporated into the metasandstone terranes will require additional detailed studies.

While the Central belt contains large areas of shale-matrix mélange in areas farther to the north (e.g., Cloos, 1982; McLaughlin et al., 2000), in western Marin and Sonoma counties, the two areas we studied in detail do not reveal that shale-matrix mélange is a dominant type of rock body in the belt. Rather, in the Sonoma-Marin area, sandstone-shale submarine-fan sequences and sandstone-matrix, olistostromal mélange and olistolith-bearing sandstones are more abundant than shale-matrix mélanges. Extensive shale-matrix mélanges are yet to be revealed anywhere in the belt by detailed studies. Thus, third, we note that overall the sandstone-rich Sonoma-Marin part of the Central belt appears to differ from the shale-richer Central belt in the more northerly Northern Coast Ranges, where, as noted, shale-matrix mélange is reported to be dominant. The implications of these differences are significant for accretionary complexes, both in relation to revealing variations within major tectonostratigraphic units and in relation to the subduction channel model of accretion of mélanges.

Accretion of tectonostratigraphic units in an accretionary complex, in part, may be a function of the nature of the incoming sediment mass as well as the rate of convergence (e.g., von Huene and Scholl, 1991; Clift and Vannucchi, 2004). Where the sediment pile is thick and sandy, accretion via thin slab faulting to yield imbricate stacking of tectonostratigraphic accretionary packages via outward stepping of faults within the subduction zone results in emplacement of sandstone-dominated units in the complex (e.g., Seely et al., 1974; Ernst, 1977; Clift and Vannucchi, 2004; Meneghini et al., 2009). In contrast, thinner, especially mud-richer sections may convert to shale-matrix, fault-zone mélange, some of which may form and accrete incrementally (e.g., Rowe et al., 2013).

The Subduction Channel model (Cloos, 1982, 1984; Cloos and Shreve, 1988a, 1988b) is used widely to explain formation and emplacement of laterally extensive and generally thick shale-matrix or serpentinite-matrix mélange units within accretionary complexes (e.g., Hansen, 1992; Vannucchi et al., 2008; Blanco-Quintero et al., 2011; Ukar, 2012; Ogawa et al., 2014; Ernst, 2015). In the Subduction Channel model, continuous ductile flow and pervasive deformation of the shale or serpentinite matrix are essential for offscraping, fragmentation, and mixing of high- and low-grade blocks and other rocks within mélange packages (Cloos, 1982; Cloos and Shreve, 1988a; Ukar, 2012). Emplacement of these serpentinite- and shale-matrix mélange belts as tectonostratigraphic units within an accretionary complex necessarily follows flow and mixing, but accretion itself may be incremental rather than en masse. Yet, in the field, it remains difficult to recognize features that distinctively signal the accretion process that would yield a packet of subduction channel tectonic mélange created by incremental construction and accretion from features that mark en masse accretion of slabs of olistostromal mélange. Both are accreted via a tectonic process. Some criteria exist. For example, in the shale-matrix mélange(s) of the northern Central belt, thought by some to represent subduction channel mélange (Cloos, 1982; Ernst, 2015), the presence of upper-plate igneous rocks in part of the mélange argues for a history involving formation via mixing of blocks and matrix prior to emplacement. Such a history for mélanges with upper-plate rocks (including high-grade rocks), involves uplift and exposure, erosion, and subsequent deposition of blocks of these rocks in a muddy matrix by submarine mass flows (MacPherson et al., 1990, 2006). Hence, mélange formation via fragmentation and mixing was a sedimentary process rather than subduction channel tectonic processes. Accretion must have followed the formation of the mélange mass. Clearly, a tectonic overprint obscures earlier history, but the existence of sedimentary mélanges and evidence of mixing of exotic upper-plate rocks within olistostromes raises the question: how many, if any, mélange units (of the Central belt and like belts worldwide) accreted via a purely tectonic Subduction Channel model accretionary mechanism?

The presence of sandstone as a dominant component of the Sonoma-Marin Central belt specifically raises problems for accretion of the Central belt in Sonoma-Marin via the Subduction Channel model. In locales such as this, where mappable, semi-coherent, sandstone-rich broken formations and sandstone-matrix olistostromal mélanges are the dominant constituents of a turbiditic accretionary package, ductile flow and mixing within the subduction zone could not have occurred. The alternative mechanism to tectonic mixing of high-grade blocks into mélanges that have low-grade matrices is a sedimen-

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tary process, such as landsliding of high-grade olistolith blocks into submarine canyons or the trench or olistostrome deposition via high-density flows that incorporate erosionally-produced exotic elements into the sandy matrix. Incorporation of upper-plate rocks into accretionary mélanges could occur in the same way.

The geometry of the broad-scale accretionary structure of the Franciscan Complex and other subduction complexes may require reassessment as more data are generated. We have shown that the olistostromes and sandstones of the Sonoma-Marin Central belt are parts of a sedimentary pile of turbidites and mass-flow deposits. Somewhat similar Central belt olistostromal rocks are also exposed in northernmost California along the coast (Aalto and Murphy, 1984) and extend into Oregon (MacPherson et al., 2006), but along the coast, a shale-matrix olistostrome is a significant component of the sequence. Thus, the shale- and mélange-richer parts of the Central belt, which are present in the type region of the northern Coast Ranges, are flanked on the north by and locally include shaly olistostrome-bearing sections and on the south by olistostrome-bearing, sandstone-rich, submarine-fan sections. This regional rock distribution pattern indicates that along-strike stratigraphic variations are preserved in architectural units within the Central belt and that they existed in the Central belt's predecessor trench. Upper-plate block compositions similarly suggest along-strike variations (MacPherson et al., 2006). In accretionary complexes in general, this means that care must be taken in defining and separating terranes from one another strictly on the basis of lithologic correlation.

Viewing this architecture and tectonostratigraphy in the context of new data on the likely depositional age of units suggests new possibilities for the accretionary complex architecture and history. The northern shale-matrix–rich part of the Central belt of the Northern Coast Ranges, based on a combination of detrital zircon data and microfossils, is predominantly of Late Cretaceous age but may extend from Middle Jurassic to Eocene age (Dumitru et al., 2015). Deposition of clastic rocks, as indicted by the detrital zircons occurred between 115 Ma and 85 Ma based on youngest zircon populations and most likely occurred between 105 Ma and 70 Ma—the preferred depositional age. The two dated sandstone-rich units of the Sonoma-Marin Central belt fall within the latter range, with the Liberty Gulch Broken Formation having a depositional age of 100 Ma (Prohoroff et al., 2012) and the King Ridge Road mélange with a depositional age of 83 Ma (Erickson, 2011). Thus, to the north, while mud was being deposited (yielding the predominant shale of the Central belt there), in the Sonoma-Marin belt sand (yielding sandstone) was the dominant sediment. In addition, at least for part of the time that mud was being deposited as the predominant sediment in the oceanic realm of the future Central belt of the northern part of the Northern Coast Ranges, sand was the dominant sediment in the region that later became the Yolla Bolly part of the Eastern belt, east of the present-day segment of northern Central belt. The Yolla Bolly section has a similar, but shorter depositional age for all sediments, based on fossils in pelagic sediments and detrital zircons (Middle Jurassic to Late Cretaceous) (Dumitru et al., 2015). These data raise the interesting possibility that a significant part of the Central belt in the north was a distal mud-rich facies equivalent of the sandy Yolla Bolly part of the Eastern belt.

During deposition of the Sonoma-Marin Central belt, that belt must have been located much farther south of the northern shaly Central belt than its present position indicates. Based on currently available, but conservative, palinspastic reconstructions that remove separations along faults of the San Andreas fault system, the Sonoma-Marin rocks were perhaps 150 km to 250 km south of their present position relative to the northern Central belt (McLaughlin et al., 1996; Wakabayashi, 1999). Hence, our fourth conclusion is that the Sonoma-Marin rocks represent a sandy facies deposited in the trench to the south of the more shaly northern Central belt. It is doubtful that the two "belts" should have the same name, since they are no more than age correlative.

In contrast to the Sonoma-Marin Central belt as a whole, in the Liberty Gulch–Azalea Hill area, we have shown that chert and/or metachert and basic metavolcanic rock blocks are largely present in thin (<10-m-thick) to medium thickness (<100-m-thick) olistostromes with mudrock matrices, although a few occur as olistoliths in sandstones. No thick exotic block-bearing olistostrome, as reported by Prohoroff et al. (2012), was discovered in the small area we studied in detail. Rather, we conclude (conclusion 5) that the dominant Franciscan unit, the Liberty Gulch Broken Formation, is a submarine-fan sequence with thin- to medium-thickness olistostromes of Facies F interlayered with grain-flow, fluidized-flow, and turbidity-current–deposited, thick- and medium-bedded Facies A, B, and C sandstones. The latter are associated locally with more distal fan-lobe Facies D and E turbidites. Shales are also locally abundant in the section.

At both locales studied (Jenner Headlands and Liberty Gulch), we found that a serpentinized metaultramafic unit was thrust faulted over underlying Franciscan rocks (conclusion 6). At the Liberty Gulch–Azalea Hill area, the Jpm-Kflg contact is everywhere sheared and, except for two locally overturned contacts within the general area of the Azalea Hill trailhead and parking area, the Jpm rocks everywhere structurally overlie the Kflg rocks. The Jpm serpentinites were synclinally folded on the macroscopic scale by open to tight folding of northwest trend; but as a result of continued early movements on the underlying thrust fault, the open folding within the Jpm is both superimposed on and discordant with folds and other structures within the underlying Kflg rocks. The structural position of the serpentinized Jpm rocks is like that of other serpentinized metaultrabasic rock bodies in the region (e.g., at Tiburon Peninsula and Jenner Headlands; Bero, 2010, 2014). The Jpm caps the tectonostratigraphy, having been thrust faulted over the underlying Franciscan Complex. In the Liberty Gulch–Azalea Hill area, we found no evidence that the serpentinized metaultrabasic rocks form an interlayer within the tectonostratigraphy and no evidence of a depositional contact of Kflg mélange on Jpm, as suggested in earlier studies (Gluskoter, 1969; Wright, 1984; Prohoroff et al., 2012). At the Hill 572/905 locale at Jenner Headlands, the serpentinite is similarly thrust, as is the underlying SMM rock, over the under-

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lying Franciscan Complex (meta)sedimentary rocks. Thus, in both locales, the structural relationships are similar to those elsewhere in the Coast Ranges, where metaultramafic rocks of the Coast Range Ophiolite occur above structurally underlying Franciscan rocks (e.g., Blake et al., 1969; Raymond, 1973b, 1974, 2014; Page, 1981; Wakabayashi, 1999, 2004; Wakabayashi et al., 2010; Bero, 2014).

At both the Russian Gulch–Hill 572/905 and the Liberty Gulch–Azalea Hill locales, the serpentinized ultramafic rocks that cap the tectonostratigraphy are underlain, in part, by mélange units (conclusion 7). In Sonoma County, on Hill 572/905, the mélange underlying the metaultrabasic rocks is a serpentinite-matrix mélange, like that on Tiburon Peninsula in southeastern Marin County (Bero, 2014). The presence of a serpentinite-matrix mélange suggests a relationship with the immediately overlying metaultrabasic rocks. In contrast, at Liberty Gulch in northwestern Marin County, a shale-matrix mélange underlies local serpentinite-matrix mélange and widespread serpentinized peridotite, but the shale-matrix mélange seems not to be ubiquitous and is related to the underlying Franciscan rocks rather than to the overlying ultramafic rocks. Thus, it fortuitously underlies local parts of the serpentinized metaultrabasic body and is absent elsewhere. Here, since the matrix is mudrock and the mélange is clearly part of the underlying stratigraphy, the polygenetic mélange is a feature of initial sedimentary origin overprinted by structural deformation, perhaps related to the thrusting.

In the Russian Gulch–Hill 572/905 area, our eighth conclusion is that a second mélange, the Heaven's Beach mélange, is polygenetic and crops out west of a NW-striking fault that separates all the other units of the area from this more westerly mélange. The Heaven's Beach mélange is a sheared, sandstone- and mudrock-matrix mélange containing exotic blocks of chert and/or metachert, low-grade basic metavolcanic rock, glaucophane schist, and serpentinite, and native blocks of sandstone and conglomerate. It has an early sedimentary history overprinted by later structural deformation.

Our mapping in Sonoma and Marin counties delineates details that constrain both the sedimentological and the deformational history of subduction complexes. Hence, ninth, we conclude that use of a hierarchical array of accretionary complex units would be beneficial for describing both the character and history of accretionary complexes. We argue that members, formations, broken formations, mélanges, and units of similar level in stratigraphic codes, units that we use in mapping, provide the first and second levels of units that comprise larger units, such as accretionary complex architectural units (terranes or belts), and we reject the idea that traditional stratigraphic units cannot be recognized and mapped as part of accretionary complexes.

Tenth, we note that three structural forms of serpentinite exist within the Jpm of Marin County, one of which has a block-in-matrix structure with blocks of serpentinite tectonite. If mappable at the 1:24,000 scale, this block-in-matrix unit is a mélange unit of likely tectonic origin, in which older serpentinite tectonite has been fragmented and mixed with a matrix of shear-fracture textured serpentinite. Within the area of our detailed mapping, the block-in-matrix unit is not thick or widely exposed enough to be mappable and is not, therefore, a mélange. Additional study is needed to clarify the nature, relationships, and extent of exposure of this member-like unit of the Jpm.

The olistolith-bearing Franciscan Complex metaclastic units of both Jenner Headlands and Liberty Gulch are extensively deformed (conclusion 11). At Jenner Headlands, the deformation is largely concealed by soil cover in the landward sections but appears to consist of both shearing and local folding of thinner bedded sandstones and shales. As a whole, the sandstone-dominated units appear to dip to the northeast, likely representing individually accreted thrust sheets. Along the coast, clear evidence of olistostromal mélange overprinted by shearing typifies the Heaven's Beach mélange. The high-angle fault here separating the western mélange from more easterly Franciscan units is likely a postaccretion structure along which lateral transport juxtaposed the Heaven's Beach mélange with the other units. The magnitude of any separation along this fault is unknown, and it is possible that it is minor, so that the Heaven's Beach mélange might represent an additional underplated thrust sheet.

In western Marin County, the olistostrome-bearing Liberty Gulch Broken Formation is extensively deformed and is complexly folded, faulted, and sheared at the mesoscopic scale. Small-scale faults are common and micro-shears are present within hand specimen–scale rocks. On the macroscopic scale, the unit apparently is a dominantly northeast-dipping unit, exhibiting broad folding that affected both the overlying Pine Mountain metaigneous rocks and the Liberty Gulch Broken Formation. Fold wavelengths of the major northwest-trending folds are on the order of 0.15–0.6 km. Smaller wavelength folds trend northeast and refold the major folds, but some smaller-scale folds apparently predate the broad, late folding. The shearing, intra-formational faulting, thrust faulting, and some intra-formational mesoscopic folding very likely are accretion-related structures; whereas the more regional folds and later smaller cross-folds are postaccretion structures.

The rocks of the Central belt in western Marin County have been shown by Prohoroff et al. (2012) to have ages equivalent to rocks of the Yolla Bolly terrane (YBT). They and we both observe, however, that the western Marin rocks differ in texture and metamorphic grade from the YBT rocks (blueschist-facies grade for YBT versus prehnite-pumpellyite–facies grade for Kflg) (also see Raymond, 2014). Sedimentologically, the rocks of the YBT and Central belt of Marin and Sonoma counties have some similarities. Abundant metawacke and chert, ubiquitous blueschist-facies metamorphism, widespread textural transformation of metasandstones to Tx2 and Tx3, and the age range of the rocks (90–125 Ma) are the main criteria for recognizing YBT rocks (Blake et al., 1984; Dumitru, 2012; Ernst et al., 2012; Raymond, 2014). Yolla Bolly terrane rocks have all of these characteristics; whereas rocks of western Sonoma and Marin counties designated as Central belt rocks have some, but not all of them. Rock units of the Central belt–type area contain abundant shale. Since (1) the rocks of western Marin County fall exactly in the age range of the YBT and contain some similar rock types, but differ in other aspects such as metamorphic grade, and (2) the Central belt is characterized by shale (-matrix mélange), our Marin observations and those of Prohoroff et al. (2012) raise doubts about

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the utility of assigning rocks in Marin and Sonoma counties that have been studied only in reconnaissance to the Central belt. Furthermore, the overlap in characteristics between rocks of the YBT and those of western Sonoma and Marin counties raises questions about the meaning of the Central terrane designation as it has been applied across the accretionary complex. The Central belt designation was fundamentally geographic, but the implications of a terrane designation are more significant structurally. We would argue that replacement of the Central belt rubric by the Central terrane name is not well founded in the rules of terrane designation (e.g., Howell et al., 1985), is debatably inconsistent with a considerable amount of local geology, and has not proven to be useful to understanding the Franciscan architecture of western Sonoma and Marin counties. Use of the Central terrane designation in western Marin and Sonoma counties should be abandoned and the use of the Central terrane name elsewhere should be reevaluated based on detailed mapping of the Franciscan rocks.

The general implication that this work reveals for accretionary complex studies is that terrane designations provide a general picture of the collage nature of accretionary complexes and some regional relationships, but the details of the architecture and the history of the complexes require elucidation through large-scale structural and stratigraphic studies. General reconnaissance and premature application of terrane designations may yield misleading results. We show that large-scale mapping reveals (1) the existence of mappable stratigraphic units, (2) the presence of interbedded mélanges of decimeter scale in submarine-fan sequences, and (3) the nature and history of syn- and postaccretion structures. These details are not accounted for via typical subdivision of accretionary complexes into terranes. The details constrain both sedimentological and deformational history of subduction complexes. A hierarchy of accretionary complex units would be beneficial to describing both the character and history of accretionary complexes, and we suggest that members, formations, broken formations, mélanges, and units of similar level in stratigraphic codes provide the first and second levels of units that comprise larger units, such as belts. Mapping such units provides the best method for clarifying the nature and history of subduction accretionary complex architecture.

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REFERENCES CITED

Aalto, K.R., 1981, Multistage mélange formation in the Franciscan Complex, northernmost California: Geology, v. 9, p. 602–607, doi:10.1130/0091-7613(198109<602:MMFITF>2.0.CO;2.

Aalto, K.R., and Murphy, J.M., 1984, Franciscan Complex Geology of the Crescent City area, northern California, *in* Blake, M.C., Jr., ed., Franciscan Geology of Northern California: Pacific Section of the Society of Economic Paleontologists and Mineralogists, Book 43, p. 185–201.

Abbate, E., Bortolotti, V., and Passerini, P., 1970, Olistostromes and olistoliths: Sedimentary Geology, v. 4, p. 521–557, doi:10.1016/0037-0738(70)90022-9.

Anczkiewicz, B., Platt, J.P., Thirlwall, M.F., and Wakabayashi, J., 2004, Franciscan subduction off to a slow start: Evidence from high-precision Lu-Hf garnet ages on high-grade blocks: Earth and Planetary Science Letters, v. 225, p. 147–161, doi:10.1016/j.epsl.2004.06.003.

Bachman, S.B., 1978, A Cretaceous and early Tertiary subduction complex, Mendocino Coast, northern California, *in* Howell, D.G. and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 419–430.

Bailey, E.H., and Irwin, W.P., 1959, K-feldspar content of Jurassic and Cretaceous greywacke of the northern Coast Ranges and Sacramento Valley, California: The American Association of Petroleum Geologists Bulletin, v. 43, p. 2797–2802.

Ballance, P.F., 1991, Gravity flows and rock recycling on the Tonga Landward trench slope: Relation to trench-slope tectonic processes: The Journal of Geology, v. 99, p. 817–827, doi:10.1086/629554.

Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., and O'Day, M., 1972, What is Franciscan?: The American Association of Petroleum Geologists Bulletin, v. 56, p. 2295–2302.

Bero, D.A., 2010, Geology map of the western portion of the Jenner Headlands, *in* Edwards, B.R., and Chestnut, A., 2012, Jenner Headlands Integrated Management Plan: Santa Rosa, California, Sonoma Land Trust and Oak Glen, California, The Wildlands Conservancy Geology, p. 4-5–4-8.

Bero, D.A., 2014, Geology of Ring Mountain and Tiburon Peninsula, Marin County, California: California Geological Survey Map Sheet 60 [with text], scales 1:12,000 and 1:6000, 2 sheets, 35 p.

Blake, M.C., Jr., 1965, Structure and petrology of low-grade metamorphic rocks, blueschist facies, Yolla Bolly area, northern California [Ph.D. dissertation]: Palo Alto, California, Stanford University, 91 p.

Blake, M.C., Jr., and Wentworth, C.M., 1999, Structure and metamorphism of the Franciscan Complex, Mt. Hamilton area, northern California: International Geology Review, v. 41, p. 417–424, doi:10.1080/00206819909465150.

Blake, M.C., Jr., and Wentworth, C.M., 2000, Structure and metamorphism of the Franciscan Complex, Mt. Hamilton area, northern California, *in* Ernst, W.G., and Coleman, R.G., eds., Tectonic Studies of Asia and the Pacific Rim: Geological Society of America International Book Series, v. 3: Columbia, Maryland, Bellweather Publishing Ltd., p. 295–302.

Blake, M.C., Jr., Irwin, W.P., and Coleman, R.G., 1969, Blueschist-facies metamorphism related to regional thrust faulting: Tectonophysics, v. 8, p. 237–246, doi:10.1016/0040-1951(69)90100-0.

Blake, M.C., Jr., Howell, D.G., and Jones, D.L., 1982, Preliminary tectonostratigraphic terrane map of California: U.S. Geological Survey Open-File Report 82-593, 9 p., plus maps, 3 sheets, scale 1:750,000.

Blake, M.C., Jr., Howell, D.G., and Jayko, A.S., 1984, Tectonostratigraphic terranes of the San Francisco Bay Region, *in* Blake, M.C., Jr., ed., Franciscan Geology of Northern California: Pacific Section Society of Economic Paleontologists and Mineralogists Book 43, p. 5–22.

Blake, M.C., Jr., Jayko, A.S., McLaughlin, R.J., and Underwood, M.B., 1988, Metamorphic and tectonic evolution of the Franciscan Complex, northern California, *in* Ernst, W.G., ed., Metamorphism and Crustal Evolution of the Western United States (Rubey Volume 7): Englewood Cliffs, New Jersey, Prentice-Hall, p. 1035–1060.

Blake, M.C., Jr., Graymer, R.W., and Jones, D.L., 2000, Geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2337, version 1.0, scale 1:75,000, 1 sheet, and pamphlet, 31 p.

Blake, M.C., Jr., Graymer, R.W., and Stamski, R.E., 2002, Geologic map and map database of western Sonoma, northernmost Marin, and southernmost Mendocino counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2402, version 1.0., scale 1:100,000, 1 sheet, 43 p.

Blanco-Quintero, I.F., Rojas-Agramonte, Y., Garcia-Casco, A., Kroner, A., Mertz, D.F., Lazaro, C., Blanco-Moreno, J., and Renne, P.R., 2011, Timing of subduction and exhumation in a sub-

Geosphere, published online on 1 July 2015 as doi:10.1130/GES01137.1

duction channel: Evidence from slab melts from La Corea Mélange (eastern Cuba): Lithos, v. 127, p. 86–100, doi:10.1016/j.lithos.2011.08.009.

Bouma, A., and Stone, C.G., eds., 2000, Fine-grained Turbidite Systems: Tulsa, Oklahoma, American Association of Petroleum Geologists Memoir 72 and SEPM (Society of Sedimentary Geologists) Special Publications No. 68, 342 p.

Bouma, A., Normark, W.R., and Barnes, N.E., eds., 1985, Submarine Fans and Related Turbidite Systems: New York, Springer-Verlag, 350 p.

Brandner, R., and Keim, L., 2011, A 4-day geological field trip in the western dolomites: Geo.Alp, v. 8, p. 76–118.

Chipping, D.H., 1971, Paleoenvironmental significance of chert in the Franciscan formation of western California: Geological Society of America Bulletin, v. 82, p. 1707–1712, doi:10.1130/0016-7606(1971)82[1707:PSOCIT]2.0.CO;2.

Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust: Reviews of Geophysics, v. 42, no. 2, RG2001, 31 p., doi:10.1029/2003RG000127.

Cloos, M., 1982, Flow mélanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, p. 330–345, doi:10.1130/0016-7606(1982)93<330:FMNMAG>2.0.CO;2.

Cloos, M., 1983, Comparative study of mélange matrix and metashales from the Franciscan subduction complex with the basal Great Valley sequence, California: The Journal of Geology, v. 91, p. 291–306, doi:10.1086/628772.

Cloos, M., 1984, Flow mélanges and the structural evolution of accretionary wedges, *in* Raymond, L.A., ed., Mélanges: Their Nature, Origin, and Significance: Geological Society of America Special Paper 198, p. 71–79.

Cloos, M., and Shreve, R.L., 1988a, Subduction channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description: Pure and Applied Geophysics, v. 128, p. 455–500, doi:10.1007/BF00874548.

Cloos, M., and Shreve, R.L., 1988b, Subduction channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 2. Implications and description: Pure and Applied Geophysics, v. 128, p. 501–545, doi:10.1007/BF00874549.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333, doi:10.1038/288329a0.

Cowan, D.S., and Pini, G.A., 2001, Disrupted and chaotic rock units, *in* Vail, G.B., and Martini, I.P., eds., Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins: Great Britain, Kluwer Academic Publishers, p. 165–176.

Crawford, K.E., 1976, Reconnaissance geologic map of the Eylar Mountain quadrangle, Santa Clara and Alameda counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-764, scale 1:24,000, 1 sheet.

Damassa, S.P., 1979a, Danian dinoflagellates from the Franciscan Complex, Mendocino County, California: Palynology, v. 3, p. 191–207, doi:10.1080/01916122.1979.9989189.

Damassa, S.P., 1979b, Eocene dinoflagellates from the Coastal Belt of the Franciscan Complex, northern California: Journal of Paleontology, v. 53, p. 815–840.

Dewey, J.F., and Bird, J.M., 1970, Mountain Belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647, doi:10.1029/JB075i014p02625.

Dickinson, W.R., 1970, Relations of andesites, granites, and derivative sandstones to arc-trench tectonics: Reviews of Geophysics and Space Physics, v. 8, p. 813–860, doi:10.1029/RG008i004p00813.

Dietz, R.S., and Holden, J.C., 1974, Collapsing continental rises: Actualistic concept of geosynclines—A review, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Society of Economic Paleontologists and Mineralogists Special Paper No. 19, p. 14–25.

Dott, R.H., Jr., 1964, Wacke, greywacke and matrix—What approach to immature sandstone classification?: Journal of Sedimentary Petrology, v. 34, p. 625–632.

Dumitru, T.A., 2012, New, much younger ages for the Yolla Bolly terrane and a revised time-line for accretion in the Franciscan subduction complex, California: American Geophysical Union, Fall Meeting, poster T11A-2543.

Dumitru, T.A., Ernst, W.G., Hourigan, J.K., and McLaughlin, R.J., 2015, Detrital zircon U-Pb reconnaissance of the Franciscan subduction complex in northwestern California: International Geology Review, Special Issue: Convergent plate margin processes and their rock record, v. 57, no. 5–8, p. 767–800, doi:10.1080/00206814.2015.1008060.

Edwards, B.R., and Chestnut, A., 2012, Jenner Headlands Integrated Management Plan: Santa Rosa, California, Sonoma Land Trust and Oak Glen, California, The Wildlands Conservancy, 164 p.

Embley, R.W., 1976, New evidence for occurrence of debris flow deposits in the deep sea: Geology, v. 4, p. 371–374, doi:10.1130/0091-7613(1976)4<371:NEFOOD>2.0.CO;2.

Erickson, R., 2011, Petrology of a Franciscan olistostrome with a massive sandstone matrix: The King Ridge Road Mélange at Cazadero, California, *in* Wakabayashi, J., ed., Mélanges: Processes of Formation and Societal Significance: Geological Society of America Special Paper 480, p. 171–188.

Erickson, R.C., 1995, The geology of the Franciscan Complex in the Ward Creek–Cazadero area, Sonoma County, California: California Geology, v. 48, p. 155–164.

Ernst, W.G., 1970, Tectonic contact between the Franciscan mélange and the Great Valley Sequence—Crustal expression of a late Mesozoic Benioff zone: Journal of Geophysical Research, v. 75, p. 886–901, doi:10.1029/JB075i005p00886.

Ernst, W.G., 1977, Mineral parageneses and plate tectonic settings of relatively high-pressure metamorphic belts: Fortschritte der Mineralogie, v. 54, p. 192–222.

Ernst, W.G., 1993, Geology of the Pacheco Pass quadrangle, central California Coast Ranges: Geological Society of America Map and Chart Series MCH078, scale 1:24,000, 1 sheet, 12 p.

Ernst, W.G., 2011, Accretion of the Franciscan Complex attending Jurassic–Cretaceous geotectonic development of northern and central California: Geological Society of America Bulletin, v. 123, no. 9–10, p. 1667–1678, doi:10.1130/B30398.1.

Ernst, W.G., 2015, Franciscan geologic history constrained by tectonic/olistostromal high-grade metamafic blocks in the iconic California Mesozoic–Cenozoic accretionary complex: The American Mineralogist, v. 100, p. 6–13, doi:10.2138/am-2015-4850.

Ernst, W.G., and McLaughlin, R.J., 2012, Mineral parageneses, regional architecture, and tectonic evolution of Franciscan metagraywackes, Cape Mendocino–Garberville-Covelo 30′ × 60′ quadrangles, northwest California: Tectonics, v. 31, TC 1001, doi:10.1029/2011TC002987.

Ernst, W.G., Dumitru, T.A., Tsujimori, T., McLaughlin, R.J., Makishima, A., and Nakamura, E., 2012, Maximum depositional ages and evolving provenance of Franciscan metagraywackes, NW California: LA-ICPMS zircon U-Pb data: American Geophysical Union Fall meeting 2012, poster T11A-2544.

Evitt, W.R., and Pierce, S.T., 1975, Early Tertiary ages from the coastal belt of the Franciscan Complex, northern California: Geology, v. 3, p. 433–436, doi:10.1130/0091-7613(1975)3<433:ETAFTC>2.0.CO;2.

Flores, G. 1955, Discussion, *in* Beneo, E., ed., Les resultats des etudes pour la recherche petrolifere en Sicilie (Italie): 4th World Petroleum Congress, Rome, Proceedings Section 1, p.121–122.

Gluskoter, H.J., 1969, Geology of a portion of western Marin County: California Division of Mines and Geology Map Sheet 11, scale 1:47,520, 1 sheet.

Hansen, V.L., 1992, Backflow and margin-parallel shear within an ancient subduction complex: Geology, v. 20, p. 71–74, doi:10:1130/0091–7613(1992)020<0071:BAMPSW>2.3.CO;2.

Helwig, J., 1974, Eugeosynclinal basement and a collage concept of orogenic belts, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication Number 19, p. 359–376.

Howell, D.G., ed., 1985, Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, Number 1, 585 p.

Howell, D.G., Jones, D.L., and Schermer, E.R., 1985, Tectonostratigraphic terranes of the Circum-Pacific region, *in* Howell, D.G., ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, Number 1, p. 3–30.

Hsü, K.J., 1974, Mélanges and their distinction from olistostromes, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication Number 19, p. 321–333.

Ingersoll, R.V., 1978, Submarine fan facies of the Upper Cretaceous Great Valley Sequence, northern and central California: Sedimentary Geology, v. 21, p. 205–230, doi:10.1016/0037-0738(78)90009-X.

Irwin, W.P., 1972, Terranes of the Western Paleozoic and Triassic Belt in the southern Klamath Mountains, California, *in* Geological Survey Research 1972: U.S. Geological Survey Professional Paper 800-C, p. C103–C111.

Isozaki, Y., and Blake, M.C., Jr., 1994, Biostratigraphic constraints on formation and timing of accretion in a subduction complex: An example from the Franciscan Complex of California: The Journal of Geology, v. 102, p. 283–296, doi:10.1086/629671.

Geosphere, published online on 1 July 2015 as doi:10.1130/GES01137.1

Kramer, J.C., 1976, Geology and Tectonic Implications of the Coastal Belt Franciscan, Ft. Bragg-Willits Area, Northern Coast Ranges, California [Ph. D. dissertation]: Davis, University of California, 128 p.

Krogh, E.J., Oh, C.W., and Liou, J.G., 1994, Polyphase and anticlockwise P-T evolution for Franciscan eclogites and blueschists from Jenner, California, USA: Journal of Metamorphic Geology, v. 12, p. 121–134, doi:10.1111/j.1525-1314.1994.tb00008.x.

Leitch, E.C., and Schreibner, E., eds., 1989, Terrane Accretion and Orogenic Belts: American Geophysical Union Geodynamic Series, v. 19, 343 p.

Lomas, S.A., and Joseph, P., eds., 2004, Confined Turbidite Systems: Geological Society of London Special Publications No. 222, 328 p.

MacPherson, G.J., Phipps, S.P., and Grossman, J.N., 1990, Diverse sources for igneous blocks in Franciscan mélanges, California Coast Ranges: The Journal of Geology, v. 98, p. 845–862, doi:10.1086/629457.

MacPherson, G.J., Giaramita, M.J., and Phipps, S.P., 2006, Tectonic implications of diverse igneous blocks in Franciscan mélange, northern California and southwestern Oregon: The American Mineralogist, v. 91, p. 1509–1520, doi:10.2138/am.2006.2177.

McLaughlin, R.J., and Ohlin, H.N., 1984, Tectonostratigraphic framework of the Geysers–Clear Lake region, *in* Blake, M.C., Jr., ed., Franciscan Geology of Northern California: Pacific Section Society of Economic Paleontologists and Mineralogists Book 43, p. 221–254.

McLaughlin, R.J., and Pessagno, E.A., Jr., 1978, Significance of age relations above and below Upper Jurassic ophiolite in the Geysers–Clear Lake region, California: Journal of Research of the U.S. Geological Survey, v. 6, p. 715–726.

McLaughlin, R.J., Sliter, W.V., Fredericksen, N.O., Harbert, W.P., and McCulloch, D.S., 1994, Plate Motions Recorded in Tectonostratigraphic Terranes of the Franciscan Complex and Evolution of the Mendocino Triple Junction, Northwestern California: U.S. Geological Survey Bulletin 1997, 60 p.

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

McLaughlin, R.J., Ellen, S.D., Blake, M.C., Jr., Jayko, A.S., Irwin, W.P., Aalto, K.R., Carver, G.A., and Clarke, S.H., Jr., 2000, Geology of the Cape Mendocino, Eureka, Garberville, and southwestern part of the Hayfork 30–60 minute quadrangles and adjacent offshore area, northern California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2336, scale 1:100,000, 30 p.

Meneghini, F., Marroni, M., Moore, J.C., Pandolfi, L., and Rowe, C.D., 2009, The processes of underthrusting and underplating in the geologic record: Structural diversity between the Franciscan Complex (California), the Kodiak Complex (Alaska) and the Internal Ligurian Units (Italy): Geological Journal Special Issue: Dynamics in Subduction Complexes, v. 44, no. 2, p. 126–152, doi:10.1002/gj.114.

Moore, J.C., Watkins, J.S., and Shipley, T.H., 2007, Summary of accretionary processes, Deep Sea Drilling Project Leg 66: Offscraping, underplating, and deformation of the slope aprons: Initial Reports of the Deep Sea Drilling Project, v. 66, Chapter 42, p. 825–836.

Mutti, E., and Ricci-Lucchi, F., 1972 (1978), Turbidites of the Northern Apennines: Introduction to Facies Analysis: Falls Church, Virginia, American Geophysical Institute Reprint Series 3, p. I25–I66.

Ogawa, Y., Mori, R., Tsunogae, T., Dilek, Y., and Harris, R., 2014, New interpretation of the Franciscan mélange at San Simeon coast, California: Tectonic intrusion into an accretionary prism: International Geology Review, doi:10.1080/00206814.2014.968813.

O'Hanley, D.S., 1996, Serpentinites: Records of Tectonic and Petrologic History: New York, Oxford University Press, 277 p.

Page, B.M., 1981, The Southern Coast Ranges, *in* Ernst, W.G., ed., The Geotectonic Development of California: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., p. 329–417.

Page, B.M., 2000, Geology of the Lick Observatory quadrangle, California, *in* Ernst, W.G., and Coleman, R.G., eds., Tectonic Studies of Asia and the Pacific Rim: Geological Society of America International Book Series, v. 3: Columbia, Maryland, Bellweather Publishing Ltd., p. 252–264.

Pessagno, E.A., Jr., Hull, D.M., and Hopson, C.A., 2000, Tectonostratigraphic significance of sedimentary strata occurring within and above the Coast Range Ophiolite (California Coast Ranges) and the Josephine Ophiolite (Klamath Mountains), northwestern California, *in* Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 383–394.

Pini, G.A., 1999, Tectonosomes and olistostromes in the argille scagliosa of the Northern Apennines, Italy: Geological Society of America Special Paper 335, 70 p.

Prohoroff, R., Wakabayashi, J., and Dumitru, T.A., 2012, Sandstone matrix olistostrome deposited on intra-subduction complex serpentinite, Franciscan Complex, western Marin County, California: Tectonophysics, v. 568–569, p. 296–305, doi:10.1016/j.tecto.2012.05.018.

Raymond, L.A., 1973a, Franciscan Geology of the Mt. Oso Area, Central California [Ph.D. dissertation]: Davis, University of California, 185 p.

Raymond, L.A., 1973b, Tesla-Ortigalita fault, Coast Range thrust fault, and Franciscan metamorphism, northeastern Diablo Range, California: Geological Society of America Bulletin, v. 84, p. 3547–3562, doi:10.1130/0016-7606(1973)84<3547: TFCRTF>2.0.CO;2.

Raymond, L.A., 1974, Possible modern analogs for rocks of the Franciscan Complex, Mount Oso Area, California: Geology, v. 2, p. 143–146, doi:10.1130/0091-7613(1974)2<143: PMAFRO>2.0.CO;2.

Raymond, L.A., 1984, Classification of Mélanges, *in* Raymond, L.A., 1984, ed., Mélanges: Their Nature, Origin, and Significance: Geological Society of America Special Paper 198, p. 7–20.

Raymond, L.A., 2007, Petrology: The Study of Igneous, Sedimentary, and Metamorphic Rocks: (Reprinted Second Edition): Long Grove, Illinois, Waveland Press, 729 p.

Raymond, L.A., 2014, Designating tectonostratigraphic terranes versus mapping rock units in subduction complexes: Perspectives from the Franciscan Complex of California, USA: International Geology Review, doi:10.1080/00206814.2014.911124.

Raymond, L.A., Yurkovich, S.P., and McKinney, M., 1989, Nature and origin of block-in-matrix structures in the North Carolina Blue Ridge Belt, Southern Appalachian Orogen, *in* Horton, J.W., and Rast, N., eds., Mélanges and Olistostromes of the U.S. Appalachians: Geological Society of America Special Paper 228, p. 195–215.

Rowe, C.D., Moore, J.C., Remitti, F., and the IODP (International Ocean Discovery Program) Expedition 343/343T Scientists, 2013, The thickness of subduction plate boundary faults from the seafloor into the seismogenic zone: Geology, v. 41, p. 991–994, doi:10.1130/G34556.1.

Russo, F., Neri, C., Mastandrea, A., and Baracca, A., 1997, The mud mound nature of the Cassian platform margins of the dolomites: A case history: The Cipit boulders from Punta Grohmann (Sasso Piatto Massif, northern Italy): Facies, v. 36, p. 25–36, doi:10.1007/BF02536875.

Seely, D.R., Vail, P.R., and Walton, G.G., 1974, Trench slope Model, *in* Burke, C.A., and Drake, C.L., eds., The Geology of Continental Margins: New York, Springer-Verlag, p. 249–260.

Shanmugam, G., and Moila, R.J., 1985, Submarine fan models: Problems and solutions, *in* Bouma, A., Normark, W.R., and Barnes, N.E., eds., 1985, Submarine Fans and Related Turbidite Systems: New York, Springer-Verlag, p. 29–34.

Steen, O., and Andreson, A., 1997, Deformational structures associated with gravitational block gliding: Examples from sedimentary olistoliths in the Kalvag Mélange, western Norway: American Journal of Science, v. 297, p. 56–97, doi:10.2475/ajs.297.1.56.

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, Actinolite 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.

Vannucchi, P., Remitti, F., and Bettelli, G., 2008, Geological record of fluid flow and seismogenesis along an erosive subducting plate boundary: Nature, v. 451, p. 699–704, doi:org/10.1038/nature06486.

von Huene, R., and Scholl, D.W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust: Reviews of Geophysics, v. 29, p. 279–316, doi:10.1029/91RG00969.

Wakabayashi, J., 1990, Counterclockwise P-T-t paths from amphibolites, Franciscan Complex, California: Relics from the early stages of subduction zone metamorphism: The Journal of Geology, v. 98, p. 657–680, doi:10.1086/629432.

Wakabayashi, J., 1999, Subduction and the rock record: Concepts developed in the Franciscan Complex, California, *in* Moores, E.M., Sloan, D., and Stout, D.L., eds., Classic Cordilleran Concepts: A View from California: Geological Society of America Special Paper 338, p. 123–133.

Wakabayashi, J., 2004, Contrasting Settings of Serpentinite Bodies, San Francisco Bay Area, California: Derivation from the Subducting Plate vs. Mantle Hanging Wall?: International Geology Review, v. 46, p. 1103–1118, doi:10.2747/0020-6814.46.12.1103.

Wakabayashi, J., 2011, Mélanges of the Franciscan complex, California: Diverse structural settings, evidence for sedimentary mixing, and their connection to subduction processes, *in* Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of Formation and Societal Significance: Geological Society of America Special Paper 480, p. 117–141.

Geosphere, published online on 1 July 2015 as doi:10.1130/GES01137.1

Wakabayashi, J., 2012, Subducted sedimentary serpentinite mélanges: Record of multiple burial-exhumation cycles and subduction erosion: Tectonophysics, v. 568–569, p. 230–247, doi:10.1016/j.tecto.2011.11.006.

Wakabayashi, J., 2013, Subduction initiation, subduction accretion, and nonaccretion, large-scale material movement, and localization of subduction megaslip recored in Franciscan Complex and related rocks, California: Geological Society of America Field Guide 32, p. 129–162, doi:10.1130/2013.0032(07).

Wakabayashi, J., 2015, Anatomy of a subduction complex: Architecture of the Franciscan Complex, California, at multiple length and time scales: International Geology Review, v.57, p. 669–746, doi:10.1080/00206814.2014.998728.

Wakabayashi, J., Ghatak, A., and Basu, A.R., 2010, Suprasubduction-zone ophiolite generation, emplacement, and initiation of subduction: A perspective from geochemistry, metamorphism, geochronology, and regional geology: Geological Society of America Bulletin, v. 122, p. 1548–1568, doi:10.1130/B30017.1.

Wright, R.H., 1984, Geology of the Nicasio Reservoir Terrane, Marin County, California, *in* Blake, M.C., Jr., ed., Franciscan Geology of Northern California: Pacific Section Society of Economic Paleontologist and Mineralogists Book 43, p. 99–111.

Zhang, Z.M., 1985, Tectonostratigraphic terranes of Japan that bear on the tectonics of mainland China, *in* Howell, D.G., ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, Number 1, p. 409–420.

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