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REVIEW

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Structural context and variation of ocean plate stratigraphy, Franciscan Complex, California: insight into mélange origins and subduction-accretion processes

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Abstract

The transfer (accretion) of materials from a subducting oceanic plate to a subduction-accretionary complex has produced rock assemblages recording the history of the subducted oceanic plate from formation to arrival at the trench. These rock assemblages, comprising oceanic igneous rocks progressively overlain by pelagic sedimentary rocks (chert and/or limestone) and trench-fill clastic sedimentary rocks (mostly sandstone, shale/mudstone), have been called ocean plate stratigraphy (OPS). During accretion of OPS, megathrust slip is accommodated by imbricate faults and penetrative strain, shortening the unit and leading to tectonic repetition of the OPS sequence, whereas OPS accreted at different times are separated by non-accretionary megathrust horizons. The Franciscan subduction complex of California accreted episodically over a period of over 150 million years and incorporated OPS units with a variety of characteristics separated by non-accretionary megathrust horizons. Most Franciscan OPS comprises MORB (mid-ocean-ridge basalt) progressively overlain by chert and trench-fill clastic sedimentary rocks that are composed of variable proportions of turbidites and siliciclastic and serpentinite-matrix olistostromes (sedimentary mélanges). Volumetrically, the trench-fill component predominates in most Franciscan OPS, but some units have a significant component of igneous and pelagic rocks. Ocean island basalt (OIB) overlain by limestone is less common than MORB-chert assemblages, as are abyssal serpentinized peridotite slabs. The earliest accreted OPS comprises metabasite of supra-subduction zone affinity imbricated with smaller amounts of metaultramafic rocks and metachert, but lacking a clastic component. Most deformation of Franciscan OPS is localized along discrete faults rather than being distributed in the form of penetrative strain. This deformation locally results in block-in-matrix tectonic mélanges, in contrast to the sedimentary mélanges making up part of the clastic OPS component. Such tectonic mélanges may include blocks and matrix derived from the olistostromes. Franciscan subduction and OPS accretion initiated in island arc crust at about 165–170 Ma, after which MORB and OIB were subducted and accreted following a long (tens of mega-ampere) gap with little or no accretion. Following subduction initiation, a ridge crest approached the trench but probably went dormant prior to its subduction (120–125 Ma), after which the subducted oceanic crust became progressively older until about 95 Ma. From 95 Ma, the age of subducted oceanic crust decreased progressively until arrival of the Pacific-Farallon spreading center led to termination of subduction and conversion to a transform plate boundary.

Keywords: Ocean plate stratigraphy, Subduction complex evolution, Subduction megathrust slip accommodation, Tectonic and sedimentary mélanges

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Introduction

Ocean plate stratigraphy (OPS) comprises assemblages of trench-fill clastic sediments overlying pelagic sediments and oceanic igneous rocks that make up the world's subduction complexes (Wahrhafig 1984; Isozaki et al. 1990; Isozaki and Blake 1994; Wakita and Metcalfe 2005; Kusky et al. 2013; Wakita 2015). The specific OPS terminology was first applied by Isozaki et al. 1990, although the concept dates back at least as far as Wahrhaftig (1984). OPS is interpreted to record initial submarine volcanism at a mid-ocean ridge generating mid-ocean-ridge basalt (MORB) or at an off-axis location generating ocean island basalt (OIB), followed by open ocean pelagic sedimentation as the ocean plate drifts and by deposition of trench-fill clastic sediments as that part of the subducting oceanic plate reaches the trench (e.g., Chipping 1971; Wahrhaftig 1984; Isozaki et al. 1990; Osozawa 1994; Wakita and Metcalfe 2005; Kusky et al. 2013; Fig. 1).

OPS is transferred from the subducting plate to the subduction complex by the process of subduction-accretion during which the subduction megathrust cuts into the subducting plate. During accretion of OPS, subduction megathrust slip is accommodated by imbrication and penetrative deformation of the OPS. During much of the history of subduction zones, no accretion of any sort takes place (e.g., von Huene and Scholl 1991) so that accretion in any given subduction complex is expected to be sporadic. Accretion is associated with an accretionary mode of megathrust slip, whereas non-accretionary megathrust horizons separate OPS accreted at different times in a subduction complex (Wakabayashi 2016a). The incorporation of OPS into a subduction complex leads to intricate age relationships. The age of the igneous and the oldest pelagic components of a slice of OPS may be much older than the clastic sedimentary component that approximates the arrival time of the

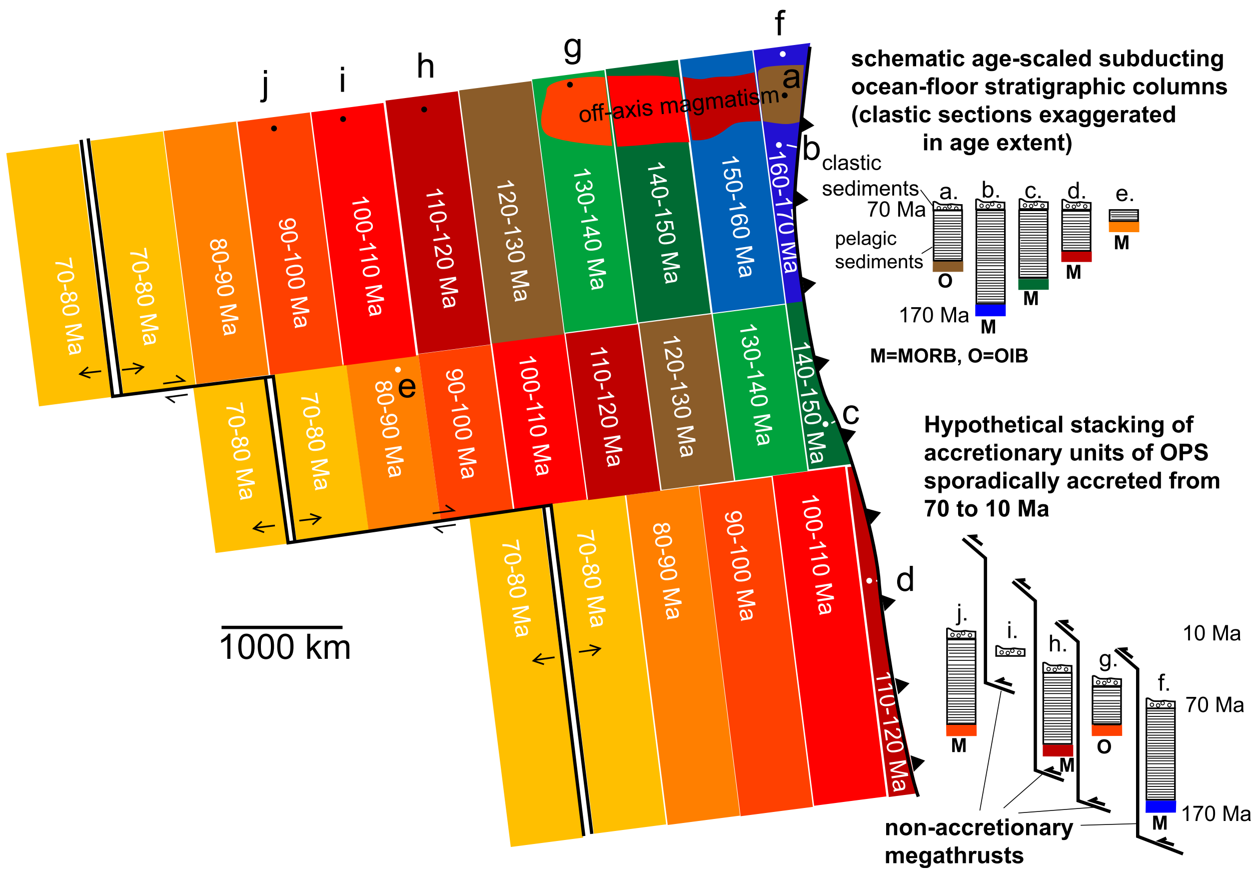

Fig. 1 Cartoon showing OPS evolution and age patterns versus accretion. The schematic stratigraphic columns are age-scaled rather than thickness-scaled. Columns **a**-**d** show how OPS arriving at the trench at the same time may vary along strike, in this case owing to subducting of fracture zones and crust formed off-axis. Obliquity of subduction relative to isochrons on the oceanic plate, which should be considered the general case, will introduce another level of complexity. Columns **a**-**e** show that pelagic sections formed far apart may share a common age range for part of their pelagic section. This suggests caution in correlating incomplete OPS sections where the basal pelagic rocks directly overlying sea floor volcanic rocks are not exposed. Columns **f**-**j** show the stacking of sporadically accreted OPS at one position along a trench. Compare to Franciscan Complex columns shown in Fig. 5b, c

piece of ocean floor at a trench shortly before subduction-accretion (e.g., Hamilton 1969; Wahrhaftig 1984; Osozawa 1994; Wakita and Metcalfe 2005; Kusky et al. 2013) (Fig. 1).

Successive episodic subduction-accretion of OPS can build a tectonic stack in a subduction complex wherein the clastic components young structurally downward across non-accretionary megathrust horizons, but the ocean crust age can have a less systematic age pattern that may trend both younger and older structurally downward (columns f to j in the lower right of Fig. 1) (Wakabayashi 2015). Nearly all of the igneous oceanic crust entering a subduction zone completely subducts and only a tiny fraction transfers to the upper plate as a part of OPS. In some cases, accretion of trench sediments may take place, but without incorporation of any of the underlying pelagic sedimentary and oceanic igneous rocks (Fig. 1, lower right "i" column).

Obliquity of plate convergence relative to isochrons of the ocean crust as well as the subduction of oceanic fracture zones, spreading ridges, and crust formed off-axis, such as seamounts, oceanic plateaus, can lead to complex along-strike patterns in the ages of oceanic crust accreted at the same time along the length of a subduction zone (Fig. 1; Osozawa 1994). Parts of the pelagic sections formed at different places and times on the ocean floor may be age correlative, but their actual sites of deposition may be far removed from one another (Fig. 1). Correlation of OPS sections lacking igneous rocks should not be made on the basis of similarity in age range of pelagic sections alone.

Whether OPS is or is not a synonym or subset of the term "ophiolite" depends on the varied definitions of ophiolite (e.g., Moores 1982; Dilek and Furnes 2011; Kusky et al. 2013). This has important implications for the connection between OPS packages and tectonic history. The largest ophiolite bodies, such as the Troodos, Semail, Bay of Islands, and Coast Range ophiolites, are assemblages that were part of the upper plate above a subduction zone, rather than the much smaller oceanic crust scraps transferred from the subducting plate to the upper plate as part of a subduction complex (e.g. Moores 1982). Large upper plate ophiolitic bodies are successively overlain by pelagic and clastic sedimentary rocks, so these have the same components as OPS slices in subduction complexes, but the tectonic-sedimentary history of such units differs markedly.

In the California Cordillera, the largest bodies of oceanic rocks (igneous rocks and overlying pelagic sedimentary rocks) are associated with the upper plate settings instead of subduction complexes. Figure 2 summarizes these relationships with various upper plate ophiolitic igneous rock bodies designated with acronyms vo, so, voc, soc, and bodies of island arc volcanic rocks designated with the acronym va. For example, the Coast Range ophiolite (voc, soc) is the upper plate ophiolite unit of the Coast Ranges, whereas "so" in the northwest Klamath Mountains is part of the Josephine ophiolite, "so" in the eastern Klamath Mountains is part of the Trinity ophiolite, and "va" along the northwestern margin of the Sierra Nevada is the Smartville arc. Large upper plate oceanic assemblages and subduction complex OPS are easily distinguished from one another in coastal California, owing to the lack of post-subduction disruption, whereas this distinction is much more difficult in many (most?) other orogenic belts (Wakabayashi 2015, 2016a). This paper will use the term OPS solely for the components of subduction complexes and will exclude the upper plate oceanic rocks, in contrast to Kusky et al. (2013; their Fig. 1) that included units interpreted by many as upper plate, but considered them to have been derived from the downgoing plate. The oceanic crustal components of Franciscan subduction complex crop out over much smaller areas than the upper plate oceanic fragments as shown by the size of outcrops labeled "vf, vfs, vrf, and va" on Fig. 2

This paper presents new information on the variety of OPS in the Franciscan Complex of the California Coast Ranges and its relationship to Franciscan Complex tectonic history and subduction processes. Kusky et al. (2013) reviewed OPS within the Franciscan Complex, but this paper presents more detail bearing on a greater variety of OPS types, and proposes different interpretations about the relationship between mélanges and the formation and deformation of OPS. Wakabayashi (2015) presented much of the field-based framework of this paper, but all of the outcrop photos and photomicrographs presented in this paper are new. In addition, the connection between OPS, subduction process, and tectonic versus sedimentary mélanges is more explicitly explained in this paper than in Wakabayashi (2015).

Review

California coast ranges regional relationships

The Coast Ranges preserve the relationship between paleoforearc basin deposits (Great Valley Group or GVG) that rest in depositional contact on a remnant of oceanic lithosphere (Coast Range Ophiolite or CRO) tectonically overlying an exhumed subduction complex (Franciscan Complex) (Hamilton 1969; Dickinson 1970: Ernst 1970; Bailey et al. 1970). These three megaunits crop out together for more than 700 km along and 100 km across strike (Fig. 2). This outcrop length is greater than 1000 km if strike-slip faulting is restored (e.g., Wakabayashi 2015). OPS, as defined herein is restricted to the Franciscan Complex. In contrast to the materials of the Franciscan Complex, that were transferred from the subducting plate to the upper plate, the

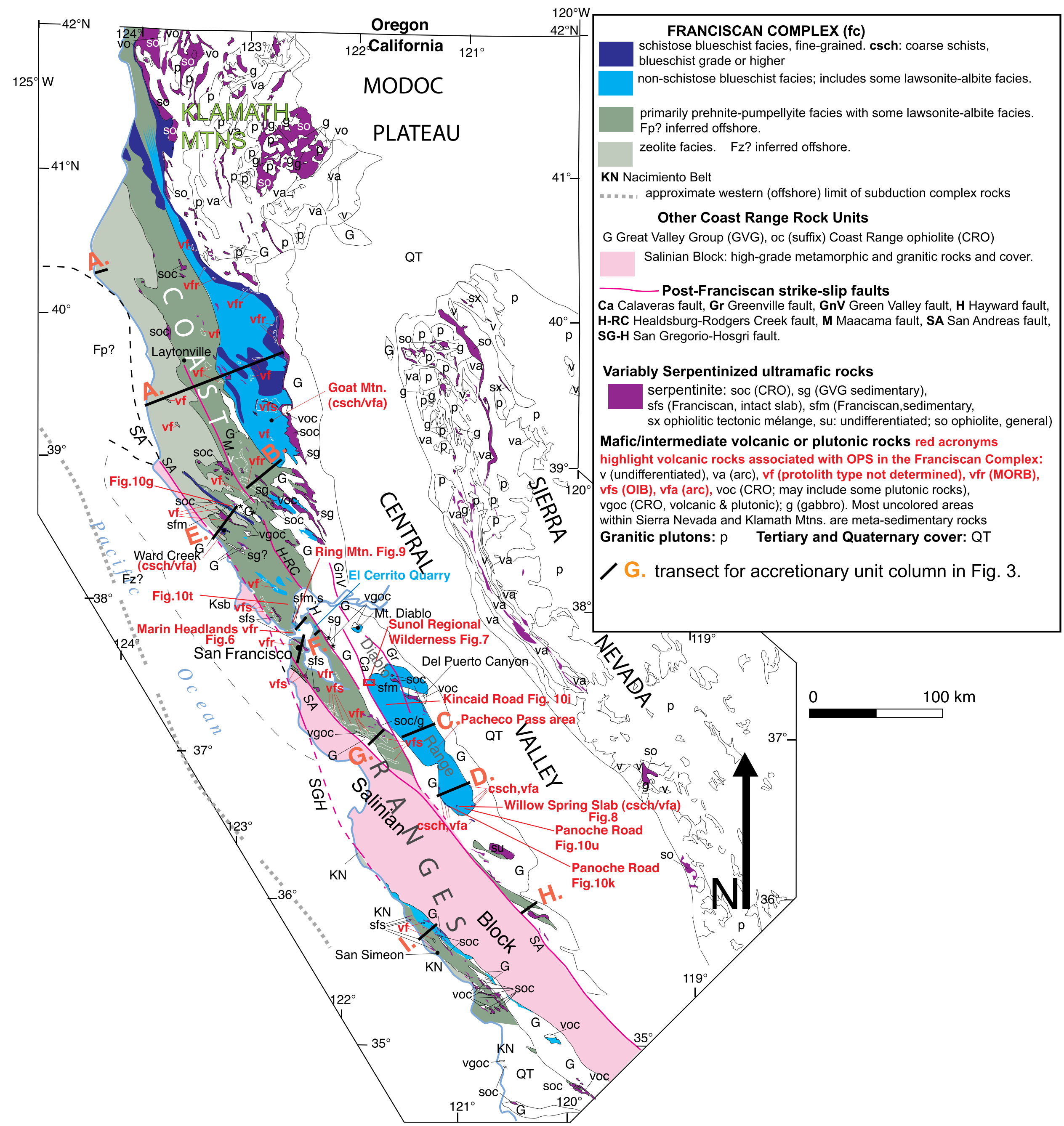

Fig. 2 Map showing general geology of north-central California and special emphasis on the California Coast Ranges. Oceanic rocks are emphasized on this map, and oceanic volcanic rocks associated with OPS are highlighted by red labels in the Franciscan subduction complex of the California Coast Ranges. In some cases the actual size of the volcanic rock exposure is exaggerated because most of the actual exposures consist of imbricated basalt, chert, and siliciclastic rocks. The largest exposures of mafic-intermediate oceanic volcanic rocks and overlying pelagic sediments are associated with accreted island arc terranes (labeled "va") or large ophiolitic sheets (some examples are labeled "voc"). Revised from Wakabayashi (2016b)

CRO and GVG were part of the upper plate of a convergent plate margin throughout their history (e.g., Hamilton 1969, Dickinson 1970; Ernst 1970; Bailey et al. 1970).

Part of the CRO, however, consists of mafic volcanic rocks, successively overlain by chert and then the siliclastic rocks of the GVG (Hopson et al. 1981; 2008). Locally, the upper part of the CRO may be imbricated along with the basal part of the GVG so that there are repeated slices of basalt-chert-siliclastic rocks (Wakabayashi 2016b) that resemble the types of field relationships seen in typical OPS in subduction complexes. There are widespread imbricate and block-in-matrix relationships within the Tehama-Colusa mélange whose affinity as CRO or Franciscan (or neither) is unclear (Hopson and Pessagno 2005; Shervais et al. 2011). In addition, large (up to hundredths of meters) blocks of basalt, chert, and basalt with overlying chert are present in olistostrome units of the basal GVG (Phipps 1984; 1992; Wakabayashi 2016a). These units can be distinguished from Franciscan rocks on the basis of the lack of burial metamorphism (excluding some blocks in mélanges/olistostromes) and their regional field relationships.

General spatial-temporal relationships of Franciscan Complex OPS

The Franciscan Complex accreted during a period of >150 Ma of continuous east-dipping subduction in coastal California from ca.165 to 12 Ma, with most accretion between ca. 120 and 32 Ma (e.g., McLaughlin et al. 1982; Dumitru et al. 2010; 2015; Wakabayashi 2015). Episodic accretion transferred material (OPS) from the downgoing plate to the subduction complex to form a structural stack of accretionary slices/units with different formational and accretion ages (Fig. 3); Dumitru et al. (2016); Chapman et al. (2016). These sheetlike accretionary units, bounded above and below by narrow (<100 m thick) non-accretionary paleomegathrust horizons, have low-angle regional dips, but dip steeply in many areas as a result of later folding (Wakabayashi 2015; 2016a) (Fig. 3). The accretionary units extend up to tens of kilometers along strike and attain structural thicknesses of up to ~3 km. In this paper, "accretionary units" and OPS units will be considered synonymous. The age of subduction-accretion of various accretionary units has been determined by ages of metamorphism where metamorphism was sufficient to generate datable metamorphic minerals and by the depositional age of clastic sedimentary rocks for rocks too low grade to yield metamorphic ages (e.g., Wakabayashi 2015) (Fig. 3).

About a fourth of the exposed accreted rocks underwent high-pressure/low-temperature (HP-LT) lawsonite-albite, blueschist or higher grade metamorphism; nearly all of the remainders are prehnite-pumpellyite or zeolite grade (Blake et al. 1984, 1988; Ernst 1993; Terabayashi and Maruyama 1998; Ernst and McLaughlin 2012) (Fig. 2). A small fraction (<<1%) of the Franciscan rocks are coarse-grained blueschist, amphibolite, garnet-amphibolite, and eclogite. Most of these rocks crop out as blocks-in-mélange termed "high-grade blocks" (Coleman and Lanphere 1971).These blocks are higher in metamorphic grade than surrounding matrix, whereas rare intact fault-bounded sheets of these rocks are found ("high-grade coherent sheets" of Wakabayashi et al. 2010; "csch/vfa" on Fig. 2).

Clastic sedimentary rocks make up most of the collective stack accreted OPS units, and the proportion of intact igneous and pelagic varies between various accreted units as well as in collective accreted stacks in different parts of the Franciscan (Wakabayashi 2015) (Figs. 3 and 4). This variability will be described further in "Examples of the variety of OPS in the franciscan complex" on specific types of OPS assemblages. The clastic sedimentary rocks of the subduction complex comprise turbidites and mélanges with non-native (exotic) blocks, such as those of higher metamorphic grade than the matrix (Wakabayashi 2015). Some have interpreted these types of mélanges having resulted from sedimentary (olistostromal) mixing of exotic blocks into matrix (e.g., Aalto 1981; Cowan 1978; Macpherson et al. 1990; Platt 2015; Wakabayashi 2015) whereas others have proposed that the introduction of blocks into matrix resulted from tectonic strain as tectonic mélanges (e.g., Cloos 1984; Cloos and Shreve 1988; Gerya et al. 2002; Hsü 1968).

The origin of mélanges with exotic blocks is important interpreting their relationship to accreted OPS units and the process of accretion and exhumation, so I will list the main arguments in favor of sedimentary origins of these bodies presented in Wakabayashi (2015), as well as presenting new evidence for the sedimentary origin of mélanges with exotic blocks in "Olistostromes as part of the clastic component of OPS." The sedimentary origin of Franciscan mélanges with exotic blocks has been proposed based on the basis of multiple criteria, including (1) sedimentary structures or features in the least deformed parts of the mélange from outcrop to submillimeter scale, (2) interbedding and interfingering of mélanges with ordinary bedded turbidites, and (3) blocks that originated at shallow levels of the upper plate. New data will be presented in support of points 1 and 2 in "Olistostromes as part of the clastic component of OPS."

In addition to the evidence for sedimentary origin of mélanges with exotic blocks, geochronologic evidence indicates episodic accretion rather than continual mixing in a progressively widening subduction channel spanning the full thickness of the subduction complex, as envisaged in some numerical models (e.g., Gerya et al. 2002). Collectively, the evidence for origin of blocks with exotic blocks, episodic accretion within a subduction complex, and narrow (<100 m thick) zones between accreted units suggests that the accommodation of subduction megathrust slip is more localized than the prediction of numerical models (Wakabayashi 2015; Wakabayashi and Rowe 2015). The analysis of the internal deformation of OPS gives additional insight into subduction slip

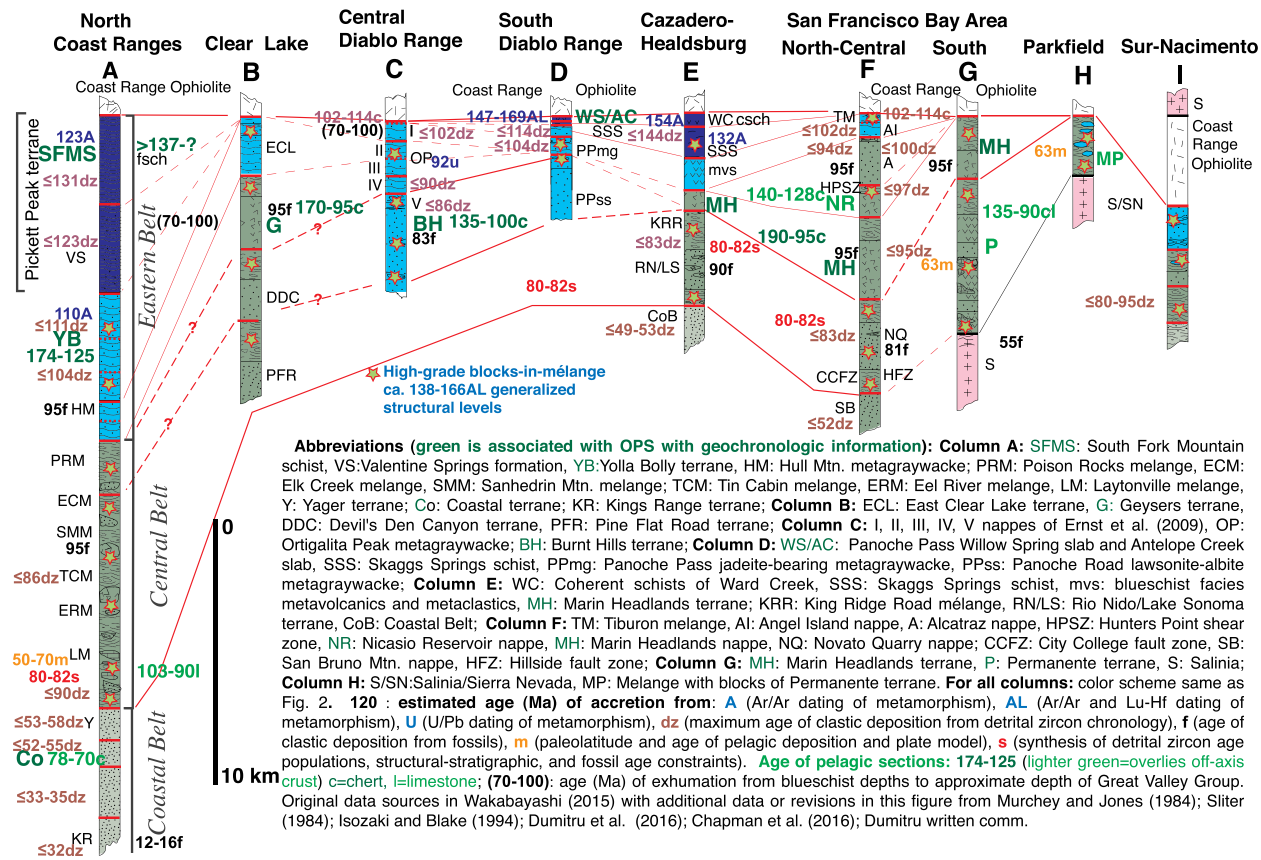

Fig. 3 Schematic diagram showing tectonic stacks of accretionary units in different parts of the Franciscan Complex. This shows the variability of the Franciscan accreted stack at different locations keyed to transects shown on Fig. 2. Units accreted at different times are separated by non-accretionary megathrust contacts shown in *bold red* (solid or dashed). Internal imbrication of each accreted unit is not depicted but the total structural thickness is estimated. The age of the pelagic sections of oceanic sections associated with accreted units is given in green but this information is not available for all units. The age of the oldest pelagic rocks in each unit approximates the age of the igneous oceanic crust. Accretion ages are also given based on different types of data, color coded with acronyms, updated from Wakabayashi (2015)

localization; new observations will be presented in “Imbrication and deformation of OPS and distinguishing tectonic from sedimentary melanges.”

The interpreted origin of the mélanges with exotic blocks as olistostromes suggests that they should be considered part of the trench-fill (clastic) component of larger scale OPS packages, whereas tectonic mélanges lack exotic blocks and formed by progressive deformation of OPS (Fig. 4) (Wakabayashi 2015). The proportion of mélange within the clastic units of the Franciscan varies from accreted unit to unit and spatially within each accreted unit.

Trace element and radiogenic isotopic data suggests that the high-grade coherent rocks and blocks-in-mélange have nascent island-arc protoliths (Wakabayashi et al. 2010), whereas lower grade coherent sheets of Franciscan metavolcanic rocks display ocean island basalt (OIB), or mid-ocean ridge (MORB), geochemical affinity (Shervais 1990; Ghatak et al. 2012). Metaigneous blocks-in-mélange, excluding the high-grade blocks, include those of OIB, MORB, and arc affinity (Macpherson et al. 1990).

Whereas the ages of clastic rocks in each accreted unit young structurally downward, the age of the oceanic crust subducted (and the age of this crust at time of subduction) shows a more complex relationship (Fig. 5a) (Wakabayashi 2015). Some of this complex age pattern resulted from periodic subduction of off-axis-generated oceanic crust, whereas the early (in subduction history) increase in the age of subducted oceanic crust has been proposed to have resulted from subduction of a dormant spreading ridge (Wakabayashi 2015). The subducted (dormant) ridge proposal conflicts with plate reconstructions that have not modeled a ridge crest near the trench at this time (Seton et al. 2012). The (dormant) ridge subduction proposal was based on geochronologic data as well as the temporal variation in peak metamorphism in the Franciscan (Wakabayashi 2015). Some of the data used to propose the (dormant) ridge subduction model was not available at the time Seton et al. (2012)) performed their analysis of paleoplate geometry. Data supporting the early increase in age of subducted oceanic

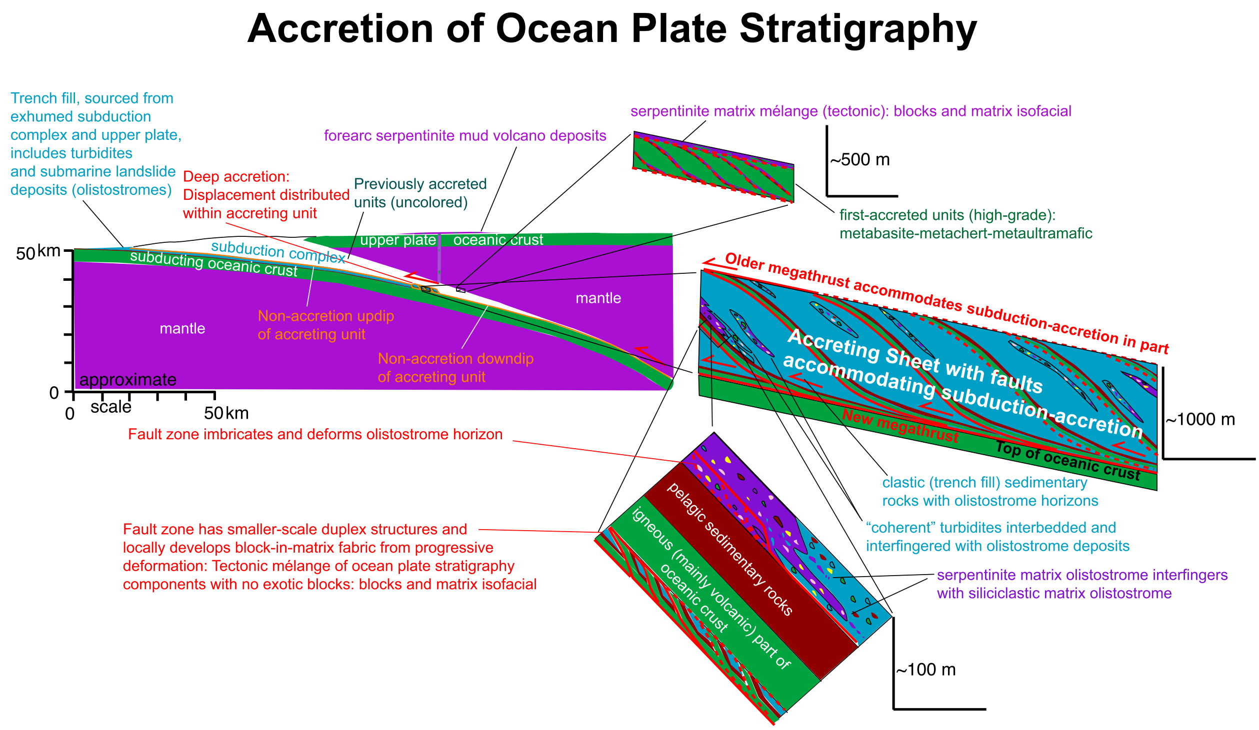

Fig. 4 Cross-sectional cartoon showing accretion of OPS and the connection between this process and the rock assemblages found in subduction complexes, including different types of mélanges. This schematic also illustrates that olistostromes of serpentinite and/or siliciclastic matrix comprise part of the clastic part of OPS

crust during Franciscan history was first presented Murchey and Blake (1993), who proposed that this age pattern resulted from subduction of an active spreading ridge at ca. 170, followed by conversion to a transform margin until initiation of new subduction at ca. 150.

Franciscan OPS sections have an apparent age gap of >10 Ma between the youngest pelagic rocks and the clastic cover, except for the OPS section of the Marin Headlands (Sliter and McGann 1992; Sliter 1984; Murchey and Jones 1984) (Fig. 5b). The age gap reflects the absence of the youngest part of the pelagic record rather than the oldest part of the clastic record because in several cases, the ages for the clastic section are maximum depositional ages. It is not clear whether the apparent age gaps are a product of the lack of original pelagic deposition during those times, excision of a deposited record by faulting and/or erosion, or incomplete biostratigraphic sampling.

Age-scaled depictions of OPS columns do not represent the relative proportions of the different OPS components in a subduction complex because the different components formed at different rates. For this reason, it is useful to consider the thickness-scaled columns of Fig. 5c for a graphical representation that better reflects the relative proportion of the various OPS components in the subduction complex.

The age relationships on Fig. 5 are a composite of the entire Franciscan Complex, and they do not necessarily reflect the subduction-accretion history at any specific reach of the trench. The accretionary unit stacks in Fig. 3 are arranged in approximate along-strike relative position after restoration of post-subduction dextral faulting. This figure illustrates the considerable along-strike variation in the Franciscan Complex, including along-strike variation in the age of oceanic crust subducted at approximately the same time. Age data is too sparse, however, to enable a more detailed analysis of the subducted plate history based on significant along-strike age variation as done by Osozawa (1994) for Japan.

For a number of the accretionary slices of the Franciscan shown in Fig. 3, ages of their assumed oceanic crustal base have not been determined because of the lack of identified pelagic-igneous imbricates, whereas the age of incorporation has been estimated from depositional ages of clastic sedimentary rocks. The schematic OPS accretionary stacks in Fig. 5b, c includes multiple accretionary units of Fig. 3 that lack pelagic-igneous imbricates and associated ocean crust age information.

In "Examples of the variety of **OPS** in the Franciscan Complex" that follows, Franciscan OPS assemblages will be categorized according to their lithologic assemblages. Following these descriptions, "Olistostromes as part of

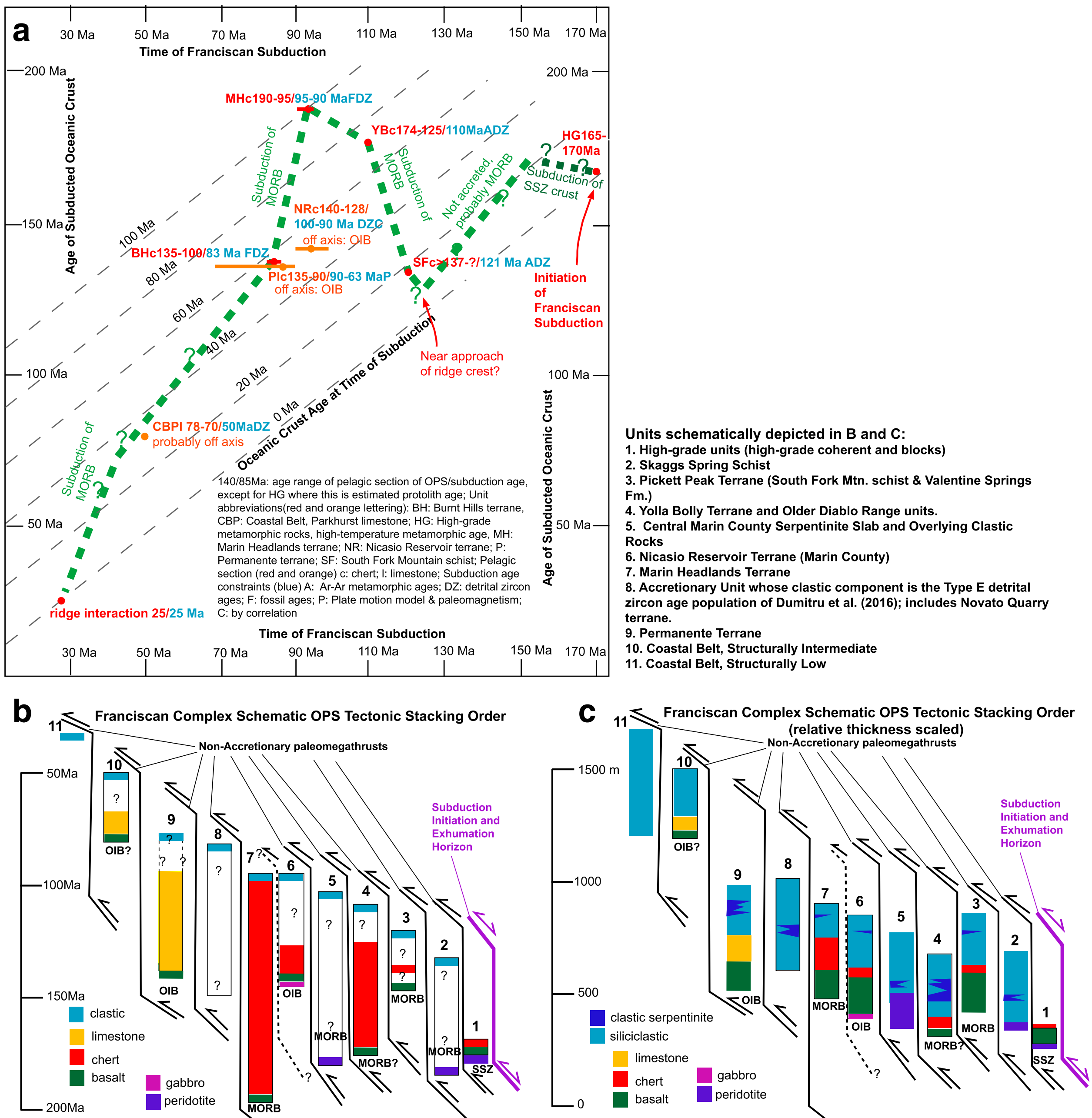

Fig. 5 a Subduction age versus ocean crust age for the Franciscan Complex. The *green dashed line* depicts the estimated age of subducted oceanic crust generated at an oceanic spreading center. For this reason, off-axis-generated oceanic crust plots younger than the *green dashed line* for any given age of subduction. Note that this diagram is a composite for the entire Franciscan Complex and does not address the potential for along-strike variation in the age of oceanic crust subducted. Existing age information (shown in Fig. 3) is insufficient at present to evaluate along-strike variation in age of subducted oceanic crust. Part a revised from Wakabayashi (2015). **b** Diagram showing the composite tectonic stacking of OPS that resulted from sporadic Franciscan subduction; the age ranges are from "**a**" and Fig. 3. As above, this is a composite of the Franciscan Complex and this does not represent a single reach along the subduction zone, and thus, it does not include all of the different accreted units. In addition, there are multiple accreted packages shown for which intact basalt and overlying pelagic sedimentary rocks have not been identified or dated. In this diagram, each accreted OPS package is separated by a non-accretionary paleomegathrust and the column height and vertical position is related to age. Accordingly, each column corresponds to an accreted unit between non-accretion megathrusts *within* a given accreted column stack on Fig. 3 rather than corresponding to an entire column on Fig. 3. The accreted OPS is imbricated by various faults that accommodated accretionary paleomegathrust zones (Fig. 4), but these are not shown on this figure. **c** Same OPS units as "**b**" but scaled to thickness within major imbricates rather than to age. This is not the total thickness of each accreted unit because each accreted unit is thickened as a result of imbricate fault repetition the clastic component of OPS" will review published work and present new data suggesting that olistostromes make up a significant component of the clastic part of OPS packages. "Imbrication and deformation of OPS and distinguishing tectonic from sedimentary melanges" will summarize the imbrication and deformation of Franciscan OPS, and "Franciscan OPS and tectonic history" will summarize the history of OPS accretion in the context of Franciscan tectonic history.

Examples of the variety of OPS in the Franciscan Complex

Basalt-chert-clastic

The most common type of OPS in the Franciscan Complex consists of basalt overlain by chert and then clastic sedimentary rocks. The basalt of most such packages exhibits mid-ocean ridge (MORB) geochemical affinity, based on comparatively sparse sampling (Shervais 1990; Ghatak et al. 2012). An exception is the Nicasio Reservoir terrane (Murchey and Jones 1984; Blake et al. 1984) that has mafic rocks of OIB affinity (Ghatak et al. 2012).

Basalt-chert-clastic OPS packages range from prehnite-pumpellyite facies for units such as the Marin Headlands and Nicasio Reservoir terranes (Wahrhaftig 1984; Blake et al. 1984) to epidote blueschist facies for the highest grade parts of the South Fork Mountain schist (Worrall 1981). The proportion of basalt and chert to clastic sedimentary rocks varies from basalt and chert-rich packages of the Marin Headlands terrane (Fig. 6) to the more common types that are dominated by clastic sedimentary rocks, such as the Sunol Regional Wilderness (Fig. 7), or the Pacheco Pass areas of the northern Diablo Range (e.g., Ernst et al. 2009). The structurally higher parts of Tiburon Peninsula of the San Francisco Bay region include a blueschist facies OPS unit of the basalt-chert-clastic type with a proportion of clastic rocks greater than Marin Headlands but less than the Diablo Range examples noted above (Bero 2014). Part of this unit (primarily the clastic component) is shown in the geologic map on Fig. 8, and the significance of these exposures will be discussed further in "Olistostromes as part of the clastic component of OPS."

The thickest stratigraphic section of chert, about 80 m, is associated with the Marin Headlands terrane, but chert horizons are thickened by thrust faults, so that structural thicknesses locally reach 300 m (Murchey 1984; Wahrhaftig 1984) (Fig. 6). The thickest chert section also records the longest depositional history of any pelagic section in the OPS of the Franciscan Complex, from Pliensbachian to Cenomanian (Murchey 1984) (Fig. 5). This is an age range of ca. 191–94 Ma, based on the 2016–12 International Commission on Stratigraphy (ICS) Time Scale (Cohen et al. 2013, updated). In addition, the Marin Headlands terrane was one of the first global localities where the fault repetition of the pelagic biostratigraphy was recognized, and the basalt-pelagic-clastic succession and its

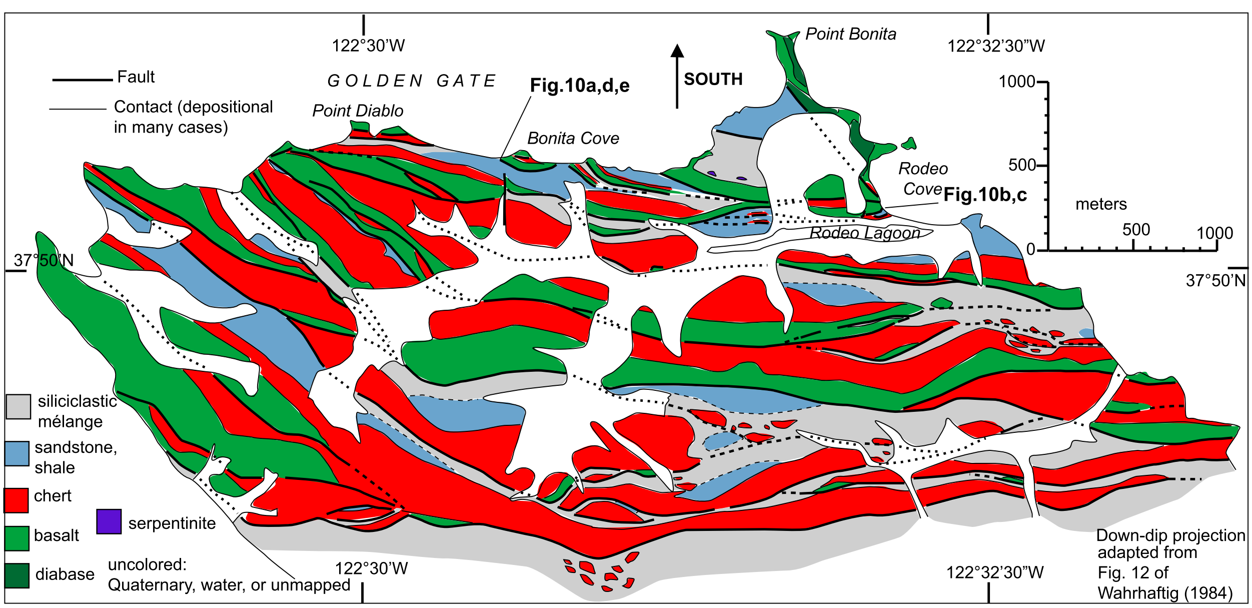

Fig. 6 Down-dip projection of the geology of the Marin Headlands region of the Franciscan Complex adapted from Wahrhafig (1984). Location on Fig. 2. This view illustrates the imbricate fault repetitions of prehnite-pumpellyite facies OPS and the true structural-stratigraphic thicknesses (from the down-dip projection) of the imbricates. This is the best example of OPS in the Franciscan Complex, but it has a higher proportion of volcanic rocks (basalt) and pelagic rocks (chert), than other OPS packages in the Franciscan

imbrication was linked to oceanic plate movement and subduction-accretion (Wahrhaftig 1984).

Chert horizons of tens of meters of structural thickness and less are typical. Volcanic sections attain structural thicknesses of up to about 500 m (Worrall 1981; Wahrhaftig 1984). Clastic sections reach thicknesses of up to about 1 km or more (e.g., Worrall 1981; Ernst et al. 2009; Prohoroff et al. 2012).

Basalt-limestone-clastic

A much less common type of OPS in the Franciscan Complex consists of basalt overlain by limestone overlain by clastic sedimentary rocks. The basalt of such packages exhibit ocean island basalt (OIB) geochemical affinity (Ghatak et al. 2012). Limestone is rare in the Franciscan Complex and much less abundant than chert (Sliter 1984). Limestone horizons are commonly tens of meters in thickness, and the thickest limestone horizon (130 m) is associated with the Permanente terrane (Sliter 1984). Owing to the faulting and deformation of the rocks, it is not clear whether this 130 m thickness was thickened relative to its original stratigraphic thickness by internal faults, but it probably was, by analogy to well-constrained chert exposures of the Marin Headlands as well as ubiquitous occurrence of imbricate faults in all OPS lithologies as will be reviewed in "Imbrication and deformation of OPS and distinguishing tectonic from sedimentary melanges." Much of the limestone section of the Permanente terrane is interbedded with chert (Sliter 1984; Murchey and Jones 1984). The longest duration of limestone deposition is recorded in the Permanente terrane ranges from early Albian to Turonian (Sliter 1984) (Fig. 5)

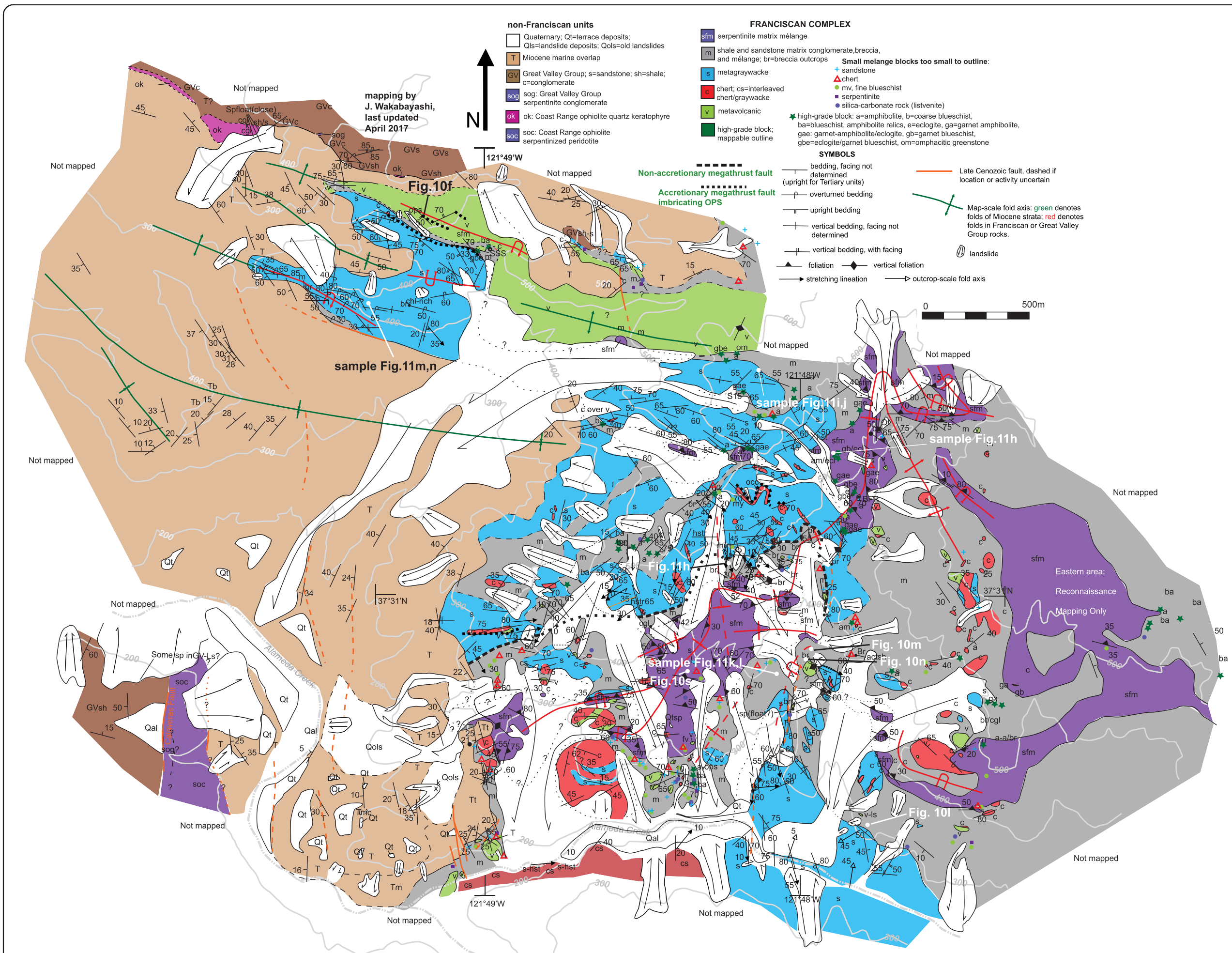

Fig. 7 Geologic map of part of Sunol Regional Wilderness in the northern Diablo Range. Location on Fig. 2. This is an example of OPS imbricates that are much richer in clastic rocks. Here, the OPS imbricates are metamorphosed to blueschist facies. The clastic rocks have a significant olistostromal component and include serpentinite matrix as well as siliciclastic matrix olistostromes, and these olistostromal units apparently interfinger with ordinary turbidite units. Repetitions of OPS in the most clastic rich parts of this region (southern part of map) are difficult to identify owing to the difficulty in distinguishing intact slices of basalt and chert from olistostrome blocks. In the more volcanic-rich area to the north, two of the imbricates are difficult to locate owing to the small amount of clastic and/or pelagic rocks associated with the fault repetition. Updated from Wakabayashi (2016b)

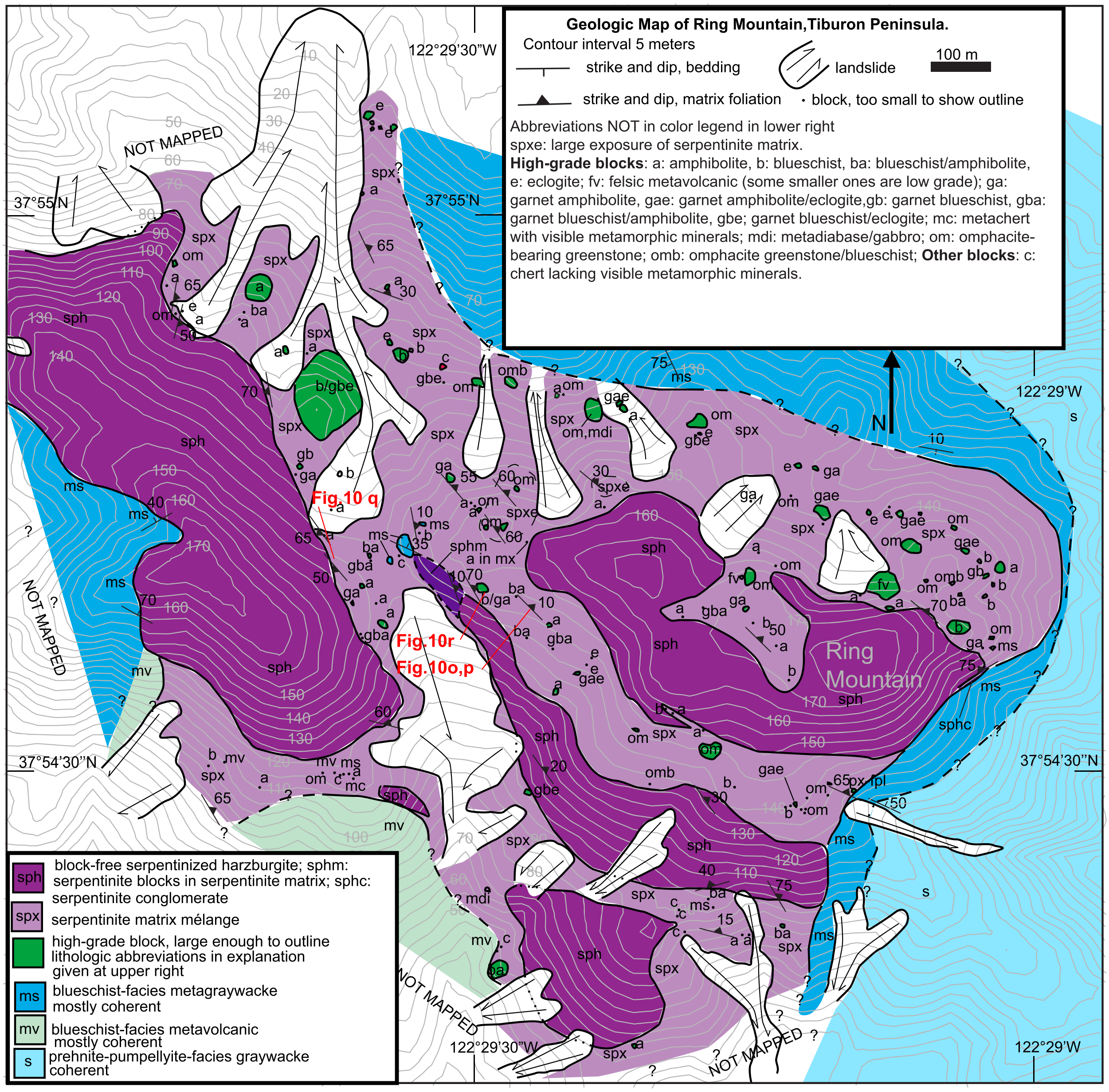

Fig. 8 Geologic map of the Ring Mountain area, San Francisco Bay area. Location on Fig. 2. This locality includes an example of sedimentary serpentinite mélange that is part of a clastic component of an accreted OPS unit, most likely of the basalt-chert-clastic type (Bero 2014). Some of the high-grade metamorphic blocks within the mélange may preserve metabasalt-metachert-metaultramafic OPS imbricates internally, preserving at a smaller scale the relationships seen in map view in the Willow Spring slab locality of Fig. 9 (see Fig. 10s). Updated from Wakabayashi (2015)

or ca. 110–90 Ma (Cohen et al. 2013, updated). The Permanente terrane has a significant clastic component, but it is less than most Franciscan units excluding the Marin Headlands. This clastic component is primarily siliciclastic, including siliciclastic-matrix mélange, but it may include sedimentary serpentinite mélange as well (Wakabayashi 2012).

Other limestone-bearing OPS units of the Franciscan include the well-known Laytonville limestone (Alvarez et al. 1980; Tarduno et al. 1990) that has a pelagic age range that overlaps with the Permanente terrane, as well as younger limestone units, such as the Parkhurst limestone (Sliter 1984). The far-traveled nature of limestone-bearing OPS has been shown by paleomagnetic studies, and the Laytonville limestone remains an enigma owing to the anomalously rapid plate motions indicated by the combination of paleomagnetic and biostratigraphic data (Alvarez et al. 1980; Tarduno et al. 1990). A new estimate for an older accretion time of the limestone based on new data from associated clastic rocks would require even higher apparent plate motions (Wakabayashi 2015).

Serpentinite-basalt-chert (with no siliciclastic rocks)

The structurally highest horizons of the Franciscan Complex include rare sheets of coarse-grained metamorphic rocks ranging up to several kilometers in long dimension and several hundred meters in thickness. These slabs have been called “high-grade coherent sheets” to distinguish them from high-grade blocks-in-mélange that have the same metamorphic mineral assemblages, lithologies, geochenmical affinity, and metamorphic ages (Wakabayashi et al. 2010).

The Willow Spring slab of the southern Diablo Range is one of the largest such slabs and serves as a good example of the characteristics of such units. It consists of an imbricate stack of primarily mafic schists ranging from medium to coarse-grained lawsonite blueschist at structurally lowest level to eclogite at the structurally highest level (Wakabayashi and Dumitru 2007) (Fig. 9). This stack of dominantly metabasite sheets structurally overlies a structural stack of metasandstones. The Willow Spring slab covers a map area of about 2 km long by 1 km wide with a structural thickness of several hundred meters. Several similar, but smaller, intact imbricated metamorphic slabs crop out in the southern Diablo Ranges, and these include slabs of predominantly amphibolite and garnet-amphibolite (Wakabayashi and Dumitru 2007) and another high-grade slab has been identified at Goat Mountain in the eastern part of the northern Coast Ranges (Ernst et al. 1970). In addition, part of the Cazadero-Ward Creek area in the western part of the northern Coast Ranges, several kilometers in long dimension, shows similar characteristics (Wakabayashi and Dumitru 2007; Wakabayashi et al. 2010).

Metabasite predominates in these high-grade rocks and has nascent island-arc affinity (Wakabayashi et al. 2010). Metachert horizons are spatially associated with antigorite schist bodies so that the inferred ocean floor stratigraphy was one where serpentinized mantle rocks were overlain by basalt and chert successively. Metaclastic rocks are absent in this package.

High-grade blocks in mélange have similar lithologic associations on a smaller (≤200 m) scale. They are composed predominantly of metabasite with small metachert layers and lack metaclastic components. Whereas they are commonly at least partly encased by actinolite-phengite-chlorite “rinds” derived from metasomatized ultramafic rock (e.g., Coleman and Lanphere 1971; Ghatak et al. 2012; Sorensen et al. 1997), some also include metaultramafic layers within them as described in “Imbrication and deformation of **OPS** and distinguishing tectonic from sedimentary melanges.”

Serpentinite-clastic

Serpentinized peridotite lacking block-in-matrix character (“coherent”) is also found within the Franciscan Complex (Wakabayashi 2004; Prohoroff et al. 2012; Wakabayashi 2015; Wakabayashi, in press). These serpentinite bodies range in structural thickness up to 1.5 km and extend for up to 30 km along strike, preserve primary peridotite textures in large domains, and lack non-serpentinite blocks other than rare gabbro (Wakabayashi 2004; 2012; 2015; in press). The serpentinized ultramafic rocks vary in texture from massive to areas with massive blocks surrounded by zones with brittle foliation, to pervasively foliated rocks. The dominant serpentine mineral in these rocks is lizardite (Wakabayashi 2004; in press). Prohoroff et al. (2012) proposed that clastic sedimentary rocks depositionally overlie the larger bodies in Marin County (“sfs” label directly above “Marin Headlands vfr” label on Fig. 2), but the contact relationships are disputed (Raymond and Bero 2015). Basalt and/or pelagic sedimentary rocks do not appear to depositionally overlie these serpentinite bodies. The parent peridotite has abyssal affinities, based on whole rock and mineral geochemistry (Barnes et al. 2013), which distinguishes it from the upper plate (Coast Range ophiolite) serpentinized peridotite, which has both arc and abyssal affinity (e.g., Choi et al. 2008; Jean et al. 2010).

Metaclastic rocks are imbricated with and may depositionally overlie serpentinized peridotite, exposed in the northwestern Diablo Range along Kincaid Road (Fig. 10i, j). The serpentinite makes up an exposure about 5.5 km long by up to 800 m wide (Wentworth et al. 1999). Most of this body is massive serpentinized harzburgite with local foliated zones. A schistose metasandstone that has been correlated to the Skaggs Springs schist of Sonoma County (Wakabayashi 1999) is locally imbricated with the serpentinite (Fig. 10k). At least one of the contacts of metasandstone on serpentinite may be depositional based on the presence of small blocks of silica-carbonate rock (Fig. 10j), a hydrothermal replacement of serpentinite also referred to as listvenite (e.g., Halls and Zhao 1995; Smith et al. 2008).

Serpentinized peridotite capping Tiburon Peninsula, including the Ring Mountain locality (Fig. 8), has been interpreted as being abyssal in origin and thus of intra-Franciscan affinity (Barnes et al. 2013), but clastic rocks have not been found in depositional contact atop this serpentinite unit (Bero 2014). This serpentininized harzburgite sheet tectonically overlies serpentinite matrix mélange interpreted to be sedimentary origin by Wakabayashi (2012; 2015; additional evidence for sedimentary origin presented in “**Sedimentary origins of mélanges with exotic blocks: interbedding with siliciclastic turbidites and internal sedimentary features**”).

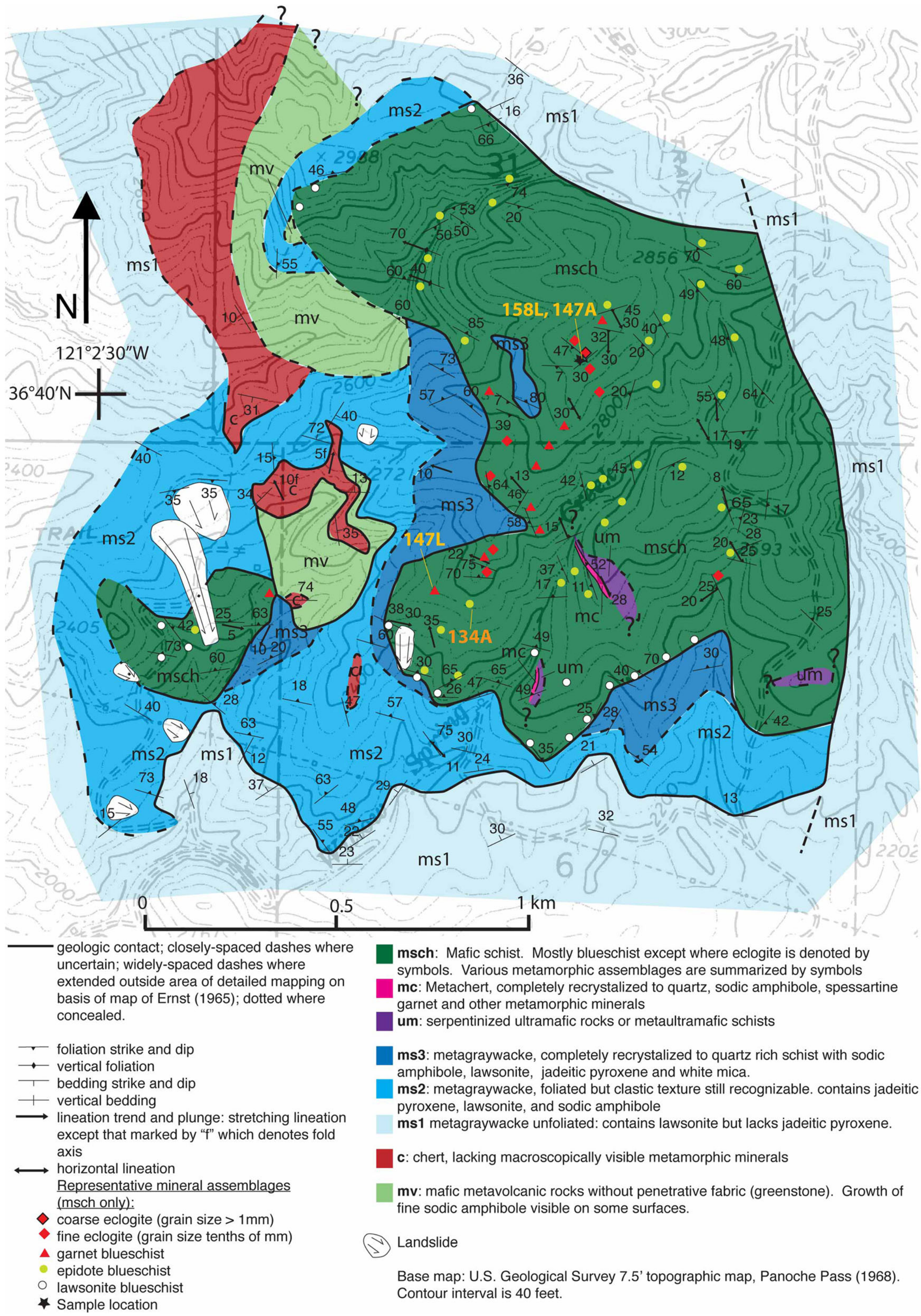

Fig. 9 (See legend on next page.)

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Fig. 9 Geologic map of the Willow Spring slab, southern Diablo Range. Location on Fig. 2. These (*dark green*, *purple*, and *magenta colors*) are among the highest grade coherent (non-mélange) rocks in the Franciscan Complex and are completely recrystallized and schistose. The Willow Springs slab is an example of OPS that is predominantly metabasite, with minor ultramafic schist and metachert, but no metaclastic rocks. These rocks tectonically overlie intact lower grade units including a *blueschist facies unit* with abundant metavolcanics (mov) and metachert (s) in addition to siliciclastic (mostly sandstone, ms2). The reconnaissance mapping done here did not completely define the extent of metachert and metaultramafic horizons in the high-grade rocks, but they certainly extend further along strike than shown. Adapted from Wakabayashi (2015)

Basalt-limestone-chert-clastic or basalt-chert-limestone-clastic

As noted earlier, limestone is rare in the Franciscan Complex and most of it is part of basalt-limestone-clastic sequences. A very small amount of limestone is present in sequences where basalt is successively overlain by chert and limestone. An example from an apparent coherent imbricated assemblage of blueschist facies rocks with this assemblage crops out along the Skaggs Road in Sonoma County (Fig. 10g). This unit may extend over a kilometer along strike based on my field reconnaissance; published data on this unit is otherwise lacking. The limestone appears limited to a thickness of 20 cm or less, whereas metchert, metabasalt, and metaclastic rocks may reach thicknesses of 10 m, several hundred meters, and about 1 km, respectively. Even rarer in the Franciscan is OPS composed of basalt overlain successively by limestone, chert, and clastic rocks. To my knowledge, these assemblages have not been previously reported in the literature on the Franciscan, but minor exposures are found as small (<20 m in size) blocks-in-mélange at Sunol Regional Wilderness (Fig. 10h).

Olistostromes as part of the clastic component of OPS

Clastic components of Franciscan OPS units are composed of variable proportions of turbidite and mélange with non-native (exotic) blocks, including those of higher metamorphic grade than the matrix. This type of mélange has been suggested to have formed by submarine sliding (as an olistostrome) prior to subsequent deformation as summarized previously (Macpherson et al. 1990; Wakabayashi 2015). The olistostromal horizons have siliciclastic or serpentinite matrix, and these matrix types may grade into and interfinger with each other as proposed by Wakabayashi (2015) and schematically shown in Fig. 4. New evidence for gradation between siliciclastic and clastic serpentinite rocks will be presented in "Interfingering, interbedding, and gradation between siliciclastic rocks and clastic serpentinite." Interbedding of siliciclastic olistostromal horizons and turbidites was proposed by Wakabayashi (2015), and additional information will be presented in "Sedimentary origins of mélanges with exotic blocks: interbedding with siliciclastic turbidites and internal sedimentary features," along with photographs showing sedimentary textures in siliciclastic and serpentinite matrix.

Sedimentary origins of mélanges with exotic blocks: interbedding with siliciclastic turbidites and internal sedimentary features

The interbedding and interfingering of sedimentary mélange and turbidites (bedded sandstone and shale) is suggested by 100 m to kilometer scale field relationships at Sunol Regional Wilderness, where the sedimentary mélange horizons include those of siliciclastic and serpentinite matrix (Fig. 7). Outcrop scale relationships from meter to 100 m scale show interbedding of siliciclastic turbidites and olistostromal horizons at many Franciscan localities (Wakabayashi 2015).

The clastic part of the Marin Headlands unit contains mélange horizons and beachcliff exposures locally show the matrix of these mélanges to be mud-rich conglomerate, pebbly sandstone, and clean sandstone (Fig. 10a, d, and e). These block-in-matrix horizons grade into or are interbedded with block-free sandstone, shale, and conglomerate (Fig. 10a). The blocks in the mélange are predominantly sandstone, chert, and basalt of prehnite-pumpellyite grade, but detailed studies have not been done to determine whether these rocks are the same as the intact Marin Headlands imbricates that have similar general character. Serpentinite blocks to tens of meters in size are present in some of the mélange zones of the Marin Headlands are (Wahrhaftig 1984). Some serpentinite blocks are found in the colluvial and landslide material draping part the outcrop shown in Fig. 10a, and the position of these blocks suggests derivation from the exposed block-in-matrix horizons. Serpentinite clasts are found in the pebbly sandstone matrix of Fig. 10d, and the tremolite-bearing metamorphic assemblage of some of these clasts (Fig. 11a) records a higher temperature metamorphism than the prehnite-pumpellyite metamorphic assemblages of the host rock and the other blocks observed.

Along Panoche Road in the southern Diablo Range, blocks of up to tens of meters in size, including serpentinite and high-grade (amphibolite, garnet-amphibolite, eclogite) rocks, as well as lower-grade (blueschist facies) blocks of a variety of lithologies, are embedded in blueschist facies siliciclastic conglomerate/sedimentary matrix (Wakabayashi 2015). The matrix contains centimeter- and millimeter-sized clasts that reflect the same lithologic range as the larger blocks. These mélange horizons are interbedded with block-free sandstone and pebbly

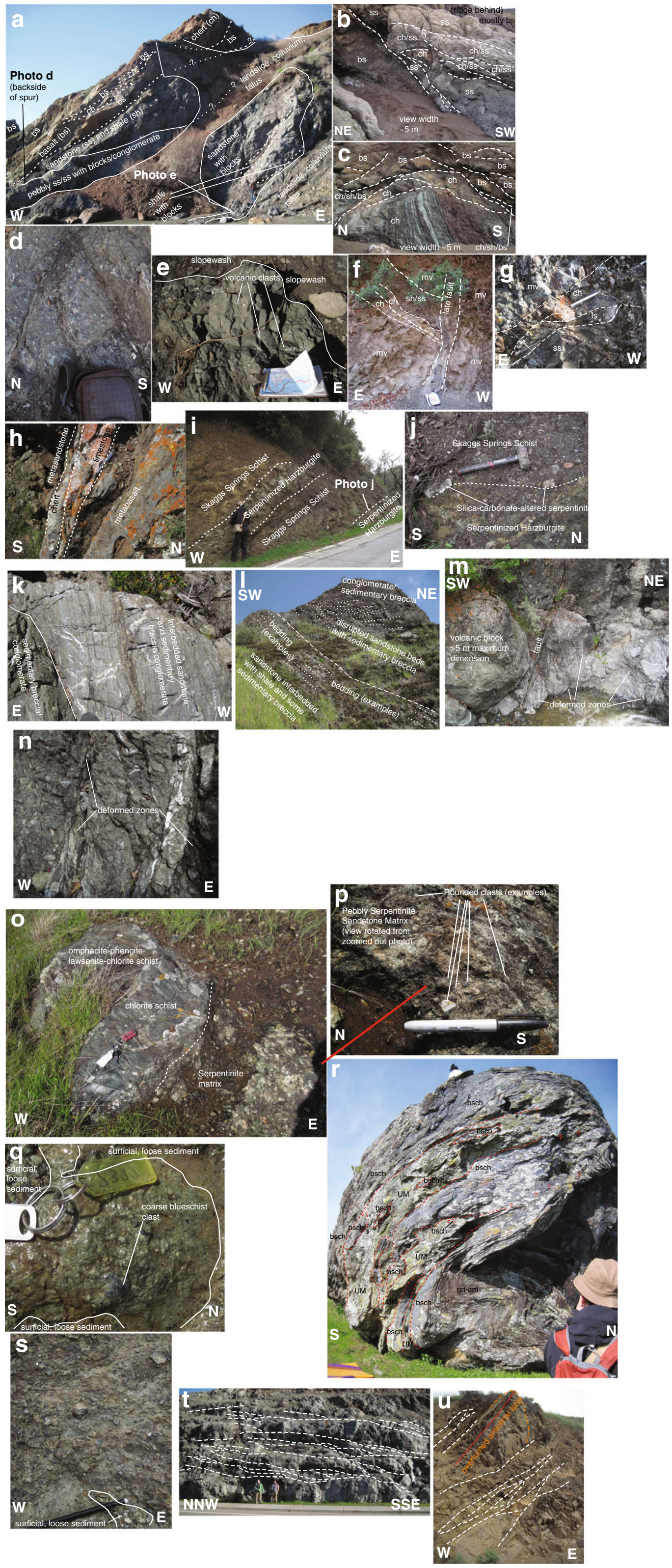

Fig. 10 (See legend on next page.)

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Fig. 10 Field photographs of OPS in the Franciscan Complex. In these photos, all contacts (*dashed lines*) of apparent "inverted" OPS stratigraphy (such as basalt over chert or sandstone, or chert over sandstone) and "omitted" OPS (clastics over basalt when pelagic rocks are present in the full sequence) are faulted. Some of the contacts in "normal" OPS stratigraphic order are depositional whereas others are faults. *Dashed lines* drawn within the same lithology represent faults. **a** Marin Headlands, prehnite-pumpellyite facies OPS imbricates at the western side of Black Sand Beach, Bonita Cove (Fig. 6), where basalt and chert (itself internally imbricated) is thrust over siliciclastic rocks. Whereas the siliciclastic section is primarily bedded with local broken formation, sedimentary mélange/conglomerate horizons are present. "**b**" and "**c**" show outcrops within the Rodeo Cove shear zone of the Marin Headlands (Fig. 6), a locality described in detail in Meneghini and Moore (2007). At the scale of Fig. 6, the Rodeo Cove shear zone is one of the faults repeating the OPS section and this imbrication is seen on a smaller scale within the shear zone itself as shown in the outcrop photos. The imbrication locally leads to block-in-matrix relationships such as the chert-in-sandstone seen in the "ch/ss" parts of "**b**", the basalt in basalt matrix part (labeled as "bs"), and the basalt and chert in shale matrix ("ch/sh/bs") part of "**c**". "**d**" and "**e**" show close ups of sedimentary block-matrix horizons in the outcrops of ("**a**"). **d** Pebbly mud-rich sandstone/conglomerate. This conglomerate grades into cleaner sandstone with blocks shown in ("**e**"), and this is interbedded with deformed shale with blocks of other lithologies. These sorts of textures and relationships are common in siliciclastic matrix mélange as seen in "**k-n**" as well as Figs. 16, 17, 18, and 20 of Wakabayashi 2015). **f** Siliciclastic-chert-basalt OPS from blueschist facies rocks, Sunol Regional Wilderness. The preserved parts of chert and siliciclastic sections in the imbricates of mainly metavolcanic exposures are very thin in this area (commonly <10 m and too small to show on the Fig. 7 map). **g** OPS stack of sandstone-limestone-chert-basalt in blueschist facies rocks along the Skaggs Road, Sonoma County (location on Fig. 2). This type of OPS stack is very rare in the Franciscan. **h** Block-in-sandstone matrix, Sunol Regional Wilderness showing OPS of sandstone overlying chert overlying limestone that overlies basalt. Coherent imbricates of this type of OPS have not been found to date in the Franciscan. **i** Skaggs Spring schist (completely recrystallized quartz-rich glaucophane-lawsonite-phengite ± jadeite schist) imbricated with intact serpentinized peridotite. Close up in "**j**" shows silica carbonate rock (hydrothermally replaced serpentinite, also called listvenite) blocks along one of the contacts that places Skaggs Springs Schist on serpentinite. This may represent a depositional contact. Note that there is a lot of surficial material draped over the outcrop in this photo. **k** Photo showing interbedded sandstone and pebbly sandstone and shale matrix sedimentary breccia/conglomerate, blueschist facies rocks along Panoche Road (location on Fig. 2). This shows the interbedding of ordinary turbidites and sedimentary mélange matrix. These horizons locally have blocks of tens of meters in size (compare with different photos in Fig. 18 of Wakabayashi 2015). **l** Interbedding of sedimentary breccia/conglomerate and sandstones and gradational depositional contact between sedimentary breccia/conglomerate (sedimentary mélange matrix), blueschist facies rocks, Sunol Regional Wilderness (location on Fig. 7). The elevation difference between the bottom of the photo and top is about 15 m. **m, n** Sunol Regional Wilderness exposures showing local deformational overprint on conglomerate/sedimentary breccia that makes up the siliciclastic mélange matrix in this area. In "**m,**" note the pencil on the center of the upper photo border for scale. In addition to the locally developed deformational fabric, note the late brittle fault in ("**m**"). The most deformed zones in these outcrops are typical of what has been interpreted as "tectonic" mélange matrix in the Franciscan Complex. **o**–**r** Sedimentary serpentinite mélange, Ring Mountain (locations on Fig. 8) **o** metamafic block in sedimentary serpentinite matrix. The block is an omphacite-chlorite schist on the left side of the photo (chlorite replaces most of the omphacite and there is late growth of lawsonite), and this grades to or is bordered by nearly monomineralic chlorite schist on the right. The matrix is serpentinite conglomerate and sandstone with many exotic clasts ranging from <0.1 mm to cm scale. **p** Close up of part of "**o**" showing texture of serpentinite conglomerate/pebbly sandstone. **q** Close of a separate outcrop of sandy/pebbly serpentinite matrix with many rounded grains, including a coarse blueschist clast. **r** Mafic block in serpentinite matrix, showing internal faulting and folding. The block is garnet amphibolite (grt-am) nearly completely overprinted by blueschist facies assemblages (bsch) in most areas. The block is internally imbricated and tightly folded resulting in repetitions of mafic (bsch/grt-am) and metaultramafic (UM) schist. The latter is composed of tremolite/actinolite + phengite + chlorite. Progressive deformation has created local block-in-matrix textures in which mafic blocks (bsch) are enclosed in metaultramafic schist (UM). Most of these block-in-matrix features are too small to be seen in this photo. Similar features are present in other blocks in this mélange. They apparently predate the incorporation into the clastic serpentinite matrix which is not part of the imbricates. The features preserved in these blocks may preserve an ocean plate stratigraphic relationship similar to that shown at map scale in Fig. 9 (Willow Spring Slab). **s** Pebbly serpentinite sandstone matrix from Sunol Regional Wilderness (location on Fig. 7) showing well-preserved sedimentary texture. This type of material lacks erosional resistance and tends to be poorly exposed, except on the steepest slopes or artificial excavations. **t, u** Examples of imbrication of siliciclastic (sandstone and shale) (locations on Fig. 2). Without good exposures, these structures are much more difficult to identify in these rocks in contrast to rock assemblages with volcanic and/or pelagic sedimentary rocks. "**t**" shows exposures of the prehnite-pumpellyite facies Novato Quarry terrane along Nave Drive in Marin County and "**u**" shows lawsonite-albite facies rocks that may be correlative to the Burnt Hills terrane along Panoche Road of the southern Diablo Range. For a higher resolution image, please see Additional file 1

sandstone at scales as small as centimeters, and the mélange matrix is commonly more mud rich than the interbedded sandstones as reflected by the darker gray color (Fig. 10k; compare with Fig. 18b, f of Wakabayashi 2015).

The blueschist facies rocks of Sunol Regional Wilderness of the northern Diablo Range include units of siliciclastic and serpentinite matrix mélange with high-grade blocks that include eclogite, garnet-amphibolite, and amphibolite to tens of meters in size, as well as a variety of lower grade (blueschist facies) lithologies ranging to block sizes of several hundred meters (Wakabayashi 2015) (Fig. 7). Several outcrops show interbedding of siliciclastic matrix, composed of conglomerate and sedimentary breccia, with block-free sandstone and shale (Fig. 10l). This matrix has centimeter and millimeter size clasts with the same lithologic range as the larger blocks (Wakabayashi 2015). Nearly undeformed conglomerate and sedimentary breccia is variably overprinted by later deformation, so that it grades into strongly deformed mélange matrix (Fig. 10m, n). The derivation of sheared matrix from conglomerate and sedimentary breccia has been shown for multiple Franciscan localities by Wakabayashi (2015, Figs. 16–18, 20). The inhomogeneous distribution of the later deformation results blocks of less-

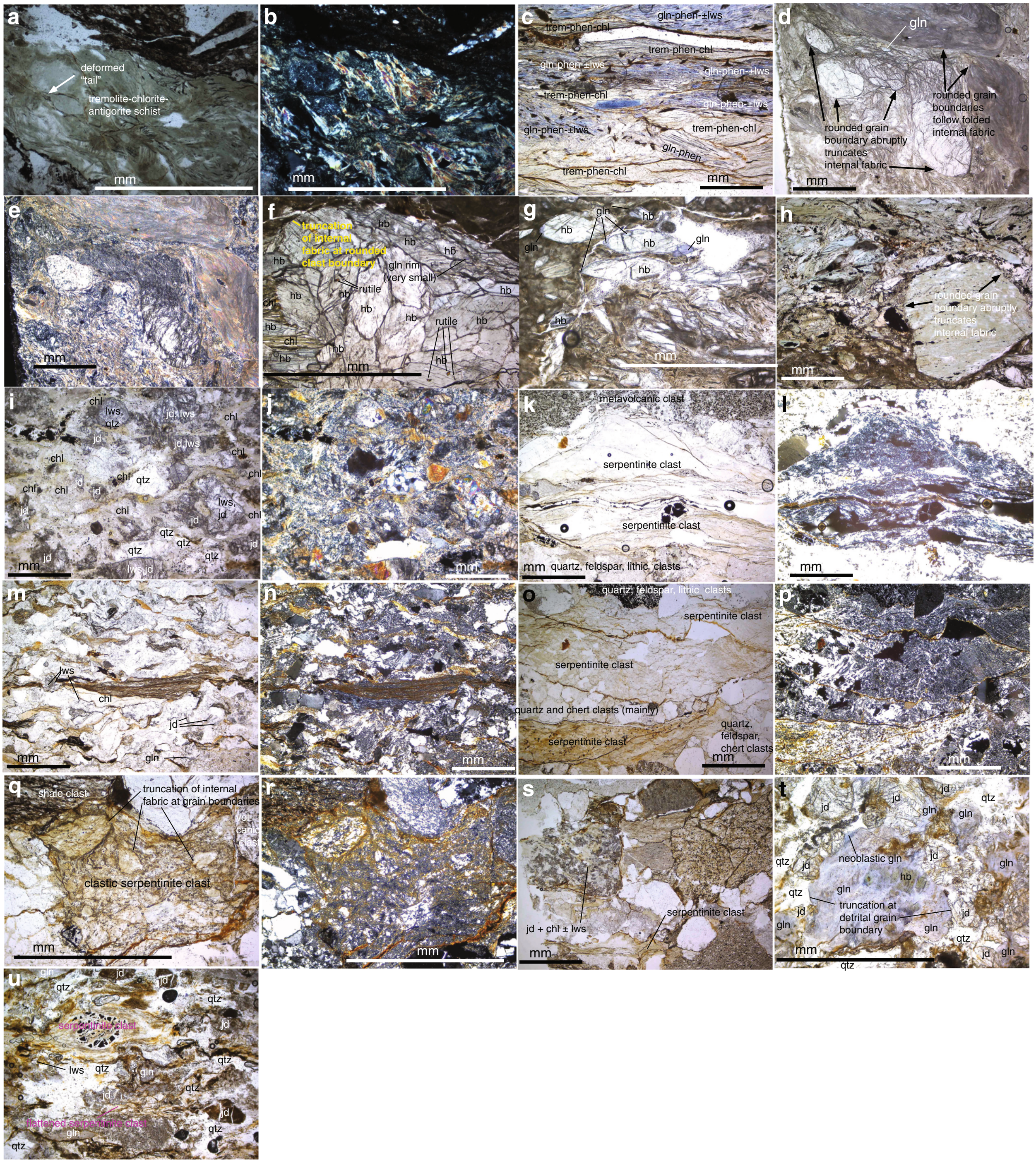

Fig. 11 (See legend on next page.)

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Fig. 11 Photomicrographs of clastic parts of OPS of the Franciscan Complex with emphasis on the clastic/olistostromal horizons. Mineral abbreviations are *chl* chlorite, *gln* glaucophane, *hb* hornblende, *jd* jadeitic clinopyroxene, *lws* lawsonite, *phen* phengite, *qtz* quartz, *trem* tremolite/actinolite. **a** Metaultramafic schist clast in the pebbly sandstone from Marin Headlands shown in Fig. 10d. The metamorphic assemblage in this clast is higher grade than the prehnite-pumpellyite facies host rock. Note that this clast exhibits an internal fabric that predates deposition, and this fabric appears to be the result of progressive deformation of serpentinized peridotite, rather than a deformational overprint on metaultramafic sandstone of the sort shown in "**e**" and ("**i**"). Plane light. **b** Cross-polarized light view of ("**a**"). **c** Imbricate and block-in-matrix zone in metaultramafic schist from the block in Fig. 10r, showing alternating blueschist layers and lenses with abundant sodic amphibole (*blue* in this plane light view) and pale tremolite/actinolite (trem)-phengite (phen)-chlorite (chl) schist. Note the contrast in textures between the metaultramafic schist and the serpentinite/metaultramafic sandstones shown in "**d**, **e**, **g**, and **h**," as well as the clast in ("**q**"). **d** Serpentinite sandstone matrix from the outcrop in Fig. 10o at Ring Mountain. The clasts in this view are primarily antigorite schist (*lighter colored*) or tremolite schist (*darker*). Although some of the rounding of the grains is a result of the folding of these grains (two examples shown with *arrows*) and development of locally curved shears, there are many rounded grain boundaries that abruptly truncate the internal grain fabric without drag; these are original detrital grain boundaries (examples shown by *arrows*). Plane-polarized light. **e** Cross-polarized light view of ("**d**"). **f** Rutile-bearing hornblendite clast (long dimension about 5 cm) in the same serpentinite matrix sampled about 1 m away from the sample in ("**d**"). The internal fabric in this clast is truncated along the rounded grain boundary with the enclosing serpentinite sandstone/conglomerate (*dark*) without drag features (most apparent in *the upper left hand part* of the view). Hornblende (*hb*) locally has small glaucophane (*gln*) rims, and there is some late growth of chlorite (*chl*). This is a cm-scale analog of the larger high-grade blocks found in this mélange. Plane-polarized light. **g** Serpentinite matrix from the same locality showing hornblende (*hb*) grains, some of which are rounded and rimmed with glaucophane (*gln*). Note the truncation of the hornblende and rim against the rounded grain boundary, best seen at the left-rounded termination of the *hb* grain in *the upper left corner* of the photo. Other grains in this view include tremolite/actinolite, and chlorite-tremolite-antiorite schist. Plane-polarized light. **h** Serpentinite matrix from serpentinite mélange, Sunol Regional Wilderness (sample location on Fig. 7) showing abrupt truncation of internal grain fabric along grain boundaries, similar to that seen at the Ring Mountain locality. Clasts in this view are primarily antigorite-chlorite schist with some grains of tremolite/actinolite, hornblende, and chlorite. Plane-polarized light. **i** Chlorite-rich sandstone from Sunol Regional Wilderness (Fig. 7). This sandstone is *medium green* in outcrop and resembles clastic serpentinite in outcrop appearance. Much of the chlorite rich zones (*chl*) have fine greenish phengite, and polycrystalline growths of chlorite form textures similar to antigorite schist. Chrome spinel is locally present in the chlorite-rich zones. The chlorite-rich zones probably originated as serpentinite clasts. Other clasts or minerals include jadeitic clinopyroxene (*jd*), lawsonite (*lws*), quartz (*qtz*), and glaucophane. Some of the metamorphic mineral grains are part of polymineralic clots (*jd*, *lws* or *lws*, *qtz* or *jd*, *lws*, *qtz*) and the polymetamorphic clots, and many of the metamorphic mineral grains have rounded grain boundaries that truncate their internal fabric, suggesting a detrital origin. Many of these grains also exhibit late neoblastic overgrowths with sharp terminations. Plane-polarized light. **j** Cross-polarized light view of ("**i**"). **k** Serpentinite clast with chrome spinel in mostly siliciclastic conglomerate, Sunol Regional Wilderness. Long dimension of the clast is about 10 mm. Such serpentinite clasts make up 5–10% of the clasts in some horizons in this conglomerate. Plane-polarized light. **l** Cross-polarized view of ("**k**"). **m** Sandstone that makes up most of non-mélange siliciclastic outcrops at Sunol Regional Wilderness. This sandstone has much less chlorite than "**i**," but some chlorite (*chl*) clasts have the appearance of serpentinite (best viewed in the cross-polarized light view of "n") such as the clast labeled that is directly below the shale chip in the center of the photo. This sample has neoblastic lawsonite (*lws*), jadeitic clinopyroxene (*jd*), and glaucophen (*gln*), but relict albite is still present as seen by the albite twinning seen in the cross-polarized light view of "**n**" (good example along *the upper left edge of photo*). **o–u** El Cerrito quarry area, eastern San Francisco Bay area (general location on Fig. 2). Two serpentinite clasts from prehnite-pumpellyite siliciclastic conglomerate, matrix of the Hillside mélange unit. This conglomerate/pebbly sandstone contains up to 15% serpentinite clasts. This photo shows a lizardite-rich and an antigorite-rich clast, both of which appear to have been derived from intact peridotite (they are not themselves clastic). Plane-polarized light. **p** Cross-polarized light view of ("**o**"). **q** Serpentinite sandstone clast from the same thin section showing the internal rounded grains that truncate fabric within them. Compare to the serpentinite matrix samples shown in "**d**" and ("**h**") The grains are primarily antigorite schist. Plane-polarized light. **r** Cross-polarized light view of ("**q**"). **s** Clast with jadeite-chlorite ± lawsonite, along with another serpentinite clast in the same thin section. **t** View of blueschist facies metasandstone unit of the upper El Cerrito quarry. This particular sample consists of more than 50% detrital blueschist clasts, most of which have hornblende relics. Much of the *blue* amphibole growth is truncated on the detrital grain boundaries indicating that these were blueschist-overprinted amphibolite clasts (equivalent of the high-grade blocks) at the time of deposition. There is also some late neoblastic glaucophane growth along one of the margins of this clast. **u** Same unit as "**t**" collected about 10 m away showing serpentinite clast with chrome spinel. For a higher resolution image, please see Additional file 2

deformed mélange surrounded by more strongly deformed zones (Wakabayashi 2015).

It is more difficult to demonstrate sedimentary features of serpentinite mélanges than siliciclastic matrix mélanges because apparent rounding of grains in the former may take place by two different tectonic mechanisms: (1) the formation of curved shear surfaces and (2) the tight folding early-formed fabrics that result in rounded apparent clast borders formed from detached fold hinges. For this reason I present outcrop and petrographic thin section photos showing what I interpret as sedimentary textures with goal of presenting more convincing relationships than those shown in my earlier papers (Wakabayashi, 2012; 2015). In addition, recent work allows a direct comparison between the textures observed in these Franciscan serpentinite mélanges to the GVG serpentinite deposits that are indisputably sedimentary in origin (e.g., Moiseyev 1970; Lockwood 1971; Phipps 1984; (Wakabayashi 2016b; Wakabayashi, in press).

Franciscan clastic serpentinite mélanges have comparatively fine-grained matrix that crops out poorly, and when it does, it forms outcrops that appear powdery from a distance owing to the lack of large pieces of more intact rock (Wakabayashi, in press). This contrasts with the blockier appearance of intact (not mélange) Franciscan serpentinized peridotite slabs or the ultramafic sections of the CRO, but is identical to the appearance of the GVG sedimentary serpentinites (Wakabayashi in press). Exposures of Franciscan serpentinite matrix range from serpentinite sandstone to serpentinite conglomerate/sedimentary breccia (Fig. 10o–s; see also Fig. 6a, b, Fig. 9 of Wakabayashi 2012, and Fig. 21c–f of Wakabayashi 2015). These textures are identical to those displayed by the sedimentary serpentinite of the Great Valley Group, but differ from the Franciscan serpentinized peridotite and Coast Range ophiolite serpentinitinized peridotite slabs (Fig. 6 of Wakabayashi, in press.

At thin section scale, certain grain boundary geometries are compatible with original detrital grain boundaries but not with formation by fracturing or shearing. Internal fabric within clasts is abruptly truncated without any drag features along rounded grain boundaries, including those grain boundaries oriented at high angles to the foliation or cleavage direction in the rock (Fig. 11d–h). There are no deformed tails associated with these clasts. The clasts include (non-ultramafic) metamorphic rock fragments and metamorphic mineral grains (Fig. 11f, g). Deformation has variably overprinted the sedimentary textures leaving lenses of relatively undeformed domains (millimeter to tens of meter scales) between strongly deformed zones (millimeter scale examples in Fig. 11d, e, g, and h). These textures differ markedly by textures that appear formed by progressive deformation, such as those shown in Fig. 11a–c that lack the grain boundary relationships, whether it is between serpentinite domains, or between non-ultramafic and ultramafic material.

The matrix at the Ring Mountain locality includes millimeter- to centimeter-scale clasts of minerals that have the same characteristics of the larger high-grade blocks in the mélange. For example, the clasts and mineral grains amphibolite grade metamorphism overprinted by blueschist facies metamorphism (Fig. 11f, g) as is common in the high-grade blocks of the Franciscan, including those of the Ring Mountain locality (e.g., Wakabayashi 1990). Abrupt truncation of sodic amphibole in these clasts and mineral grains by detrital grain boundaries suggests the blueschist overprint of the earlier higher temperature metamorphism took place prior to incorporation (sedimentation) (Fig. 11g).

The serpentinite mélange at Ring Mountain and at Sunol Regional Wilderness also contains lower grade metamorphic blocks, such as metachert lacking macroscopic metamorphic minerals, metavolcanic rocks with preserved igneous textures and incipient growth of fine-grained (mostly <0.1 mm) blueschist facies minerals such as lawsonite and glaucophane, and metasandstone that displays neoblastic growth of jadeitic clinopyroxene, lawsonite, and glaucophane (Wakabayashi 2015). At Sunol Regional Wilderness, the (non-serpentinite) block types in serpentinite matrix mélange are the same as those in the adjacent siliciclastic matrix mélange.

Interfingering, interbedding, and gradation between siliciclastic rocks and clastic serpentinite

Interbedding and interfingering of siliciclastic rocks an clastic serpentinite is suggested by map relationships at 100 m and larger scales, as well as the comparatively common occurrence of blocks of serpentinite and hydrothermally altered serpentinite (silica-carbonate rock or listvenite) in siliciclastic matrix mélange, as well as similar (non-serpentinite) block populations in clastic serpentinite and siliciclastic mélanges at Sunol Regional Wilderness (Fig. 7). However, outcrops demonstrating depositional relationships between clastic serpentinite and siliciclastic horizons have not been found in the Franciscan Complex. This contrasts to the Great Valley Group where depositional contacts of serpentinite over siliciclastic rocks and gradation between clastic serpentinite and siliciclastic rocks has been shown (Wakabayashi 2016b).

Petrographic inspection provides evidence for mixed siliciclastic and clastic serpentinite deposition in Franciscan rocks. Serpentinite clasts are more common in horizons of siliciclastic mélange matrix (Fig. 11a, b, k, l, and o–r) than “ordinary” sandstones (Fig. 11m, n). Serpentinite clasts may make up at least 15% of the rock (Fig. 11o), and the detrital serpentinite consists of intact serpentinite (no internal detrital grain boundaries, Fig. 11a, b, k, l, o, and p) and redeposited serpentinite sandstone (Fig. 11q, r). The host rocks have high-pressure metamorphic detrital clasts that are higher grade than the post-sedimentary burial metamorphism including clasts equivalent to Franciscan high-grade blocks (Fig. 11s, t). Whereas serpentinite or metaultramafic mineralogy is preserved in some detrital serpentinite clasts, in other cases, the original mineralogy has been altered, commonly to chlorite, or chromium-rich white mica (fuchsite), or a combination of the two (Fig. 11i, j). The serpentinite origin of such detrital grains may be ascertained in some cases by the presence of chrome spinel or the pseudomorphing of serpentinite textures by polycrystalline chlorite clots. Sandstones rich in chlorite clasts of the type noted above have an unusual green color in outcrop and resemble serpentinite.

Most Franciscan siliciclastic sandstones have small amounts of detrital serpentinite, whether inferred by textures in chlorite clasts (Fig. 11m, n) or directly verified by presence of preserved serpentinite. Larger amounts of detrital serpentinite are found in siliciclastic mélange matrix, and in limited horizons of pebbly sandstone within otherwise block-free sandstone, such as one pebbly sandstone from El Cerrito Quarry that is locally so rich in blueschist clasts (Fig. 11t) as to have a blue color in outcrop.

In summary, the common occurrence of detrital serpentinite clasts in siliciclastic rocks (both siliciclastic mélange matrix and bedded sandstones), a similar range of block types in siliciclastic and serpentinite mélanges in contact with one another, map-scale contact relationships, and serpentinite blocks in siliciclastic matrix mélange, suggest that interbedding, interfingering, and gradation between siliciclastic and clastic serpentinite horizons is common in the Franciscan.

Imbrication and deformation of OPS and distinguishing tectonic from sedimentary melanges

Internal imbrication of OPS is easily seen where the igneous and pelagic components of OPS are common, such in the Marin Headlands unit (Fig. 10a–c). Internal imbrication of the clastic and volcanic units is difficult to evaluate in most cases owing to the lack of obvious marker horizons. In the metavolcanic-rich domains of northern Sunol Regional Wilderness, imbrication is shown by siliciclastic and/or chert horizons, commonly less than 10 m in thickness (Fig. 10f). Owing to the thinness of these non-volcanic layers, they have not been found outside of one continuous set of roadcut exposures. In mélange rich exposures, it is difficult to distinguish throughgoing imbricate faults from a series of isolated blocks such as in the central part of the Sunol Regional Wilderness map of Fig. 7. With high-quality exposures, however, internal imbrication is observed to be ubiquitous in clastic Franciscan rocks (examples in Fig. 10t, u, as well as the spatially variable deformation in mélange matrix of Fig. 10m, n). The magnitude of penetrative strain in most rocks is small, so most of the deformation and accordingly accommodation of accretionary megathrust slip takes place along discrete faults or narrow (less than tens of meters thick) fault zones (Fig. 10a–c, m, n, t, and u).

Fault zones that repeat the OPS section, such as the Rodeo Cove shear zone of the Marin Headlands, locally exhibit block-in-matrix textures (Meneghini and Moore 2007) (Fig. 10a, b). In such cases, none of the blocks are exotic and all are of the same metamorphic grade, unless this late imbrication and deformation involves a clastic section that has olistostromal horizons that have exotic blocks (schematically shown in Fig. 4). Such deformation can result in blocks of sedimentary mélange within a tectonic mélange, as illustrated by the deformational overprint shown in Fig. 10m, n (see also Wakabayashi 2015, Fig. 18c, d).

Examples of Franciscan tectonic serpentinite mélange, developed by the progressive deformation of metaultramafic and metabasite/metachert may be preserved in some high-grade blocks in sedimentary mélange, as shown at outcrop (Fig. 10r) and thin section scale (Fig. 11c, d). In such examples, all of the blocks in the metaserpentinite matrix are of the same metamorphic grade and compatible with the metamorphic mineralogy of the matrix. Such relationships are similar to serpentinite mélanges found in the Alps and Iran that have been shown to have developed by progressive deformation of ultramafic-bearing OPS (e.g., Angiboust et al. 2012; 2013; Balestro et al. 2015; Vitale Brovarone et al. 2014), but differ markedly from the sedimentary serpentinite mélanges described in this paper and by Wakabayashi (2012; 2015; in press). Intact equivalents of such tectonic serpentinite mélanges have not been found in Franciscan rocks, but imbricated high-grade slabs such as the structurally high Willow Spring slab, whose imbricates include serpentinite, may locally have such serpentinite-matrix mélanges (Fig. 9).

Franciscan OPS and tectonic history

The Franciscan OPS exposures exhibit a large range in lithologic combinations, reflecting a correspondingly large range in character of oceanic crust subducted during the >150 Ma of the assembly of this accretionary complex. The lack of post-subduction disruption in the Franciscan results in good preservation of the variation in OPS packages and their relationship to the architecture of the subduction complex, and hence their relationship to the tectonic history. In addition, the lack of post-subduction disruption facilitates distinction between Franciscan subduction complex rocks (transferred from lower to upper plate of subduction system) and rocks that were always part of the upper plate (CRO and GVG).

The earliest accreted OPS units of the Franciscan are high-grade coherent sheets ("Basalt-limestone-chert-clastic or basalt-chert-limestone-clastic") and related blocks-in-mélange that underwent high P-high T metamorphism at about 150–170 Ma (Ross and Sharp 1988; Anczkiewicz et al. 2004; Wakabayashi and Dumitru 2007; Ukar et al. 2012; Mulcahy et al. 2014; Cooper et al. 2011). These rocks may have formed during or shortly after subduction that initiated at ca.165–170 Ma within young oceanic arc lithosphere, in an environment lacking clastic sediment input (Wakabayashi et al. 2010).

Following subduction initiation and early accretion of island arc crust, subsequent oceanic igneous rocks subducted and accreted were of MORB affinity with lesser amounts of OIB. A significant gap in accretion of tens of million years followed the initial accretion of the high-grade material (Dumitru et al. 2010; Wakabayashi 2015). Following subduction initiation, the age progression of accreted oceanic crust, as well as the progression of metamorphism, suggests that a ridge crest approached the trench (120–125 Ma) but probably shut off prior to subduction (Wakabayashi 2015) (Fig. 5a). After this near ridge-trench encounter, the age of subducted oceanic crust became progressively older until about 95 Ma (subduction accretion of the Marin Headlands terrane), after which the age of the subducted oceanic crust became progressively younger until termination of subduction and conversion to a transform plate boundary. In contrast to the age of the subducted oceanic crust, the age of clastic sedimentary rocks in each OPS package was progressively younger with each successively accreted unit.

These OPS packages had significant components of trench fill overlying the pelagic sedimentary rocks. This trench fill included both turbidites as well as siliciclastic and serpentinite matrix olistostromes. Some of the oceanic crust that subducted had serpentinized peridotite exposed on the sea floor (e.g., Coleman 2000; Wakabayashi 2004), resulting in OPS composed of abyssal serpentinized peridotite and overlying clastic trench fill.

In contrast to the Franciscan OPS, imbricates of the upper CRO and basal GVG were formed by shortening of the upper plate rather than by transfer from the subducting plate to the upper plate. Some of this shortening may have taken place synchronous with Franciscan subduction, whereas some may have taken place after subduction termination and conversion to a transform plate boundary (Phipps 1984; 1992; Wakabayashi and Unruh 1995). This imbrication did not result in burial metamorphism or penetrative deformation in these rocks, in contrast to Franciscan OPS.

Conclusions

OPS in the California Cordillera consists both of oceanic assemblages that were never part of a subducting plate (upper plate assemblages) and were not incorporated into subduction-accretion complexes as well as materials transferred from the subducting plate to the upper plate to form subduction complexes such as the Franciscan. Whereas the largest oceanic crustal remnants in the California Cordillera are of the upper plate type, the subduction complex materials reflect the OPS concept as commonly applied (e.g., Wahrhaftig 1984; Isozaki et al. 1990; Isozaki and Blake 1994; Wakita and Metcalfe 2005; Kusky et al. 2013).

Franciscan OPS varies considerably in characteristics. This variation reflects both the variety of ocean crust subducted during the ca. 150 million years of Franciscan subduction as well as a variety of processes of subduction-accretion and trench sedimentation. The variation in OPS and its relationship to tectonic process is more complex than generally considered in studies of these types of rocks.

The clastic component of OPS includes olistrostromal (sedimentary mélange) horizons that are interbedded with and interfinger with bedded turbidites. The olistostromal component includes units of both siliciclastic and serpentinite matrix, and the different types of matrix may be interbedded, interfinger, or grade into one another.

Non-accretionary megathrust horizons separate OPS accreted at different times, whereas megathrust slip during accretion was accommodated by internal deformation of OPS, chiefly imbrication of OPS along discrete faults. Such deformation results in local block-in-matrix horizons (tectonic mélanges) that differ from the olistostromal horizons noted above in the lack of exotic blocks. However, because the deformed OPS packages include olistostromal horizons, pieces of the olistostromes that include exotic blocks may be incorporated as blocks in tectonic mélanges.

Additional files

Additional file 1: Higher resolution image of Figure 10. (JPG 9779 kb)
Additional file 2: Higher resolution image of Figure 11. (JPG 3932 kb)

Abbreviations

CRO: Coast range ophiolite; GVG: Great valley group; MORB: Mid-ocean-ridge basalt; OIB: Ocean island basalt; OPS: Ocean plate stratigraphy

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Authors' contributions

All works were conducted by the (single) author.

Authors' information

Wakabayashi has conducted research on subduction complexes for over 30 years with emphasis on the Franciscan Complex of California, starting with his Ph. D. dissertation research with Eldridge Moores that began in the early 1980s. His first exposure to ocean plate stratigraphy came from geologic mapping of the Marin Headlands as an undergraduate student (1980) under the guidance of Clyde Wahrhaftig who several years later authored a well-known paper on the Marin Headlands in the context of the ocean plate stratigraphy concept (Wahrhaftig 1984 cited in the manuscript). Recent work by Wakabayashi in the Franciscan Complex has included many studies based on geologic mapping, with much new information published in Wakabayashi (2015, cited in manuscript). Much of the primary field observations presented in this paper are derived from Wakabayashi (2015) but there are new observations presented in this paper as well, in addition to review of work and concepts not previously presented.

Competing interests

The author declares that he has no competing interest.

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