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Review

Origin of Mélanges of the Franciscan Complex, Diablo Range and Northern California: An Analysis and Review

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Abstract: The Franciscan Complex of California is characterized in part by the presence of mélanges. In general, mélange origins are attributed to sedimentary, tectonic, or diapiric processes—or a combination of these. Published reviews list the main features of mélanges characteristic of each type of origin. In this review, particular diagnostic features typical of sedimentary, tectonic, and diapiric mélanges are used to assess 15 specific mélanges, which in some cases have been interpreted in contrasting ways in the literature. The data do not support the view that most Franciscan mélanges were formed by sedimentary processes, but rather that both tectonic and sedimentary processes are important. There is little evidence that diapirism contributed significantly to Franciscan mélange genesis. Tectonic features present in most mélanges of subduction accretionary complexes create challenges in assessing mélange-forming processes. Notably, although tectonic overprints commonly mask the primary diagnostic fabric of sedimentary mélanges, some diagnostic features—such as depositional contacts, fossils in mélange matrix, and interlayering of mélange and non-mélange units—are critical to recognition of mélanges of sedimentary origin.

Keywords: mélange; olistostrome; Franciscan Complex

1. Introduction

The Franciscan Complex of California and southwestern Oregon (Figure 1) is widely considered to be the archetypal subduction accretionary complex [1–3]. Notable among its attributes are blocks and large masses of blueschist facies rocks, large masses of submarine fan sediments, blocks with ocean plate stratigraphy (OPS), and mélanges. Understanding Franciscan mélanges is central to understanding both the architecture of the Complex and its history, yet the mélanges have been the focal point of several controversies that cloud the architectural analysis.

The definitions, the character, and the origins of Franciscan and other mélanges have all been controversial [2–20]. Mélange definitions vary, but one of four prominent definitions is commonly selected as the basis for mélange discussions, specifically that of Hsu [16,17], Raymond ([21], and Raymond's definition in [5]), Silver and Beutner [22], or Cowan [13]. All agree that mélanges are characterized by a block-in-matrix structure. Long ago, Hsu [16] posited that fragmentation of rocks and mixing of different rock types were the critical processes in formation of these block-in-matrix structures. These now are known to form via tectonic, sedimentary, and diapiric processes [23–25]. Yet, whether or not mélanges must be mappable, must contain exotic blocks, or only form via tectonic processes have been major issues of controversy with regard to both character and to classification. The issues of definition, classification, composition, structure, and origin are reviewed elsewhere [2,15,19,21,26,27], but for the purposes of this paper, the definition of mélange used is that of Raymond [21]: a mélange is "a body of rock mappable at a scale of 1:24,000 [or 1:25,000] or smaller and characterized both by the lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmented matrix of finer-grained material." This definition serves as the basis for the discussion below and clarifies some fundamentals of structure and composition as I use them here. Note that this mélange definition requires both mappability and exotic blocks but does not specify mode of origin. Exotic blocks are here considered to be "variably sized masses of rock occurring in a lithologic association foreign to that in which the mass formed" [5,19]. Clearly, as used here, the term mélange refers neither to fabrics and structures nor to all block-in-matrix units (e.g., compare [18,21] with [13]). Specifically, the definition excludes dismembered formations from the mélange category of rock units [19,21].

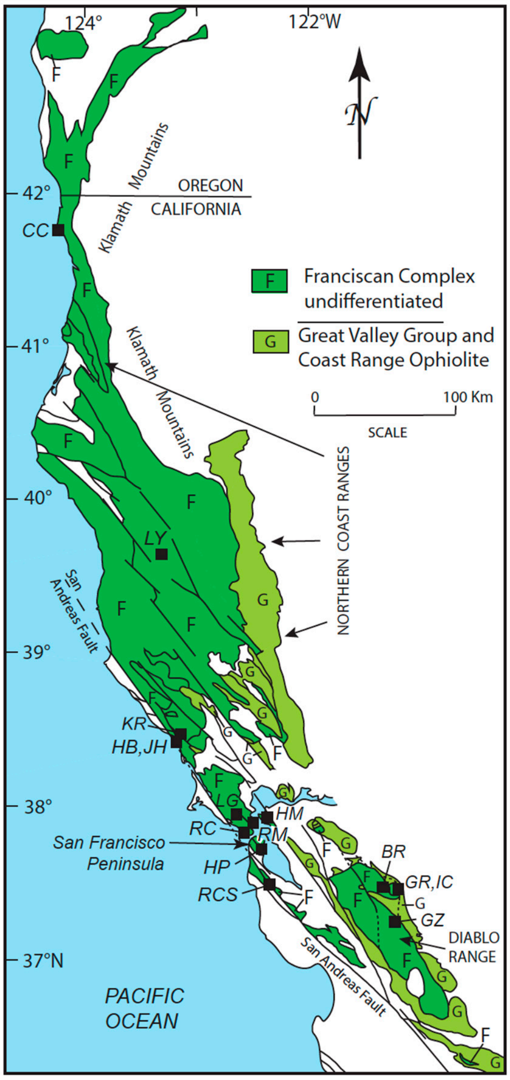

Figure 1. Generalized map of the Franciscan Complex of Oregon and the Northern Coast Ranges and Diablo Range of California, showing the general distribution of Franciscan rocks and the locations of exposures of mélanges described in the text. From north to south the mélanges are CC = Crescent City Olistostrome, LY = Laytonville Mélange, KR = King Ridge Road Mélange, HB = Heavens Beach Mélange, JH = Jenner Headlands Mélange, LG = Liberty Gulch Mélange, HM = Hillside Mélange of El Cerrito, RC = Rodeo Cove Mélange, RM = Ring Mountain Mélange, HP = Hunters Point Mélange, RCS = the Serpentinite Mélange of Redwood City, BR = Blue Rock Springs Mélange, GR = Gerber Ranch Mélange, IC = Ingram Creek Mélange, and GZ = the Garzas Mélange.

Given the definitions set out above, the primary purpose of this paper is to review the characteristics of several relatively well-described Franciscan mélanges and relate the descriptive features to the proposed origins of the mélanges. Specifically, I discuss the origins of individual Franciscan mélanges viewed in the light of the composite set of published criteria for each type of mélange origin, and I add new descriptive material on selected mélanges. This review focuses attention on some conflicting interpretations of available data and on the contrasting emphases placed on particular criteria in determining the origins of particular Franciscan mélanges. In addition, this study documents the fact that, rather than being largely sedimentary in origin, Franciscan mélanges have formed by both tectonic and sedimentary processes.

2. Distinguishing Sedimentary, Diapiric, and Tectonic Mélanges

Over several decades, various workers have set out criteria for distinguishing sedimentary, diapiric, and tectonic mélanges from one another ([2,13,15,21,25,27–29] and Figure 20.2 of [29]). Table 1 presents a composite set of criteria based primarily on the work of Raymond [2] and Festa et al. [27]. These criteria include compositional, structural, and spatial aspects of mélanges formed in various ways.

Among the criteria characteristic of mélanges formed via the various processes are several features developed via more than one process plus a few definitive features particularly indicative of each formative process (Table 1). Mélange origins are clearly linked to the processes of fragmentation and mixing. For mélanges of deformational origin in which fragmentation and mixing is primarily a tectonic process (tectonic mélanges), the most definitive features are sheared or deformed contacts, the presence of S-C and P-R fabrics, and the presence of a pervasive scaly microfabric that may or may not be accompanied by microbreccia, pseudotachylite, or both (Table 1). In contrast, a sedimentary origin is particularly signaled by depositional or gradational contacts with sedimentary units, interbedding with sedimentary units, well rounded mesoscopic clasts and microscopic grains of diverse rock types, and in situ fossils in the mélange matrix (Table 1). Inasmuch as rounding of clasts may result from sedimentary, tectonic, diapiric flow, or a combination of weathering and other processes [30–32], it is important that rounded clasts be of diverse compositions to eliminate some of the alternative tectonic, diapiric, and weathering causes of rounding from consideration as formative processes. Mélanges formed via diapirism are best indicated by elliptical to circular zoned map patterns and mélange core zones with randomly oriented clasts plus marginal zones with steeply inclined fabrics (Table 1). Many mélanges are polygenetic, having formed via one process and subsequently experienced additional fragmentation and mixing via another. Sedimentary mélanges are notably imprinted with post-depositional tectonic deformation features.

Table 1. Comparison of features and origins of selected Franciscan mélanges.

Mélange –> **Criteria** [a]	**Crescent City Olistostrome**	**Laytonville**	**King Ridge Road**	**Liberty Gulch**	**Hillside**	**Blue Rock Springs**	**Garzas**	**Ingram Canyon**	**Gerber Ranch**	**Rodeo Cove**	**Jenner Headlands**	**Hunters Point**	**Ring Mountain**	**Redwood City**	**Heaven's Beach**
Author Proposed Formation Mechanism [b]	S	S	S	S	S	S	T	T	T	T	T	T	S, T	D	P (S,T)
Sedimentary Mélanges															
Irregular to tabular in map view	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Lenticular to tabular shape in section	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Depositional to gradational contacts [c]	√	√	Possibly	√	√										
Irregular to sub-parallel stratigraphic boundaries	√	√		√	√	√									
Interbedded with stratigraphic layers	√	√		√		√	√								
Highly disordered isotropic fabric	√, in some		√	√, In part	Locally in enclaves										Only in blocks
Matrix = mudrock (m), Sandstone (s), metabasites (b), Serpentinite (u)	√ (m)	√ (m,s)	√ (s)	√ (m)	√ (m,s)	√ (m)	√ (m±s)	√ (m)	√ (m,u)	√ (b,m,s)	√ (u)	√ (m,u)	√ (u)	√ (u)	√ (m,s)
Weak scaly cleavage at base		√			√										
Clast composition diverse	√	√	√	√	Not very	√	√	√	√	Not very	√	Not very	√		√
Native and exotic blocks	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Block size <1m–>1km	√	√	√	√, small	√, small	√	√	√	√	√	√	√	√	√	√
Blocks rounded, irregular, angular, or tabular	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Well rounded clasts of various rock types	√			√	√	√							√		√
Block margins sharp to diffuse with soft sediment deformation features	√	Locally													
Fossils in matrix															
Number of the 15 features matched	13 (3 of 4 major)	12 (2 of 4 major)	9 (1 of 4 major)	12 (3 of 4 major)	11 (3 of 4 major)	10 (2 of 4 major)	8 (1 of 4 major)	7 (0 of 4 major)	7 (0 of 4 major)	6 (0 of 4 major)	7 (0 of 4 major)	6 (0 of 4 major)	8 (1 of 4 major)	6 (0 of 4 major)	8 (1 of 4 major)
Tectonic Mélanges															
Elongate to lenticular or irregular map shape	√	√	√	√	√	√	√	√	√	√	√	√		√	√
Wedge to lenticular or tabular shape in section	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Sheared/deformed contacts		Minor Local	Locally	Minor Local	Locally	√	√	√	√	√	√	√	√	√	√
Structurally ordered block-in-matrix (anisotropic) fabric	√, in part	√			Locally	√	√	√	√	√	√	√	√	Locally	√
Matrix composition mudrock, mudrock + sandstone, or serpentinite	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Block compositions variable	√	√	√	√	√	√	√	√	√	√	√	√	√	Slightly	√
Native and exotic blocks	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Facoidal, sigmoidal, tabular, to lenticular blocks	√			Some	Common	√	√	√	√	√	√	√	√	Locally	√
Blocks = <1m–>1km	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Microfabric scaly ± microbreccia and pseudotachylite	√	√			In black rock zone at top of mélange	√	√	√	√	√	√	√	√	Locally	In part
Anastamosing shears and microshears	√	√		Locally	Locally	√	√	√	√	√	√	√	√	Locally	√

Table 1. *Cont.*

Mélange –> Criteria [a]	Crescent City Olistostrome	Laytonville	King Ridge Road	Liberty Gulch	Hillside	Blue Rock Springs	Garzas	Ingram Canyon	Gerber Ranch	Rodeo Cove	Jenner Headlands	Hunters Point	Ring Mountain	Redwood City	Heaven's Beach
S-C, P-R fabrics							√	√		√			√	√	
Boudinage common	√	√			√			√	√	√	√				√
Folds common	Slump folds	In some blocks and matrix	In some blocks		√	Overprint/ Cenozoic folds		In blocks	In some blocks and matrix	In veins			In blocks		
Striations common								√	√		√		√		√
Veins common	Mudrock							√	√	√	√		√	√	
Number of the 16 features matched	13 (1 of 3 major)	11 (1 of 3 major)	8 (1 of 3 major)	8 (0 of 3 major)	13 (2 of 3 major)	11 (2 of 3 major)	12 (3 of 3 major)	15 (3 of 3 major)	15 (2 of 3 major)	14 (3 of 3 major)	14 (2 of 3 major)	11 (2 of 3 major)	14 (3 of 3 major)	12 (3 of 3 major)	13 (2 of 3 major)
							Diapiric Mélanges								
Internal structural zoning of body from anisotropic to isotropic															
Circular to elliptical on maps; commonly zoned													√		
Section conical to cylindrical															
High angle discordant to conformable contacts	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Deformation zoned with core noncylindrical folds and rim scaly fabric															
Native and exotic blocks	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Blocks irregular in core; phacoidal blocks in rim															
Blocks = <1m–15+ m; smaller in rim zone															
Block composition variable, but sandstone common and serpentinite possible	√	√		√	√	√	√	√	√	√		√		No-Mainly Serpentin-ite	√
Clasts randomly oriented in core zone															
Marginal zone has aligned elongated clasts															
S-C fabric in marginal zone															
Sub-vertical microfabric in Matrix relative to nearby sedimentary layers															
Number of the 13 features matched	3 (0 of 4 major)	3 (0 of 4 major)	2 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	3 (0 of 4 major)	2 (0 of 4 major)	3 (0 of 4 major)	3 (1 of 4 major)	2 (0 of 4 major)	3 (0 of 4 major)
Sources	[6,34–38]	[28,39,40]	[41]	[32,42]	[20,42–44]	[2,45]	[2,11,42,46–49]	[2,45–48]	[2,45,48]	[23,50,51]	[7,52,53]	[54]	[3,55,56]	[57]	[3,32]

[a]—Criteria based on references [2,3,27,33] and observations of the author; [b]—S = sedimentary (olistostromal), D = diapiric, T = tectonic, P = polygenetic; [c]—Major definitive criteria are bold face.

3. Data from Selected Franciscan Mélanges

Fifteen of the most well-known, thoroughly studied, or widely distributed mélanges mapped within the Franciscan Complex of northern California and the Diablo Range are selected for review here. The general locations of these mélanges are shown on Figure 1. The selected mélanges have been assigned origins spanning the range of origins noted above. Most of the selected mélanges have been described by a single author or an author and colleagues. In some cases, however, multiple authors have studied a mélange and proposed contrasting origins. For others, I provide alternatives to the proposed origins.

3.1. Sedimentary Mélanges

Mélanges that clearly exhibit most of the definitive features of sedimentary mélanges are common in the Franciscan Complex. In some cases, the definitive features indicating an origin are obscured by later tectonism, whereas in others, they are obvious.

3.1.1. The Crescent City Olistostrome

The Crescent City Olistostrome, a sedimentary mélange, is exposed along the northern California coast from the vicinity of Pt. St. George south to Crescent City and beyond (CC, Figure 1) [6,34–38]. Multiple exposures, particularly in beach-facing cliffs, clearly reveal the features of the mélange.

In terms of map and cross sectional appearance, the mélange is elongate and lensoidal to tabular ([6], [34] and Figures 2&8 therein, [37] and Figure 28 therein). In cliff exposures, the Crescent City Olistostrome occurs as an interbedded, tabular layer between two submarine fan facies B sandstone units (fan facies terminology follows Mutti and Ricchi-Lucchi [58]). Stratigraphic boundaries between the mélange unit and enclosing sandstones are depositional, and the contacts of the mélange are parallel to subparallel with contacts within the bounding units (Figure 2A).

Internally, the Crescent City Olistostrome displays a range of fabrics [6,34,37]. The matrix is locally sandy mudrock with variable amounts of sand and silt [37] (but note that Aalto, at times, designated the rock as argillite, e.g., [6]). Local areas of isotropic fabric are present, especially in zones of soft sediment deformation and fluidized sediment injection (Figure 2B). Scaly fabric with anastomosing fractures occurs in many exposures. Microbreccia is present locally. Soft sediment deformation features include folds, sandstone dikes, and floating sand masses that take on the appearance of clasts.

Blocks and clasts (olistoliths) in the Crescent City Olistostrome include a variety of native to exotic rock types [6,37] (Table 2). The dominant clasts are "immature sandstone", but ocean plate stratigraphy fragments (OPS fragments, i.e., serpentinite, peridotite, basic volcanic rocks ± radiolarian chert, radiolarian chert, pelagic limestone, and sandstones) plus phyllite and a range of volcanic and plutonic rocks, such as tonalite and porphyritic dacite, also occur as clasts [6,37]. The bulk of the clasts are sedimentary (sandstones), and the parent rocks likely formed in a submarine fan environment. Most clasts other than the dominant arenite sandstones are exotic. Clasts are angular to subangular but include both primary sub-rounded to rounded forms and secondary rounded to discoidal shapes, the latter where clasts are more deformed [37]. Blocks up to 37 meters in diameter have been observed in matrix and blocks inferred to be part of the olistostrome ranging up to 200 m in length [6]. Mafic volcanic rocks tend to form the largest blocks.

Multiple deformation events affected the rocks [37]. In particular, an earlier phase of extension produced tensional joints, some "soft-sediment faults," and some shear fractures, whereas a later episode of compression induced shortening that yielded folds and faults. These deformations affected the matrix fabric and the overall structure of the olistostrome.

Table 2. Exotic block content of selected Franciscan mélanges.

Mélange [a] —>	King Ridge Road [c]	Laytonville	Hillside	Heaven's Beach	Gerber Ranch	Garzas	Liberty Gulch	Crescent City	Blue Rock Springs	Rodeo Cove	Hunters Point	Ingram Canyon	Jenner Headlands	Ring Mountain	Redwood City
Author Proposed Origin [b]	S	S	S	P (S,T)	T	T	S	S	S	T	T	T	T	S, T	D; (T-herein)
Matrix type [c]	Ss	MS	MS	MS	MS	MS; M	M; MS	M	M	M	M + Sp	M + Sp	Sp	Sp	Sp
Ocean Plate Stratigraphy Rocks (see rock types below)															
Serpentinized peridotite, pyroxenite			√	√				√			√		√	√	√
Serpentinite	√			√					√		√	√	√	√	√
Basalt and metabasalt	√	√	√	√	√	√	√	√	√	√	√	√	√	√?	√
Chert and metachert	√	√	√	√	√	√	√	√	√	√	√	√	√	√?	√
Sandstone and metasandstone	√?	√	√	√	√	√	√	√	√	√	√	√	√	√?	√
Conglomerate and metaconglomerate			√	√	√	√			√			√	√		
Other Exotic Rocks															
Glaucophane schist	√	√		√		√	√		√		√	√	√	√	√
Eclogite	√					√						√	√	√	
Hornblende schist and gneiss	√			√		√					√	√	√	√	√
Volcanic rocks other than basalt	√							√	√			√		√	
Granitoid rocks	√			√				√	√						
Other	√	√		√	√	√		√	√		√	√	√	√	√
[a]—**Sources**	[40]	[28,39,40]	[20,42–44]	[3,32]	[2,45,48]	[2,11,43,46–49]	[32,42]	[6,34,36–38]	[2,45]	[23,50,51]	[54]	[2,45,48]	[7,52,53]	[3,55,56]	[57]

[a]—Sources; [b]—S = sedimentary, D = diapiric, T = tectonic, P = polygenetic; [c]—Arranged by matrix type: Sandstone (Ss), Mudrock + Sandstone (MS), Mudrock (M), Serpentinite (Sp).

The evidence of a sedimentary origin for the Crescent City Olistostrome is compelling (Table 1), hence the name. Three of four defining features of sedimentary mélanges are exhibited, as are a total of 13 of 15 features characteristic of sedimentary mélanges. Nevertheless, later tectonism has given this mélange a tectonic overprint, resulting in some shearing and folding characteristic of tectonic mélanges (Table 1). As a result, 13 of 16 features characteristic of tectonic mélanges, including one of the definitive features of this type of mélange (scaly fabric with microbreccia), are present. Most fragmentation and mixing, however, are attributable to erosion and sedimentary processes, thus the mélange is fundamentally sedimentary in origin.

3.1.2. The Laytonville Mélange

The Laytonville Mélange, exposed in the central northern Coast Ranges (Figure 1, LY), occurs in mountainous terrain generally known as the "Central Belt" of the Franciscan Complex [5,28,39,59]. The unit was named for rocks in the vicinity of Laytonville, California [28], but small-scale mapping suggests that the unit may be laterally extensive [39].

Mapping of the Laytonville Mélange in the Laytonville region—and to the west, north, and south—was conducted by Gucwa, Kleist, and Jayko et al. [28,39,40]. The reconnaissance mapping of Jayko et al. [39] lumps all mélange rocks in the region together, apparently under the assumption that the Central Belt is predominantly a single large mélange unit (with admixed, smaller kilometer scale masses of other rock). Under such an assumption, in the geographic regions underlain by mélange, the mélange cannot be subdivided into multiple mélange (and non-mélange) units; yet, Gucwa [28,60] did so. The presence of distinctive red (Laytonville) limestone and unusual Fe-rich rocks (ironstones) exclusively in this mélange makes this mélange unique relative to others in the Franciscan Complex [28,39,60–62].

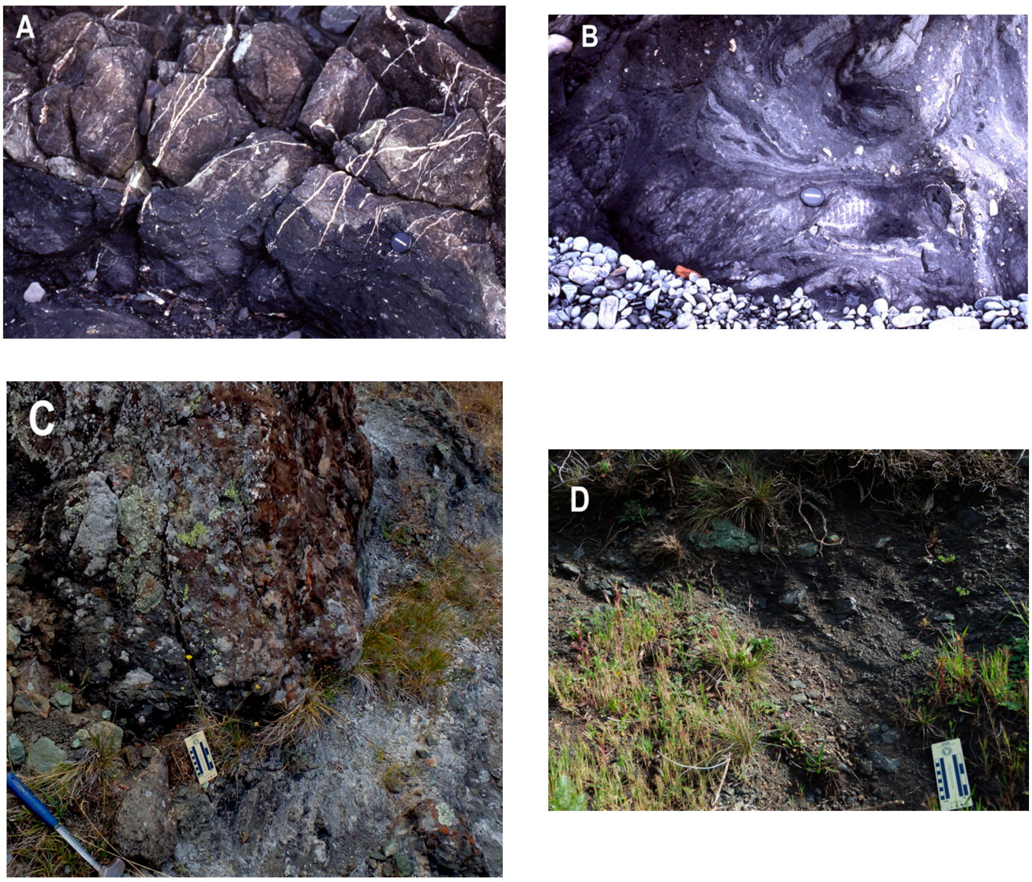

Figure 2. *Cont.*

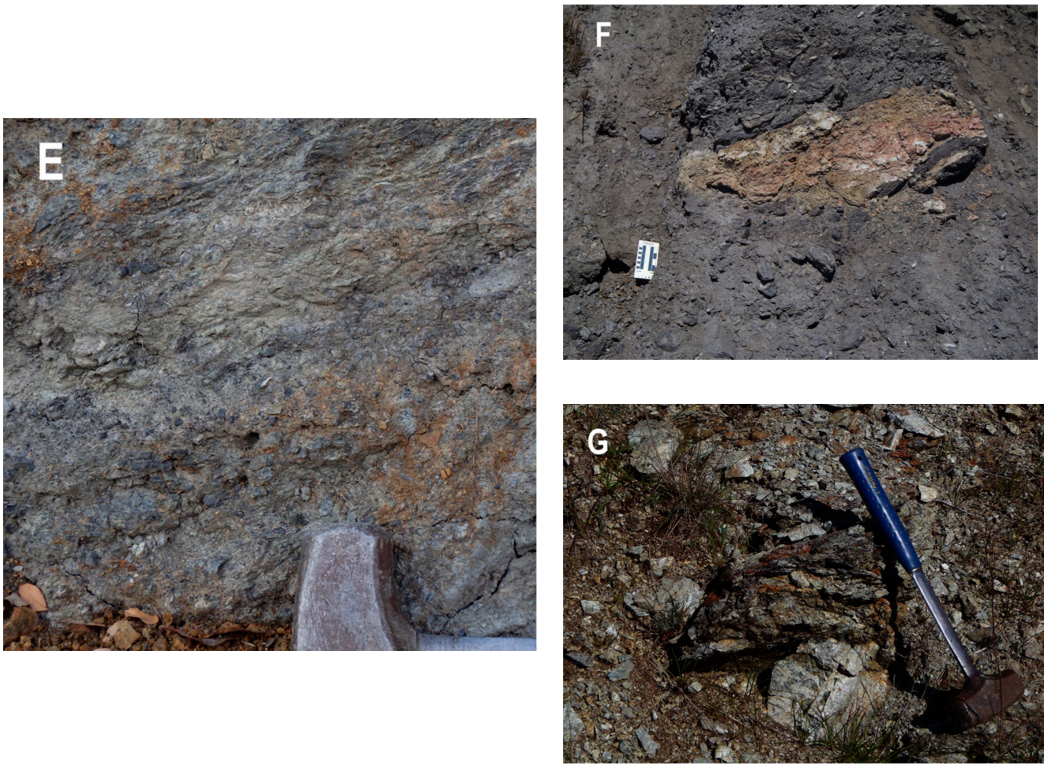

Figure 2. Photographs of outcrop features supporting mélange origin interpretations. **A**–**C** support sedimentary interpretations. (**A**) Overturned depositional contact of Crescent City Olistostrome (dark) on gravelly turbidite (medium gray), Pt. St. George, California (see [6]). Note that both turbiditic gravelly sandstone and muddy olistostrome are overprinted by approximately layer-parallel spaced cleavage and orthogonal veins. (**B**) Soft sediment folding, injection, and associated deformation with zones of pebbly, isotropic fabric. Crescent City Mélange, Pt. St. George, California. Circle in center is lens cap (approximately 5 cm diameter). (**C**) Metasandstone olistolith (upper left) in bedded mudrock matrix (see beds in lower center-below scale). Liberty Gulch Broken Formation, Member 1, Central Marin County, California [32]. **D**–**G** support tectonic history. (**D**) Metabasite ("greenstone") and metasandstone phacoids in scaly shale matrix, Rodeo Cove Mélange, below Conzelman Rd., east of Battery Rathbone. (**E**) Scaly mudrock and mudrock-metasandstone breccia, mélange matrix, Garzas Mélange, Mines Road, Section 13/24 boundary north of Western Mines Rd., California, near 37°24′ N, 129°29′ W. (**F**) Scaly and breccia matrix enclosing chert block. Heavens Beach Mélange, northern Blind Beach, south of Goat Rock (see [3,32], Figure 6 of this report). (**G**) Scaly serpentinite matrix enclosing serpentinite block in serpentinite-matrix, Ring Mountain Mélange, southwest of the crest of Ring Mountain, Tiburon Peninsula, California (see [55]).

In map and cross sectional views, Gucwa [28,60] suggests that the unit is tabular and about 8.5 km thick, which is astonishingly thick and unlikely for a single sedimentary mélange or even a sedimentary mélange complex. Folding in the unit may mean that the thickness is substantially less [40]. On maps, the contacts tend to appear somewhat irregular. To the east, Gucwa [28,60] depicts the Laytonville mélange as depositionally overlying a Cretaceous sandstone unit along a predominantly sharp contact. To the west, Kleist [40] shows the mélange to overlie Cretaceous to Eocene "Coastal Belt" sandstones along a locally overturned contact that displays no evidence of shear or other deformational features. He discusses both olistostromal and fault juxtaposition of the two units here but reaches no conclusion. Jayko et al. [39] depict the eastern contact as a thrust fault and the western contact as a combination of a wide shear zone and various local, high-angle faults. The presence of possibly young Coastal Belt rocks below the Laytonville Mélange in less well-exposed relationships on the west may favor faulting along the western contact, but on the east, the Laytonville Mélange clearly appears to depositionally overlie a stratigraphic unit.

The matrix of the Laytonville mélange is clastic and is described by Kleist [40] as consisting of "greywacke-siltstone-mudstone". Jayko et al. [39] refer to the matrix of all mélanges in the region as "argillite". The muddy parts of the matrix, in particular, display scaly fabric.

Blocks in the mélange appear in angular to subrounded forms and range from a few centimeters to hundreds of meters in length [28,39,40]. No well-rounded blocks or clasts are reported in the mélange. The largest blocks are mafic volcanic rock, chert, and (meta)sandstone masses (OPS fragments) of 2–3 kilometers in length [28,40], and Kleist [40] suggests that the sandstones may be interbeds rather than clasts. OPS fragments of pillow basalt, diabase, and volcanic breccia are the most abundant of the OPS fragments, but various chert and OPS affiliated sandstone blocks are also present in the mélange. In addition, the Laytonville Mélange contains blocks of red limestone, conglomerate, gabbro, serpentinite, "greenschist," glaucophane schist, and rare quartz-stilpnomelane-riebeckite schist and gniess [28,40,42,61,62]. Clearly, both exotic and native blocks are present.

Detailed analyses of deformational features in the Laytonville Mélange have not been reported. Some folds and scaly fabric are the only structural elements reported to date [40].

The origin of fragmentation and mixing within the Laytonville Mélange appears to have been a combination of weathering, erosion, and transportation processes that took place, at least in part, as mass flows in a submarine environment. In particular, the presence of blocks of formerly subducted rocks now metamorphosed to blueschist facies assemblages, such as blocks of glaucophane schist, testify to uplift, erosion, transportation, and re-deposition of previously subducted and metamorphosed accretionary complex rocks. That such Franciscan metamorphic and OPS rocks (and those of similar complexes) have been recycled is well documented [32,41,63,64]. This evidence combined with the depositional contact of the Laytonville Mélange with underlying rocks and the total of 12 of 15 features compatible with a sedimentary origin (Table 1), including the presence of three of the four major indicators, supports a sedimentary origin for at least a part of this unit.

The large thickness (8.5 km) of the Laytonville Mélange reported by Gucwa [28], however, remains a problem. This is simply too thick for an origin as a single mass flow deposit. While the unit exhibits 80% of the features indicative of a sedimentary origin, it has 11 of 16 (69%) of the features indicative of a tectonic origin. Could the Laytonville Mélange be an amalgamated unit consisting of multiple parts, including at least one sedimentary part and one tectonic part? Has folding given the mélange the appearance of excessive thickness by repeating section ([40], cf. Garzas Mélange, below)? Clearly, more detailed analyses are needed.

3.1.3. The King Ridge Road Mélange

Unlike the mudrock-matrix and mudrock + sandstone-matrix Crescent City and Laytonville mélanges, the King Ridge Road Mélange is a sandstone-matrix mélange [41]. The mélange is exposed in an area north of the lower reaches of the Russian River in Sonoma County, California (KR on Figure 1) and east of the well-known Jenner eclogite locality on the coast. The sandstone matrix of one exposure of mélange contains detrital zircons that suggest a maximum depositional age for the unit of 83 Ma [41]. Sources of detrital zircons in the 85 to 55 Ma age range—and especially in the range 75 and 55 Ma—have limited possible provenance areas in western North America, thus the actual depositional age could be younger [59,65–71].

The structural position of the main mass of King Ridge Road Mélange and the low K-feldspar content of the rocks (≤ 5%) suggest an affiliation with rocks of the traditional "Central Belt" of the Franciscan Complex. On the other hand, since the depositional age is on the young end of the "Central Belt" age range and the old end of the Coastal Belt age range, the unit could be part of the traditional "Coastal Belt". The dated samples were collected from a body of rock assigned to the King Ridge Road Mélange by Erickson [41] but exposed to the west of the main body of King Ridge Road Mélange and separated from the latter. These rocks are atypical of the "Central Belt" and more typical of the "Coastal

Belt" in being relatively high in K-feldspar (see K-feldspar data in Bailey et al. [72]). Thus, the age and the K-feldspar content combined with the structural position of the sampled body more likely indicate an affiliation with "Coastal Belt" rocks. The alternative is that the two masses of sandstone-matrix mélange are different units.

The King Ridge Road Mélange may be equivalent to the Wren Rock unit of Raymond and Bero [32] exposed near Jenner on the coast. That unit has a depositional contact with an underlying unit, has a sandstone matrix, and is dominated by OPS blocks—a contrast with the King Ridge Road Mélange, which has a more diverse clast content. The Wren Rock and the King Ridge Road units have similar structural positions, but it may be significant that the Wren Rock unit is not known to have the diversity of clast types present in the King Ridge Road Mélange, as reported by Erickson [41].

The clast population of the King Ridge Road Mélange is more diverse than many other mélanges described in the Franciscan Complex (Table 2) [41]. The blocks and the smaller fragments include some typical fragments of OPS and an array of other rocks types, including granitoid rocks and intermediate-silica volcanic rocks, plus glaucophane schist and re-metamorphosed eclogite. Block and clast sizes range from less than 2 m to about 1 km [41].

As with the Laytonville Mélange, the King Ridge Road Mélange contains clasts and blocks that have a pre-fragmentation and mixing history (e.g., blocks with foliation cut by the block margin). Considering the sandstone matrix of the mélange, they could represent uplifted, eroded, transported, and re-sedimented rocks formed via fragmentation and mixing that was a sedimentary process. Although the King Ridge Road Mélange is known to have only nine of the features typical of sedimentary mélanges, the sandstone matrix, the block-matrix contact described by Erickson [41], the diversity of clasts from non-oceanic sources, and the depositional contact between the potentially equivalent Wren Rock unit and underlying rocks all favor a sedimentary origin.

3.1.4. Hillside Mélange

The Hillside Mélange of El Cerrito was described in considerable detail by Wakabayashi [20,43,44]. In map view, the Hillside Mélange forms a rather narrow, linear outcrop belt [43], and cross sections show it to be tabular with a structural thickness of less than 50 to 200 meters [2,44]. The contact is reportedly a depositional one of mélange on prehnite-pumpellyite facies metawacke [44], although extensive overprinting by spaced cleavage renders that relationship obscure.

The mélange consists of OPS blocks in a sandy to muddy matrix [3,44]. The matrix has a fabric that ranges from anisotropic scaly to isotropic, the latter in little deformed domains where the textures are clastic conglomeratic to breccia textures. Near (but not at) the base, the rock is foliated above the contact [44]. Blocks and clasts consist of "greywacke," chert, metabasites, and rare peridotite. Maximum block size is 60 m, and the blocks range from rounded to angular.

The upper contact zone of the mélange is a "black rock" fault zone interpreted by Wakabayashi and Rowe [44] to be a megathrust. The zone is 20–30 m thick with local areas of breccia, pseudotachylite, and ultramylonite.

The Hillside mélange exhibits 11 of the 15 features of sedimentary mélanges (73%), including two of four major features. No fossils in the matrix or interlayered sedimentary units are known. The superimposed "megathrust" fault at the top of the unit and the zones of scaly fabric within indicate that the mélange had a significant structural history. It exhibits 13 of 16 features characteristic of tectonic mélanges (81%), including two of the three major features.

3.1.5. Other Sedimentary Mélanges

The other sedimentary mélanges listed in Tables 1 and 2 include the mélange of Liberty Gulch [32] and the Blue Rock Spring Mélange [2,45]. The Blue Rock Spring Mélange has a diverse clast population such as the King Ridge Road Mélange but has a mudrock matrix (Table 2). The Mélange of Liberty Gulch also has a mudrock matrix, but the clast population is limited, consisting primarily of OPS rocks and rare glaucophane schist (Table 2).

The Mélange of Liberty Gulch is mapped as part of a sedimentary sequence [32]. It forms the uppermost unit of a four-member broken formation and overlies a second member of the formation along a somewhat sheared contact interpreted to be a locally deformed depositional contact (Figure 3). Truncated foliations at block margins, blocks apparently resting within the matrix and deforming the underlying matrix slightly at the contacts (Figure 2C), and stratigraphic concordance with surrounding stratigraphic layers support the sedimentary histories of both the Blue Rock Spring and the Liberty Gulch mélanges. Each mélange has 10 or more features characteristic of sedimentary mélanges and two or three of the major indicators of a sedimentary history (Table 1).

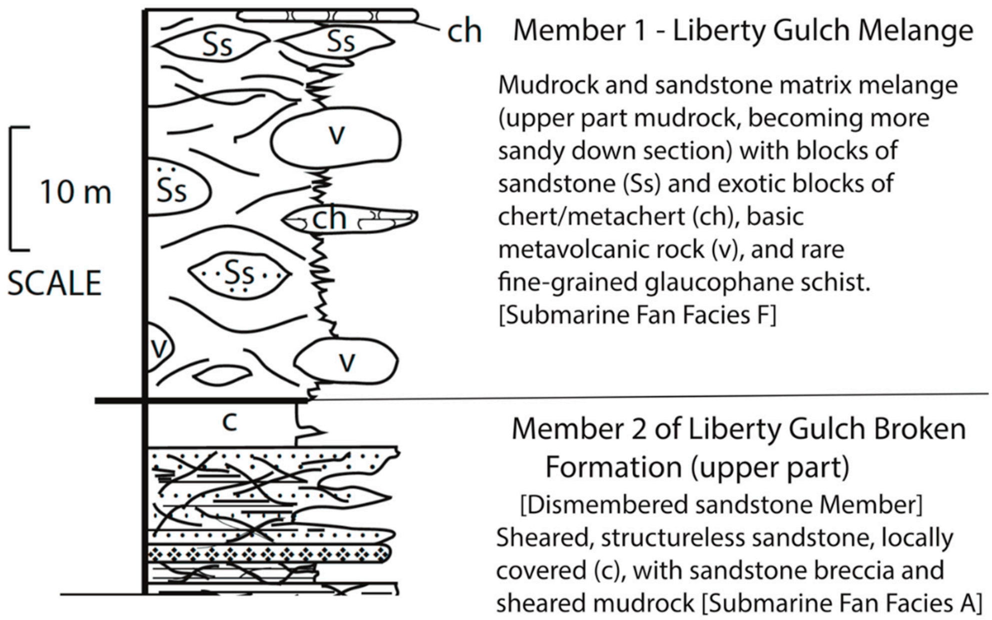

Figure 3. Section of Liberty Gulch Mélange (member) and underlying Dismembered Formation Member 2 of Liberty Gulch Broken Formation. Mélange (submarine fan facies F) conformably overlies Dismembered Sandstone Member 2, a sheared submarine fan facies A unit with local interbedded sheared mudrock (modified from [32]).

The Blue Rock Spring Mélange in the northeastern Diablo Range (BR, Figure 1) was mapped by Raymond [19,45] and Raymond and Maddock (unpublished, but see Wagner et al., [73]). It is a minimum of 300 m thick. The unit is tentatively considered to be a mass flow deposit complex. The matrix, which is dominantly mudrock, encloses clasts of metawacke with metamudrock, metaconglomerate, metachert, metabasalt, metadiabase, metagabbro, siliceous metavolcanic rock, glaucophane schist, marble, chlorite schist, and mica schist (Figure 4B,C). The largest indisputable blocks, the larger of which is about 400 meters long, are two metagabbro ± metadiabase ± metabasalt + metachert OPS fragments with minor inter-pillow, weakly recrystallized limestone (structurally dominated by relict bedding but with large carbonate ghost-crystals) (Figure 4B). Four large layers of submarine fan facies metawacke—including one 90 meters thick and 3.5 kilometers long and another more than 6 kilometers long—occur within the outcrop belt (Figure 4A) [45]. These masses of metawacke are (1) interbeds within mélange, (2) large slabs rafted downslope into the trench basin within a large submarine landslide, or (3) slabs of subducted submarine fan incorporated into a tectonic mélange underplated beneath the middle accretionary complex of the sequence shown in Figure 4. The data are inconclusive. The Blue Rock Springs Mélange has 10 of 15 features characteristic of sedimentary mélanges (67%), including two of the four definitive features, but it also has 11 of 16 features of tectonic mélanges (69%), including two of three definitive features (Table 1). In spite of having sheared contacts, the mélange is currently interpreted to be a mélange complex of sedimentary origin.

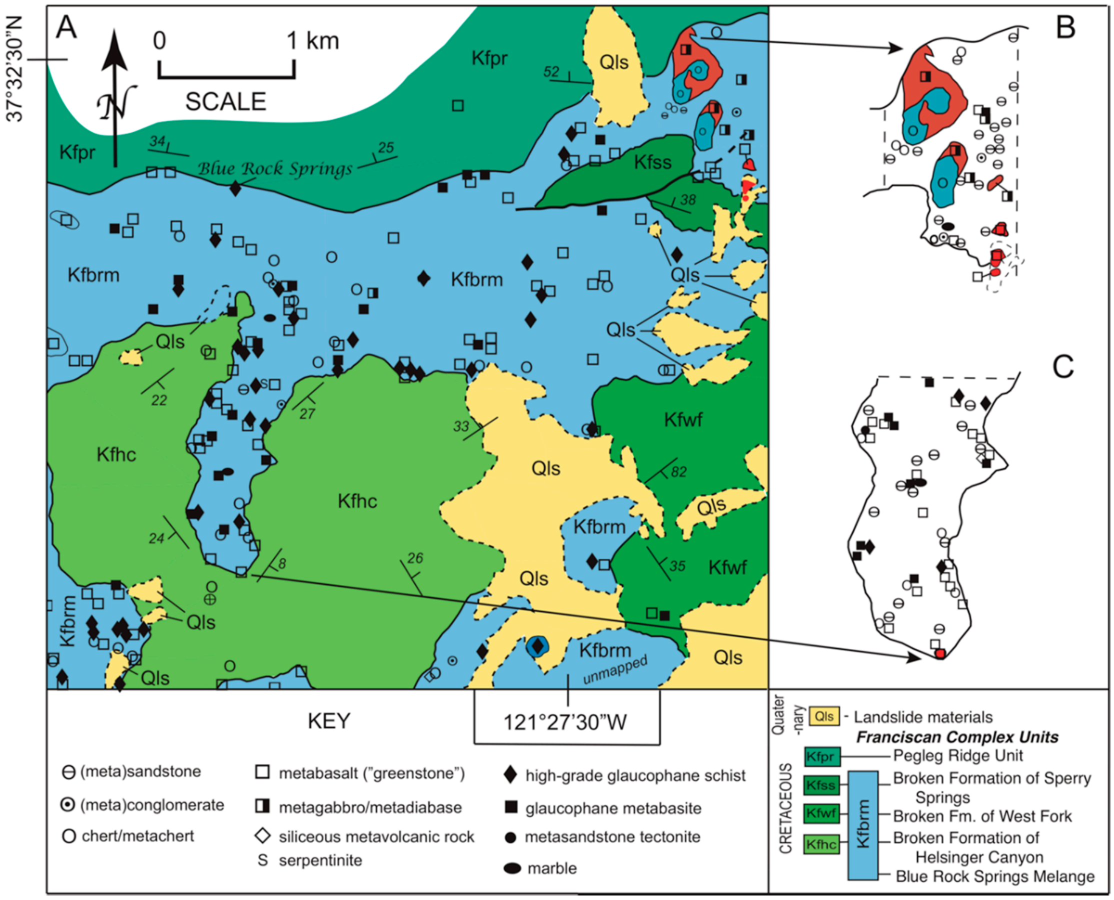

Figure 4. Maps of parts of the Blue Rock Spring Mélange. (**A**) General map of the Blue Rock Spring Mélange (Kfbrm) in the SW1/4 of the Lone Tree Creek 7.5′ Quadrangle, California. Note metasandstone slabs associated with and largely surrounded by the Kfbrm (including Kfss, the metawacke of Sperry Springs; Kfwf, the Metawacke of West Fork; and Kfhc, the Metawacke of Helsinger Canyon (units from [2]). Qls is Quaternary landslide material. The structurally overlying unit is the Broken to Dismembered Formation of Pegleg Ridge (Kfpr)/Pegleg Ridge Mélange (nature of unit is unresolved). Exotic blocks are diverse but not evenly distributed in the Kfbrm. Details of block distribution showing more blocks than the general map are shown for two areas of the mélange (shown in **B** and **C**). (**B**) Block map of area B, which contains some large masses of ocean plate stratigraphy (OPS), specifically metagabbro/metadiabase overlain by metachert (with local, red, interpillow weakly recrystallized metalimestone). Although the OPS blocks are the largest, native and exotic metasandstones are most abundant. The key shows other exotic block types. (**C**) Map of blocks in area C. See key for rock types. Metsandstones and metvolcanic metabasites are the most abundant, but high-grade blocks (mostly glaucophane schist) and lower-grade glaucophane metabasites and zeolite to greenschist facies metabasites ("greenstones") are relatively common. Note that non-oceanic rocks such as siliceous volcanic rocks are very minor components of the mélange. The maps show a representative sample of block types in the larger mélange, and it is likely that not every large block was discovered, but in general, only blocks larger than about 1 meter in diameter are mapped. An exception is that small masses of marble (any > 15 cm) are included on the map.

3.2. Tectonic Mélanges

From the late 1960s to the 1980s, many—perhaps most—Franciscan mélanges were thought to be tectonic in origin [8–11,16,74–77]. Tectonic mélanges were also thought by some to be massive units representing the entirety of an accreting subduction complex at a particular point in time [78,79]. While early arguments for sedimentary origins existed [21,28,80,81], those arguments were not widely applied to Franciscan rocks until later. Current conversations at meetings and the published observations and comments of researchers such as Cowan [12], MacPherson et al. [82,83], and Wakabayashi [3,20,43] suggest that tectonic mélanges may be less common than previously thought and may be decidedly subordinate to sedimentary mélanges in the Franciscan Complex [43]. Wakabayashi [3,33] even argues that many serpentinite-matrix mélanges had fragmentation and mixing histories that are primarily sedimentary in character.

Tectonic mélanges are still recognized in the Franciscan Complex and some are universally accepted as such. The one tectonic mélange described relatively recently by Wakabayashi [3] is the Rodeo Cove shear zone. He earlier also attributed fragmentation and mixing of the Hunters Point Mélange to tectonic processes [54]. The well-known Ring Mountain (serpentinite-matrix) Mélange is considered by Bero [55] to be tectonic in origin; however, as is discussed below and by Raymond [2], it has a disputed origin. A similar mélange at Jenner is considered to be of tectonic origin [52,53].

3.2.1. Rodeo Cove Mélange

The Rodeo Cove Mélange is a fault zone mélange (i.e., a tectonic mélange) within the Marin Headlands Block of the Franciscan Complex located a short distance north of San Francisco (RC on Figure 1) [19,23,50]. This mélange was called the Rodeo Cove thrust zone by Meneghini and Moore [23], the Rodeo Cove mélange shear zone by Meneghini et al. [51], the Rodeo Cove shear zone by Wakabayashi [3], and a mélange comprising unit six of Marin Headlands by Raymond et al. [46,47]. In the most fully described section of the mélange at Rodeo Cove, the Rodeo Cove Mélange is atypical of tectonic mélanges, because the mélange is zoned, and parts of the described shear zone do not have typical block-in-matrix structure [23]. The mélange is traceable from west to east across the southern Marin Headlands and appears as a lenticular mass of variable thickness on maps and in sections (Figure 5). It lies structurally between two accretionary units (AUs) that contain broken formational OPS masses. The overlying unit, AU5 of Raymond et al. [46,47], is dominated by oceanic metabasalt but contains some (meta)chert. The underlying unit (AU7) is the Black Sands-Conzelman AU, which contains parts of three OPS components—metabasalt, chert/metachert, and metasandstone (with meta-mudrock).

Inasmuch as the Rodeo Cove Mélange is a fault zone mélange, its boundaries with adjoining units are sheared, as is the matrix. The matrix varies from sheared metabasites to sheared mudrock, and it exhibits scaly foliation and cataclasite, but in the Rodeo Cove exposure, the matrix diminishes from the core towards the margins, especially the structurally lower margin (toward the north) [23]. Thus, the fault zone at Rodeo Cove is zoned in terms of deformation features. The southern edge of the shear zone, as defined by Meneghini and Moore [23], consists of structurally interlayered and juxtaposed broken formations of (meta)chert and metasandstone (not mélange). Towards the top of this zone of interlayering, stratal disruption increases and the shear-fractured-matrix derived predominantly from metabasalt and containing clasts of chert (one in excess of 10 m long) becomes the dominant rock of the mélange. The mélange displays P-R and S-C structures, notably in the core zone [23].

East of the excellent exposures studied by Meneghini and Moore [23], the Rodeo Cove Mélange is hidden beneath a lagoon and colluvium. Both Meneghini and Moore [23] and Raymond et al. [46,47] show the mélange extending east from beneath the colluvium and the lagoon, but Raymond et al. interpret the mélange to be unit six, whereas Meneghini and Moore interpret the mélange to be a unit two layers structurally lower (i.e., unit eight of Raymond et al. [46,47]). Here, I adopt the interpretation of Raymond et al. [46,47].

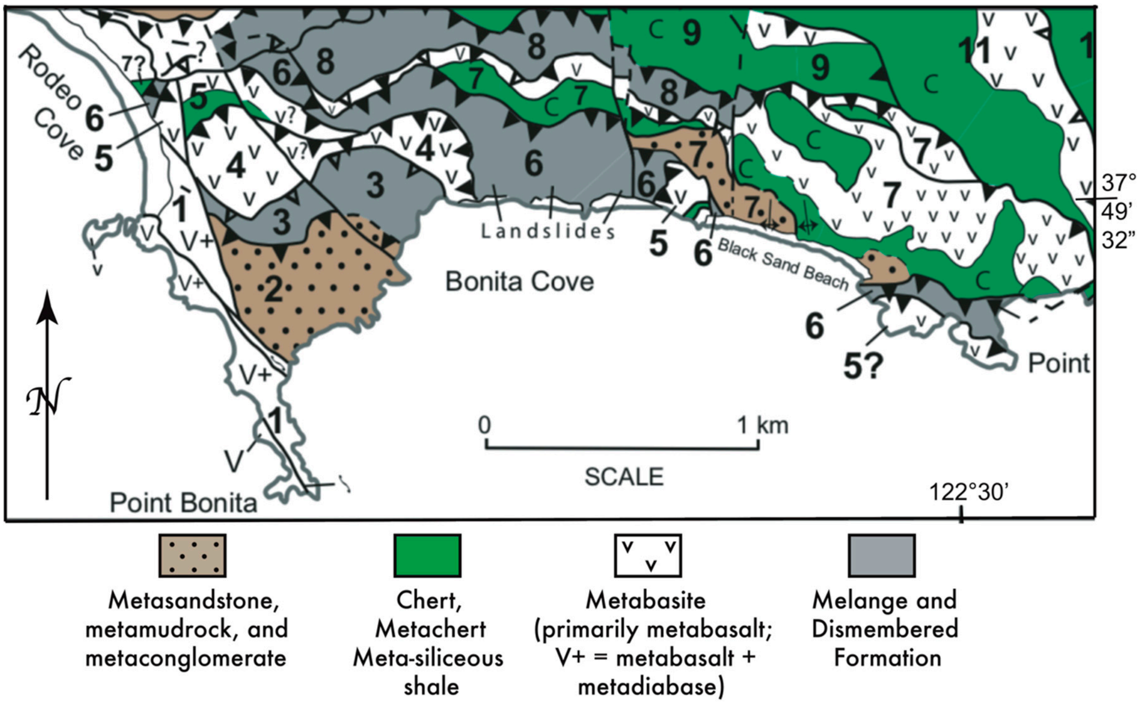

Figure 5. Geologic map of the southwestern, OPS-dominated, Marin Headlands block of the Franciscan Complex (after [46,47] and based on [23,50,51,84] and mapping by the author). Unit six is the Rodeo Cove Mélange.

The zone of mélange east of the lagoon is thicker and has a wider map dimension than exposures at Rodeo Cove (Figure 5). Here, the amount of matrix appears to increase, and "black rock" (pseudotachylite?) zones occur within this matrix. Large to small masses of metasandstone and metachert are exposed on steep slopes in the lower middle section of the mélange, and these are separated from one another by zones of scaly matrix containing small phacoids of metabasite, metasandstone, and metachert (Figure 2D). All of the clasts in the mélange appear to be OPS fragments and hence are metabasites, (meta)chert, or metasandstone ± metamudrock. To date, the largest blocks known are several tens of meters long, but detailed mapping of the entire mélange has not been completed.

The tectonic origin of the Rodeo Cove Mélange is not in dispute. The mélange has 14 of the 16 features characteristic of tectonic mélanges and exhibits all three of those that are definitive (Table 1). Its structural position, character, and lack of any of the definitive features of diapiric or sedimentary mélanges strongly support a tectonic origin.

3.2.2. The Ingram Canyon Mélange

In contrast to the Rodeo Cove Mélange, the Ingram Canyon Mélange contains a diverse array of clast types. The unit (formerly called the Rocky Point Mélange [48]) forms an accretionary unit in the northeastern Diablo Range and lies at the structural top of the Franciscan tectonostratigraphy [45–47]. The Ingram Canyon unit may be correlative with the Garzas Mélange described to the south ([11,47–49,85,86], and see below), but the latter has been studied in less detail than the Ingram Canyon Mélange. Details of the nature and the structural relationships of the Garzas Mélange are not well enough known for a definitive correlation between the two units.

The Ingram Canyon Mélange forms a lenticular unit in map view and is tabular to wedge-shaped in cross section [2,45–47,85]. All contacts are faulted (sheared), but most faults on the north, the northeast, and the east are late Cenozoic strike-slip faults [2,85,86]. The fault at the structural base of the unit likely had a diachronous history. Following early thrusting beneath the overlying Coast Range

Ophiolite (CRO) and later underthrusting by the Gerber Ranch Mélange, subsequent normal-slip movement likely occurred as the core of the Diablo Range rose during the late Cenozoic orogenic episode [87]. The block-in-matrix fabric is anisotropic and exhibits S-C fabrics and possible P-R fabrics (cf. S-C fabrics in the Garzas Mélange to the south [88]). Boudinage of clasts is common, and phacoids resulting from plastic extension are characteristic [48]. Folds occur in many blocks, but no regular mesoscopic folding is known within the mélange matrix. Scaly fabric pervades the matrix. Veins and striated phacoids and mélange "scales" bounded by anastomosing shears are common.

Both native and exotic blocks occur in the mélange and locally can be observed within the matrix, which varies from a serpentinite-mudrock mix in the north to a mudrock matrix in the south (see the map of block distribution for the mélange in [47,48]). In general, the scaly fabric of the matrix wraps around blocks, as is typical in tectonic mélanges. Blocks in the mélange range from serpentinite to sandstone and include conglomerate, garnet-glaucophane schist, chlorite-glaucophane metabasites (metagabbro and metabasalt), OPS fragments (including chlorite metabasites, chert and metachert, and metasandstone), plus uncommon siliceous metavolcanic rocks and chlorite schist [46–48]. In addition, rare actinolite schist, retrograde metamorphosed and veined eclogite, and aragonite marble occur locally.

The Ingram Canyon Mélange has been studied only by Raymond [45,47] and Raymond and Maddock [46,47]. It exhibits all of the features of tectonic mélanges, including the three diagnostic features. It has been argued, however, by Wakabayashi [3] (following MacPherson et al.) [82] that conglomerates and breccias with clasts of upper plate rocks, such as siliceous volcanic and plutonic (arc) rocks, suggest a sedimentary origin for a mélange. The conglomerates and the breccias are considered to represent remnants of the original sedimentary protoliths of the mélange, whereas the siliceous volcanic and the plutonic rocks, it is argued [3,82], must be clasts eroded via surficial processes from hanging wall terranes. While early-formed conglomerates, breccias, and diamictites may be overprinted by deformation and fragmented to form mélanges, as is clearly indicated by observational data [3,32,63], the existence of arc-type rocks is not absolute evidence that all such rocks found in a mélange require sedimentary processes for the formation of the mélange. One alternative, a variant of the protolith argument, is that conglomerate and breccia fragments in mélanges may just be individual components of the trench sedimentary sequence that later becomes a tectonic mélange beneath the mid- to inner accretionary complex. Both versions of the protolith argument are especially tenable if the arc rocks occur as relatively small, well rounded clasts.

A second alternative to the argument that arc-like plutonic and volcanic rocks *must* represent upper plate rocks surficially eroded from an upper plate source and deposited in the trench to become parts of the protolith of a sedimentary mélange is a tectonic alternative. Angular or tectonically rounded clasts and large blocks of arc-like plutonic and volcanic rocks may represent components of the igneous forearc, off-scraped during subduction erosion and subsequently mixed with other rocks to form tectonic mélanges [19,89–94]. It seems unlikely, however, that more siliceous varieties or arc rock, which occur in mélanges such as the Ingram Canyon Mélange, could be produced by subduction erosion in an abscherungzone setting [19] during initiation of subduction. Such a process would contribute clasts to a tectonic mélange that most likely would be basic to ultrabasic lower arc rocks. For upper arc (more fractionated) rocks to be tectonically eroded at the subduction interface, the arc would need to be extended and thinned, exposing abbreviated sections of arc rocks, including upper arc rocks, to tectonic erosion. Such thinned sections of suprasubduction zone arc rocks are present above the fault separating the Ingram Canyon Mélange from the overlying Coast Range Ophiolite (CRO) forearc section [45,47,85]. Thin and incomplete, 200 to 350 m thick sections of the CRO forearc that include the siliceous Lotta Creek Tuff structurally overlie—above a sub-ophiolite fault—the Ingram Canyon Mélange.

A similar configuration exists southwest of King Ridge Road near Occidental, California, where siliceous volcanic rocks in a highly thinned incomplete CRO section are juxtaposed with serpentinite-matrix and mudrock/sandstone-matrix mélange, the latter assigned to the "Central

Belt" [95]. The presence of thinned forearc arc sections with siliceous components structurally overlying mélange that contains arc-like rocks provides a setting in which subduction erosion of ophiolite could yield arc rock-bearing mélange. The geometry is not conclusive evidence but is supportive of an alternative mode of mélange origin that should be considered.

The Ingram Canyon Mélange contains only seven features of sedimentary mélanges and none of those most definitive of that origin. In contrast, it contains 15 of the 16 features of tectonic mélanges, including three of the most indicative features. Thus, in spite of the presence of siliceous volcanic blocks in the mélange, the strong evidence of deformation suggests that this mélange formed via tectonic fragmentation and mixing.

3.2.3. The Jenner Headlands Mélange

At Jenner, there are two mélanges exposed in the sea cliffs/near-shore area and on surrounding hillsides (Figure 1, labels HB and JH; Figure 6) [7,32,53,96,97]. The cliffs expose the polygenetic Heaven's Beach Mélange [32], whereas areas on the hills near the ridge crest to the east of the cliffs (and north of the Russian River) have exposures of a serpentinite-matrix mélange [7,53], here called the Jenner Headlands Mélange. The Jenner Headlands Mélange is structurally overlain by serpentinized peridotite and locally overlies, above a thrust fault boundary, either an unnamed jadeitized, foliated metawacke unit (on the north in Figure 6) or the Wren Rock unit (an olistolithic broken formation or sandstone-matrix mélange) [7,32,53].

In map view, the serpentinite-matrix Jenner Headlands Mélange forms several irregular to linear masses scattered across the terrain north of Jenner, California. It is a thin tabular to irregular unit in cross section [2]. The contacts are not well exposed but in all cases appear to be sheared, as are the exposed contacts between matrix and blocks.

The serpentinite matrix of the Jenner Headlands Mélange exhibits a scaly fabric that contains a variety of exotic blocks and clasts [53]. The matrix is anisotropic in structure with anastomosing shear planes, and it wraps around clasts and blocks (Figure 7A). The clasts and blocks range up to several tens of meters in long dimension and are rounded to lensoidal in shape [53]. Block rock types include typical metamorphosed OPS rocks [metabasites (metabasalt and metagabbro), metachert, and metasandstone] and conglomerate plus hornblende and glaucophane schist with chlorite-actinolite rims and veins, chlorite and serpentinite schists, and rare eclogite. Essentially, all of the blocks are exotic.

The fault-bounded Jenner Headlands Mélange is decidedly tectonic in origin, exhibiting 14 of the 16 features of tectonic mélanges, including two of the three definitive features. With the possible exception of some rounded blocks, the mélange has none of the definitive features of diapiric or sedimentary mélanges and only modest numbers of features that occur in two or more mélange types.

Of note here is that the tectonostratigraphy present at Jenner Headlands is repeated elsewhere in the region. The uppermost trectonostratigraphy of the Franciscan Complex includes a mélange—typically a serpentinite-matrix mélange that structurally underlies a blocky serpentinized to massive peridotite unit usually assigned to the Coast Range Ophiolite. Beneath the mélange, the common units that occur successively downward are a foliated blueschist facies unit and a structurally underlying prehnite-pumpellyite facies, metasandstone-metamudrock unit. This sequence occurs at Jenner, at Freestone to the southeast, and on the Tiburon Peninsula near San Francisco (RM on Figure 1) [2,7,32]. Partial or similar sequences with the same order occur near Occidental (southeast of Jenner) and at El Cerrito (HM on Figure 1) [2,44,53,95,98]. In central Marin County, blocky serpentinized peridotite is underlain by a sheared serpentinite unit that is arguably a serpentinite-matrix mélange, and that unit is underlain by an olistostrome-bearing, prehnite-pumpellyite facies, metasandstone-metamudrock unit [32]. A blueschist facies unit has not been recognized in central Marin County. Repetition of a tectonostratigraphy across the northern San Francisco Bay region argues for a similar tectonic accretion history for the region and a similar history for the serpentinite-matrix mélanges.

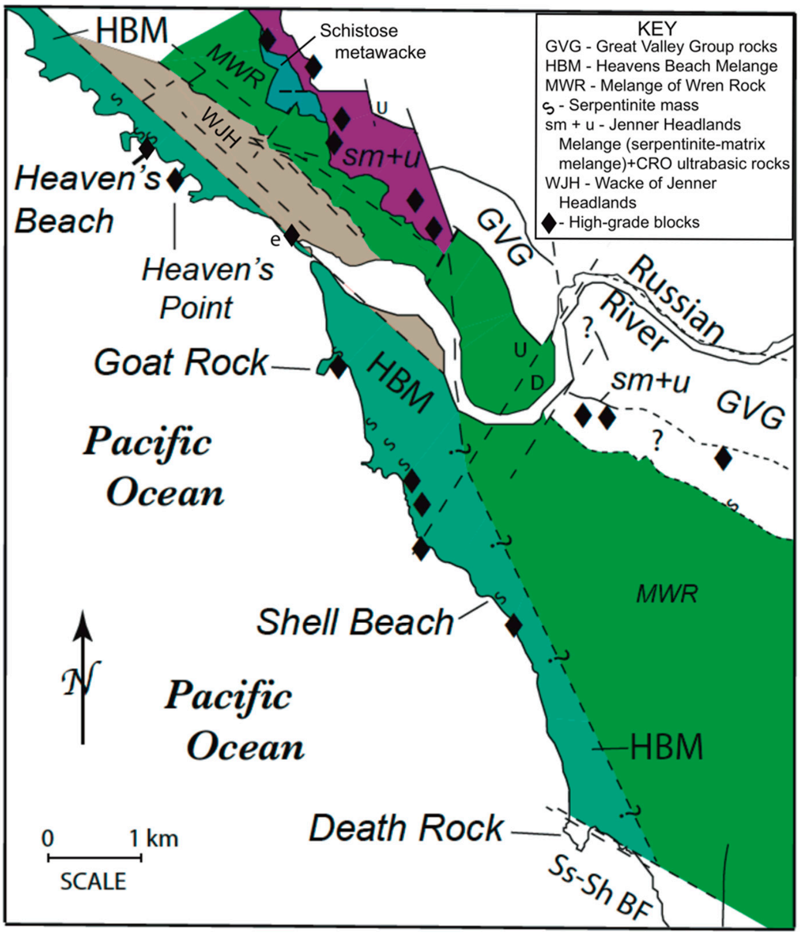

Figure 6. Simplified reconnaissance geologic map of part of the Sonoma County coast, California, showing the location of the eclogite-bearing Jenner Headlands Mélange and overlying rocks of the Coast Range Ophiolite (CRO), labeled together as sm+u, and the general extent of the Heaven's Beach Mélange (see [3,7,32,52,53,99–101]). Part of the northern area was mapped in detail by Bero [7] and Raymond and Bero [32]. The area between Goat Rock and Shell Beach was mapped in reconnaissance by Wakabayashi [3] and the author (unpublished). Preliminary reconnaissance south of Shell Beach was done by the author. The eastern contact, a high-angle fault, is largely concealed beneath Quaternary marine terraces, landslide materials, and colluvium. The western contact is largely concealed beneath the Pacific Ocean. The well known Jenner eclogite locality, containing eclogites moved by landsliding from the Jenner Headlands Mélange to the road and beach downslope, is marked with a high-grade block symbol and the letter "e" (see [52,53]).

3.2.4. Other Tectonic Mélanges

Several other mélanges that have been designated as tectonic in origin are listed in Table 1. These include the Garzas Mélange, the Gerber Ranch Mélange, and the Hunters Point Mélange. The Garzas Mélange (GZ on Figure 1) is a shale-matrix mélange that is exposed over a wide area in the northeastern Diablo Range [11,45,49,102]. Preliminary regional structural analysis suggests that the mélange may not be as thick as it seems, inasmuch as the folding patterns shown by Raymond [2,45,87] for the region result in repetition of mélange sections. The mudrock-matrix Garzas Mélange has a relatively diverse range of native and exotic block types, including blocks of so-called "high-grade" glaucophane schist [11,49]. Scaly and brecciated textures are common in the matrix (Figure 2E) and define an anisotropic fabric that is also reflected by S-C fabrics in metawackes [88].

The Gerber Ranch Mélange structurally underlies the Ingram Canyon Mélange [45–49]. It is distinct from the latter in its lack of both serpentinite bodies and blocks of "high-grade" glaucophane schist and related rock types. Numerous blocks of lower grade glaucophanized metabasites occur in the Gerber Ranch Mélange, and these are accompanied by other OPS fragments of metachert and metasandstone, all metamorphosed under jadeite blueschist facies conditions [45,48,85]. Other clasts and blocks include conglomerate plus rare marble and actinolite schist. The blocks tend to be elliptical, reflecting elongation parallel to the strike of the scaly mudrock fabric of the mélange.

The Hunters Point Mélange on the San Francisco Peninsula (HP, Figure 1) is a complex body that is not well understood, in part because of the limited outcrops available within a city environment. The unit was mapped by Schlocker [103] and Bonilla [104] and designated by Schlocker as the Fort Point-Potrero Hill-Hunters Point Shear Zone, shortened to Hunters Point Shear Zone by Wakabayashi [3,54,105]. Wakabayashi [54] describes a layered/zoned map pattern with a large serpentinite mass between regional layers of shale-matrix mélange. In detail, however, the zones of sheared (scaly) matrix in the mélange vary spatially from serpentinite to serpentinite+ mudrock to mudrock [103]. The matrix contains rounded to elongate blocks and clasts of various rock types, including sandstone, chert, metabasites (including gabbro), serpentinite, and metamorphic rocks (e.g., hornblende schist) [54,103,105]. The largest block is approximately 1 km in length, but most are substantially smaller. The Mélange of Hunters Point exhibits two of the definitive features of tectonic mélanges and 11 features of such mélanges overall.

3.3. Diapiric Mélanges

Diapiric mélanges are rare in the Franciscan Complex. Two descriptions of diapiric mélanges in the Sur-Obispo Complex (formerly included in the Franciscan Complex—see [2]) are presented by Becker and Cloos [106] and Ogawa et al. [107]. The only Franciscan mélange assigned a diapric history in the region covered by this review is the Serpentinite Mélange of Redwood City [57]. As indicted by the name, the mélange is a serpentinite-matrix mélange exposed on the peninsula south of San Francisco (RCS on Figure 1).

The Serpentinite Mélange of Redwood City has discordant, sheared contacts and native and exotic blocks [57]. Blocks range up to a few meters in maximum dimension and most are serpentinite, at least some of which are massive antigorite. Rare glaucophane schist with remnant omphacite occurs locally. The mélange presents an elongated, irregular map pattern, a sheet-like shape in section, P-R structures, anisotropic and local scaly fabric, and common veins. Of critical importance in understanding the mélange history is that it displays sheared contacts with an Eocene sandstone unit that unconformably overlies other Franciscan units [108]. This indicates that diapirism is of post-accretionary complex age, suggesting late Cenozoic remobilization of mélange materials formed earlier [109].

The mélange contains only three characteristics of diapiric mélanges and displays neither of the two definitive features of such mélanges. In contrast, it displays 12 of 16 features that occur in tectonic mélanges and all three of the definitive features of tectonic mélanges (Table 1). As such, the age of fragmentation and mixing is open to question and may be pre-diapirism. I here consider the mélange to be polygenetic as currently exposed but ultimately of tectonic—not diapiric—origin. All things considered, this mélange would better fit below within Section 3.4, which covers polygenetic mélanges and mélanges of disputed origin.

3.4. Mélanges of Polygenetic and Debated Origin

3.4.1. The Heavens Beach Mélange

The polygenetic Heavens Beach Mélange crops out near Jenner, California, north of San Francisco (Figure 1, HB; Figure 6) and was named for a beach of that name [32]. The almost continuous mélange exposures have an along-strike length of more than 10 kilometers, encompassing the type section north of Jenner and rocks to the south at Goat Rock to Shell Beach and beyond [3,32,53,99]. The mélange unit as a whole is irregularly linear in map view. The western contact of the mélange is concealed beneath waters of the Pacific Ocean. In rare exposures, the eastern boundary appears to be a high-angle fault and is thus a sheared contact. Inasmuch as the western contact is concealed, the cross-sectional nature of the mélange is unknown.

Internally, the mélange has a metasandstone-metamudrock matrix that locally has scaly fabric with anastomosing cleavage [53] and breccia zones (Figure 2F). Hence, the matrix is in part anisotropic. Within this matrix are large and small blocks of both native and exotic blocks. The native blocks are low-grade metasandstone of mid-fan character. Exotic blocks range from prehnite-pumpellyite facies metasandstones (dominantly sandy Fan Facies A, B, C, E) and dominantly metashale (Fan Facies D) to largely reconstituted, foliated, high-pressure metamorphic rocks (blueschist facies metasandstone tectonite, glaucophane schist, and hornblende schist and gneiss) [3,32]. Notable blocks are several serpentinite bodies (Figure 6), at least two of which include masses of serpentinite-matrix mélange. In addition, blocks include a mass of distinctive red chert-bearing conglomerate and a muddy sand-matrix olistostrome with stratigraphically overlying (but structurally underlying) conglomerate, both containing clasts of glaucophane schist. Both the olistostromal mélange of the tectonic block and the tectonic successor mélange contain blocks of mafic metabasite, metachert, and metasandstone, but the olistostromal unit and the conglomerate within the tectonic block also contain clasts of plutonic igneous rocks. Blocks and clasts range in size from a few centimeters to blocks of about 600 m in length [3,32]. Some of the smaller blocks likely were derived by fragmentation and intermixing of blocks of the olistostrome into the matrix of the successor tectonic mélange. Blocks are angular and blocky to subrounded to lenticular in shape, with the latter displaying local deformation “tails.” Some blocks display folds—primarily metachert and “high-grade” glaucophane schist/amphibolite blocks—but the matrix displays no obvious regional folding.

The olistostromal block in the Heavens Beach Mélange reveals sedimentary fragmentation, mixing, and deposition of sediment containing reworked Franciscan rocks (metabasites, metachert, metasandstone, glaucophane schist). The Heavens Beach Mélange in its present state, however, developed the dominant character of large to small blocks in a matrix of sheared sandstone-mudrock after deposition of the sandstone-, conglomerate-, and olistostromal diamictite in units that gave rise to blocks now present in the mélange. Thus, the mélange in part had a sedimentary precursor mélange that provided some material to the mélange. The now dominant block-in-matrix character is of tectonic origin. The mélange has 13 of the features characteristic of tectonic mélanges and two of the three definitive features (Table 1).

3.4.2. The Ring Mountain Mélange

The Ring Mountain Mélange is the most studied mélange of the Northern Coast Range–Diablo Range Franciscan Complex (Figure 1, RM, between RC and HM). Numerous studies of various aspects of the exotic blocks in the serpentinite-matrix mélange [52,55,56,105,110–114], limited study of the serpentinite matrix [3,115], and large-scale (detailed) mapping [3,55,56,111] have both clarified many details of the mélange and led to conflicting interpretations (contrast [55] and [3]).

In map view, the Ring Mountain Mélange appears as an irregular, slightly elliptical, elongated ring-like body overlapped by irregular elliptical to ring-like masses of serpentinized peridotite capping parts of Ring Mountain [55,56]. In the cross section, the body is a thin, folded sheet [55,56]. The contacts are sheared. Internally, the serpentinite matrix displays anisotropic, scaly fabric with anastamosing shears that bound unsheared to less sheared phacoids of serpentinite and wrap around larger exotic blocks (Figure 2G). Apparent P-R structures contribute to the sheared character of the matrix. Macroscopic asymmetrical folds in the mélange are later-formed features that affect both overlying serpentinized harzburgite and underlying mélange. Mesoscopic folds also characterize many of the exotic blocks (Figure 7B) and the matrix (Figure 7C).

The blocks in the mélange are relatively abundant and both exotic and native in character [3,43,55]. Abundant native serpentinite blocks of a range of sizes are the most common. Exotic blocks and clasts ranging from a few millimeters to 140+ m in long dimension occur as a variety of rock types. These include both higher and lower grade blocks. The “high grade” blocks are garnet-hornblende gneisses and schists, eclogites, and glaucophane schists. The lower grade blocks include talc-chlorite ± actinolite schists (that likely represent rims from or retrograde masses of higher grade blocks) and relatively rare folded schistose serpentinite tectonite (Figure 7B), dense knobby serpentinite tectonite, and siliceous volcanic rock. Some chert/metachert and foliated metasandstone masses in structurally ambiguous positions may be exotic blocks as well.

The features and the inferred origin of the mélange and its matrix are debated. Bero [55] essentially argues that the matrix is a tectonite formed at the base of the overlying harzburgite during thrusting over the underlying Franciscan rocks. Essentially, the structural position, the pervasive scaly fabric, the common serpentinite rims on clasts, the presence of boudins that could not survive sedimentary transport, and the regional distribution of similar rocks in tectonostratigraphic-like settings favor a tectonic interpretation.

A sedimentary origin is favored by Wakabayashi [3,33], who called the mélange the Tiburon Mélange. Three primary lines of evidence are offered in support of that view—(1) textural/structural evidence of rounding of grains and blocks, (2) breccia structure, and (3) photomicrographic evidence of various non-serpentinite, sand-size grains in the matrix. Rounded shapes of serpentinite blocks and clasts, as well as other clasts in the mélange, are a central issue. With regard to rounding, Bero [55] and Raymond and Bero [32] offer the alternative processes of weathering and tectonic erosion for the production of rounded serpentinite blocks that appear both on slopes and within the matrix (Figure 8A). Tectonic rounding has affected other Franciscan rocks [30] and reasonably may have affected the serpentinites. O'Hanley [31] describes and illustrates weathering "kernals" with rounded edges in serpentinites that result in rounded clasts. The Ring Mountain Mélange definitely has many rounded clasts of serpentinite and other rocks. A rounded block of glaucophane schist in the serpentinite matrix at Ring Mountain, for example, is reportedly enclosed in "serpentinite pebbly sandstone" [43] (Figure 8B). My examination revealed one area of serpentinite breccia (br) in the outcrop, a strongly to weakly foliated, scaly to blocky serpentinite matrix (sp) that wraps around small and large blocks and clasts, and a strongly and concentrically-foliated glaucophane schist block (gs), the internal foliation of which is paralleled at its margin by some foliations in adjoining serpentinite (Figure 8B). Overall, the fabric that appears sedimentary to Wakabayashi [43] appears tectonic to me.

Figure 7. *Cont*.

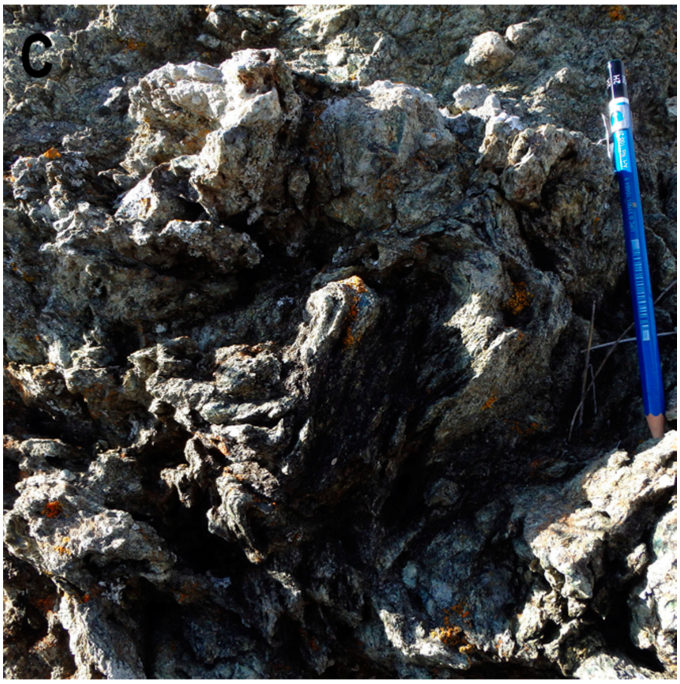

Figure 7. Some structures in serpentinite-matrix mélanges. (**A**) Boudin and foliation. The foliation in the serpentinite matrix (dark) bends to wrap around a large chert block (light) in the Jenner Headlands Mélange. Note the bend in foliation towards parallelism with the contact at the lower right behind grass and at the left center, where the matrix encloses a small boudinaged layer of chert (modified from [54]); 40 cm hammer provides scale. (**B**) Folds in exotic serpentinite tectonite (schist) block in the Ring Mountain Mélange. Author's arms point in directions of dip, away from the antiformal axis. Note the smaller synformal fold axial region to the left. (**C**) Folds in the serpentinite matrix of Ring Mountain Mélange. Pencil, for scale, is about 6 cm long.

In the absence of other compelling evidence of sedimentary processes acting on the mélange matrix, tectonic rounding—and in some cases, weathering—seem the better explanation for the rounding. The same seems reasonable for other evidence. Local breccias consisting of serpentinite fragments in a serpentinite matrix may be attributed to tectonism. Sand-size grains in the serpentinite matrix, the grains reported by Wakabayashi [3,33], include hornblende, glaucophane, plagioclase, garnet, and rutile—all components of the blocks included in the mélange. More compelling would be the presence of abundant quartz grains or grains not derived from exotic blocks (e.g., mudrock lithic clasts, K-feldspar grains, fossils). In the absence of the latter, the reasonable and less astonishing argument can be made that tectonic erosion of exotic blocks yields grains to the matrix, as the larger blocks are rounded during tectonic movements. Inasmuch as most outcrops and microfabric images show penetrative anisotropic fabrics, a tectonic origin following the view of Bero [55] is favored here.

A tectonic origin is also favored by the sum of the features present in the rocks. The Ring Mountain Mélange exhibits 14 of 16 of the features common to tectonic mélanges, including all three of the diagnostic features. In contrast, the mélange has only has eight of 15 features characteristic of sedimentary mélanges, one of four features (rounding of clasts) considered diagnostic of sedimentary mélanges, and three of 13 features common to diapiric mélanges (Table 1). If the mélange had a sedimentary history, the subsequent tectonic history has nearly obliterated evidence of that sedimentary history.

3.4.3. Other Mélanges

The Laytonville Mélange and the Serpentinite Mélange of Redwood City are both mélanges for which origins different than those advocated by the reporting authors seem reasonable. The Laytonville Mélange may be an amalgamated mass of multiple units or a deformed mass in which duplication of the unit gives the appearance of greater thickness. The features of the Serpentinite Mélange of Redwood City suggest a tectonic, pre-diapirism history. In these cases, however, debates on the origins have not been fully developed in the literature.

Several other mélanges in the Franciscan Complex have been assigned sedimentary or tectonic origins. In most cases, only a few features have been used to decide on the origin. The comprehensive list of features now available for discriminating among mélange origins (Table 1) should be used to re-evaluate the origins of all mélanges not thoroughly studied.

Figure 8. Rounding of serpentinite clasts in mélanges and serpentinite broken formations. (**A**) A combination of jointing, weathering with exfoliation, and shear at the block boundary is producing rounded serpentinite masses in this serpentinite-matrix mélange block that originally had a phacoidal shape. Exposure is near Liberty Gulch in Marin County, California; 40 cm hammer provides scale. (**B**) Coarse-grained (foliated) glaucophane schist (gs) block in Ring Mountain Mélange. Note the concentric foliation of the block. A serpentinite breccia zone (br) occurs at the right side of the block within the serpentinite (sp), which totally surrounds the block in the plane of exposure. Red lines mark foliation planes within the glaucophane schist and shear-fracture planes within the surrounding serpentinite. See text for additional discussion.

4. Discussion and Conclusions

Considering the information reviewed above, it is clear that, through careful analyses, individual mélanges can be distinguished from one another, and their origins can be revealed on the basis of mélange characteristics, such as kinds of exotic blocks, sizes of included blocks, nature of structures, and matrix composition. These features aid in determining specific processes of fragmentation and mixing in the formation of the mélange. Thus, the features of the mélange reveal its origin.

It is important to note here that there is convergence in the nature of some fabrics developed in sedimentary and tectonic mélanges, especially in shallow parts of subduction zones, where sediments are poorly consolidated ([27,116–118] and Figure 6 of [27]). Stratal disruption, development of boudinage, soft-sediment shears, and mixing are all reported within shallow levels of some accretionary complexes. Thus, the duality of origins of some features common to both sedimentary and tectonic mélanges creates challenges in assessing mélange-forming processes. Tectonic overprints that mask the primary diagnostic fabric of sedimentary and diapiric mélanges further complicate assessment of mélange origins.

The representative Franciscan mélanges evaluated here appear to have formed by either tectonic or sedimentary processes. This preliminary analysis does not support the view that most Franciscan mélanges are sedimentary in origin. While diapirism is known in accretionary settings [119], most California Coast Range mélanges with evidence of diapirism show evidence of re-mobilization and later intrusion rather than syn-accretionary syntectonic diapirism [109,120,121]. In general, mélanges assigned a tectonic origin have features matching 10 or more of the typical characteristics of such mélanges and two or three of the definitive features. Similarly, most mélanges reviewed here assigned a sedimentary origin also have a dominance of features currently accepted as representative of a sedimentary history [2,15,27].

Unequivocal sedimentary mélanges with mudrock, sandstone-mudrock, and sandstone matrix materials are widely distributed within the Franciscan (accretionary) Complex. Although sedimentary serpentinite-matrix mélanges are known in the overlying forearc Great Valley Group [122,123], the serpentinite-matrix mélanges examined here lack features that make a compelling case for a sedimentary history. The most definitive features indicative of a sedimentary origin are (1) depositional to gradational contacts, particularly in relation to underlying units, (2) an interbedded stratigraphic setting, (3) rounded clasts, especially if those clasts have diverse characters and petrologic histories, and (4) in situ fossils. Some mélanges, such as the Crescent City Olistostrome, clearly exhibit most of the characteristic and defining features of sedimentary mélanges. Other mélanges previously assigned a sedimentary origin, such as the Ring Mountain Mélange, do not.

Tectonic mélanges are particularly characterized by sheared and deformed contacts, by the presence of S-C or P-R structures (or both), and by scaly microfabrics, especially where those are accompanied by microbreccia and pseudotachylite. Mélanges such as the Rodeo Cove Mélange and the Ingram Canyon Mélange not only display the three definitive features of tectonic mélanges, they also have most other features found in mélanges of that origin. Clearly, they have a tectonic history.

Given that the accretionary complexes form in dynamic interplate settings, it is not surprising that most Franciscan mélanges have numerous tectonic features (Table 1). In sedimentary mélanges, these are superimposed on the sedimentary features, and it is clearly the case that even those Franciscan mélanges with definitive sedimentary histories exhibit some tectonically generated features (Table 1). It is possible that, in some cases, evidence of an early sedimentary history has been obscured or obliterated entirely by later post-formation tectonism. In the most extreme of such cases, we are left with no recourse other than to describe only the tectonic history. Arguments that a particular mélange had an early sedimentary history should be supported by at least two or more features that establish a compelling case for such a history. Since rounding of clasts may result from a variety of processes, rounded clasts by themselves do not make a compelling case for a sedimentary history.

Table 2 and the published literature reveal that mélanges of all origins may have either a petrologically limited or a diverse set of clasts, blocks, and phacoids. Clearly, that is true of Franciscan mélanges. In general, native clasts of sandstone are the most common. OPS fragments are ubiquitous as well and are present in every mélange evaluated in this review. High-grade glaucophane schists, however, while widely distributed, are not abundant. Fragments such as granitoid clasts, marbles, limestones, and mica schists are relatively sparsely distributed to rare.

Since clasts, blocks, and phacoids of diverse character apparently occur in both tectonic and sedimentary Franciscan mélanges, block content alone is not indicative of mélange origins. Block size also fails as a discriminator between sedimentary and tectonic mélanges. A definitive study of mélanges such as the Garzas Mélange and the Ingram Canyon Mélange that lie structurally adjacent to and immediately beneath eroded upper plate Coast Range Ophiolite (CRO) rocks to determine if these mélanges and the enclosed large and small upper plate blocks are the product of tectonic erosion would be useful and illuminating.

Additional studies of Franciscan mélanges, especially more studies including fabric and structural analyses, will further our understanding of Franciscan Complex architecture. Both the group of mélanges reviewed here and the larger group of remaining Franciscan mélanges would benefit from further study. Table 1 might be used as a beginning point in directing future studies. Clarifying the relationship of Franciscan mélanges to other architectural units of the accretionary complex will also aid in our understanding of overall subduction accretionary complex architecture. Ultimately, an understanding of the roles of mélanges in the archtypical Franciscan (subduction accretionary) Complex will allow use of the Franciscan mélanges and their relationships to serve as a guide to understanding other subduction accretionary complexes.

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