ABSTRACT

The Franciscan Complex comprises the largest bedrock unit of the California Coast Ranges, so it impacts many engineered projects in coastal California, but the ignorance of basics of Franciscan geology plagues many projects. The stratigraphic name given by engineers or geologists in many projects, 'Franciscan Formation', a term abandoned by research geologists nearly four decades ago, illustrates some of this misunderstanding. The "layercake" stratigraphy inferred by 'Formation' differs markedly from reality, for faults separate most Franciscan rock units, and chaotic block-in-matrix units, known as melanges, are widespread. While the layercake view results from a pre-plate tectonic understanding, others mistakenly believe that the entire Franciscan is a melange. Research shows that the Franciscan consists of both intact units ("coherent") and melanges. Franciscan geology knowledge continues to progress, but researchers have virtually no understanding of the engineering significance of these rocks, while the engineering community remains largely unaware of the current research knowledge. There is substantial potential benefit from better communication between the engineering and geologic research communities. Education is also critical, for as undergraduate field studies continue to diminish in geology programs, most existing field classes tend to focus on areas of layercake stratigraphy and excellent exposure, providing dismally poor preparation for professionals who might work in areas such as coastal California.

INTRODUCTION

Melange units, composed of a weak matrix enclosing stronger blocks, make up a significant proportion of the world's bedrock in areas of former subduction zones [1,2]. Recognition of melanges is important for engineering geology and related engineering because their physical properties differ markedly from simple bedded or isotropic rock [3,4,5,6]. Because of their discontinuous, rather than continuous structure and/or stratigraphy, particular care must be taken in terms of interpretation of field data, be it the interpolation between or extrapolation from boring or surface geologic information, or the scaling between outcrop and boring levels of observations to the scale of engineering interest [6,7,8,9,10,11]. These studies [3-11] provide a good framework for engineering characterization of melanges, but a non-trivial step is to recognize that a melange is present or not [12]. It is here where a huge gap exists between the state-of-knowledge of the research geologic community, in which melanges have been common knowledge for at least 40 years, and the applied geoscience community (the term I will use to define engineering and environmental geology and related engineering fields) where it is still common to think of all geologic units as either being homogeneous and isotropic (as an idealized granite) or a layered sedimentary stack (herein termed "layercake stratigraphy" as one might expect in the Grand Canyon). In this paper I will discuss misconceptions about melanges (or failure to recognize them) within the context of the evolution of geologic thought on the Franciscan Complex of California, one of the world's most famous localities for melanges and also a geologic unit upon which a large population lives and
builds many engineered structures. I will then offer some tips for identifying melanges in the field and show how melanges have a number of characteristics that can be recorded that may be useful in engineering characterization. I will conclude with some concerns about the state of field studies in geologic curricula and its impact on melange characterization, with some recommendation for better communication between the academic ("research") and applied geosciences.

Fig. 1: Map showing the distribution of the Franciscan Complex and related rocks (gray) as well as some other units in northern and central California that contain melanges. Adapted from [18].
MELANGES AND THE FRANCISCAN COMPLEX: THE OUTCROPS DID NOT CHANGE, BUT OUR VIEWS DID

Melanges were first recognized by Greenly [13] who coined the term based on exposures in Wales, although chaotic, non-stratiform (i.e., not layercake) rocks had been noted decades earlier by geologists working in the Alpine region of mainland Europe [2]. In spite of Greenly's work, and research of others (whose observations and interpretations were parallel and independent of those of Greenly) conducted in other parts of the world in the decades following Greenly's work, nearly five decades elapsed before Hsü [14] published his historic paper on melanges and the concept became widely accepted throughout the geologic community [2], or more accurately, the research geologic community. Front and center in Hsü's work was the Franciscan Complex of coastal California (Fig. 1). Today we know the Franciscan Complex as the world's type subduction complex, because the pioneers of the Plate Tectonic Revolution first used the Franciscan to illustrate the connection between subduction and high-pressure/low-temperature metamorphism [15], and the tectonic shuffling of oceanic and continentally derived materials [16]. The melange concept, while not originally envisaged in a subduction context by Greenly or Hsü, now became part of the plate tectonic paradigm [16], so the Franciscan became triply recognized for three critical components in development plate tectonic theory.

Investigations in the late 60's and early 70's showed that the Franciscan consists of both melange terranes and so-called "coherent" (non melange) terranes and that the proportion of melange to coherent terranes varied spatially within the Franciscan [21]. Workers such as Blake et al.[22,23] and Wakabayashi [17,18] extended the studies of Maxwell [21] and his students, so that the dual melange and coherent components were mapped throughout the Franciscan.

As pointed by Wakabayashi and Medley [12], outcrops have not changed over the past 40 years, but prevailing theories have, so that the same set of outcrops have been or are interpreted three ways: (1) stratigraphic (pre-1968), (2) all melange (the next step, post-1968), (3) mixed coherent and melange (Fig.2). This points out an often unappreciated aspect of field geology: Field studies do not represent a purely objective, non-analytical "stamp collecting" exercise as wrongly believed (and even ridiculed) by many field-phobic academicians. The latter see little value in geologic mapping, because the geologic maps exist for every part of the Earth (at least above sea level). Rather, field geology has a highly interpretive aspect to it, with our drawing of contacts tied to prevailing geologic thinking. Why? We never have a fully 3-dimensional set of field data without gaps. Interpolation and extrapolation comprise a critical part of our field mapping and the prevailing theories dictate how we "connect the dots".

We now view the Franciscan as a product of subduction that began about 165 million years ago and continued for over 140 million years [17]. Faults bound major units, and the age of incorporation into the Franciscan youngs structurally downward (across major faults), as a consequence of progressive offscraping of material from the downgoing plate [17,18]. This contrasts markedly with a sedimentary/stratigraphic view held prior to the acceptance of plate tectonic theory and the melange concept. Although the spatial distribution of ages made little sense from a stratigraphic standpoint (i.e. a sedimentary sequence that youngs progressively upward), researchers resolutely tried to force fit the Franciscan into a layercake stratigraphic model [19]. The term "Franciscan Formation", a formal stratigraphic term that most researchers discarded in 1968, represents the pre-melange/pre-plate tectonic view of the Franciscan Complex as a sedimentary sequence.

Following the recognition of melanges, some workers viewed the entire Franciscan as a melange [20], and indeed the informal name of the entire complex as the "Franciscan melange" still finds common usage. Such a view of the Franciscan can have as disastrous consequences in engineering investigations as the mistaken view of layercake stratigraphy, because some default the Franciscan to an intrinsically chaotic unit from which one cannot extract any meaningful spatial field data.
This summary of the evolution of thought on melange and the Franciscan Complex illustrates how much prevailing thoughts and knowledge have changed over the past four decades in the research community. Sadly, a large fraction of the applied geoscience community still holds pre-1968 views of the Franciscan. Fig. 3 represents a cross section from a project somewhere in the Franciscan done within the last 10 years (location not named for confidentiality, and the cross section has been redrafted from the original) wherein a layercake interpretation is given to geology that is almost certainly melange in part. Huge errors, such as mistaking the melanges for a surficial unit ("soil with boulders"; imagine how far deeply one might have to excavate to find "bedrock"), or the usual layercake stratigraphic interpretation (consistent with the "Franciscan Formation" view), continue occur at alarming rates. Such blunders commonly have costly consequences. Although this summary criticizes the ignorance shown by parts of the applied geoscience community, I hold research geologists equally culpable. Academic geologists typically have little or no awareness of "real world" (ie engineering or environmental) issues connected with the rocks they so enjoy studying. For example, in spite of the interest that studies in melanges have generated in the academic community over the last few decades, I have yet to encounter a fellow academic who has even a remote understanding of the engineering issues associated with melanges. In a later section, I will return to this theme to discuss role of
undergraduate geologic education in improving the awareness of melanges in the applied community.

**MELANGES: DIFFERENCES BETWEEN GEOLOGIC ISSUES AND ENGINEERING ISSUES**

The applied geoscience community commonly has difficulty recognizing melange terranes, but academic geologists do not realize that not all melanges they map comprise melanges from the standpoint of the engineer. As a result, applied geoscientists reading the research literature may be led astray. An "engineering melange" has notably stronger blocks than matrix, whereas some "geologic" melanges lose this contrast as a result of metamorphism that results in the recrystalization of the matrix to form a hard and strong schist. In metamorphic grade, this commonly corresponds to greenschist facies or higher (rock experienced metamorphic temperatures exceeding 300°C). For example, large tracts of melange in the central and southern Sierra Nevada are not "engineering" melange because former shale matrix that has recrystalized to a resistant quartz-mica schist [24,25] (Fig.1). In the Franciscan Complex, the vast majority of melanges are "engineering" melanges with significant block-matrix strength contrast. A reason for this is the low metamorphic temperature (less than 300°C in most cases) that the matrix of Franciscan melanges were subjected during their sojourn at depth within the Earth [15].

In the research community considerable debate still rages over the comparative importance of tectonic (shearing, faulting) and sedimentary (submarine landsliding) processes in the generation of melange. These research issues have comparatively little bearing on engineering issues, because origin of a melange carries far less importance than the physical and spatial properties of the unit.

**WHERE IS THE MELANGE? USEFUL CRITERIA TO NOTE IN THE FIELD**

![Caught by the Melange Police](image)
The first challenge an applied geologist faces in the Franciscan or similar terrane faces is whether or not the study area includes melange. After reviewing existing geologic mapping, geomorphic expression is first level of analysis. Because of its lack of erosional resistance, melange matrix seldom forms good outcrops. Melanges form lumpy topography commonly known as "plum pudding topography" (Fig. 4) with irregular slopes and big resistant blocks that commonly represent the only exposed bedrock (the plums). This looks like classic landslide topography as well it should, because melanges are notoriously prone to slope failure. Recognizing intact melange from slope-mobilized melange presents a challenge even to the most hardened "Franciscanologist", but at minimum a geologist should recognize that they have encountered either melange or landslides within one.

Fig. 4: Typical “plum pudding” topography in shale and serpentininite matrix melange, Franciscan Complex, Tiburon Peninsula, San Francisco Bay area. The large blocks seen in the background are blueschist and higher grade metamorphic rocks set in an unexposed serpentininite matrix. In contrast, the outcrops seen in the fore and middle ground consist of massive serpentininite that lacks blocks.

Geologists should avoid the Franciscan melange default mode, wherein they record "melange" simply because geologic maps show their bedrock unit as Franciscan. Within coherent (non melange) Franciscan, there exist erosional resistance contrast that may falsely lead a geologist (especially with a preconceived all-Franciscan-as-melange view) to map melange. In Fig. 5 the resistant outcrops consist of chert whereas the rocks not showing obvious outcrops consist of coherent basalt and sandstone. Although this looks superficially similar to melange topography the slopes attained on these rounded hills are steeper than one typically encounters in melange terranes. Indeed, in poorly exposed areas the slope angle is a good indicator of coherent (or large block) versus melange. Another clue to local coherence in the Franciscan is the presence of strike ridges of various types of bedrock that one can walk out for some distance (Fig. 6). Such a long aspect ratio of a block is unlikely in a melange.
Fig. 5: Somewhat misleading topography in Franciscan chert, basalt, and sandstone, Coyote Hills, San Francisco Bay area. The big outcrop in the center is a resistant part of a fairly continuous band of chert and the small outcrops on the right are part of a much larger basalt body making up most of the lower part of this hill. Completely coherent relations are seen in a quarry on the opposite side of the hill. Much of the slope is a bit steeper than average for a slope underlain by melange. Further clues to the coherent nature of the bedrock that would help in the absence of the quarry are shown in Fig. 6.

Fig. 6. Another view of the Coyote Hills, showing a resistant set of chert beds in the center of the photo. This outcrop extends for much further than visible in the photo, and the aspect ratio of such a set of beds is inconsistent with them being a block in melange.
Geomorphology provides the best clue to the presence of melange, in part because the slope has a direct relationship to the strength of the material. However, melange zones that are fairly thin (in structural thickness) versus the slope they cross may not result in diagnostic geomorphic characteristics. Fig. 7 shows an example of a steep slope formed on bedrock that is either coherent, or a large block in melange versus the plum pudding topography just across the stream that has developed on melange bedrock. Some of the steep slope in Fig. 7 is laced with very thin melange zones, although they make up a small fraction of the slope compared to hard bedrock.

Fig. 7. A view of topography west of Panoche Pass along the Panoche Pass road, southern Diablo Range, California. The steep slopes in the background left (north) of the road are underlain by either a very large block in melange (km scale), or a coherent unit, although some shear zones of several meters thick (mini melanges) cut across these hard rocks. The two geologists in the foreground are sitting on a metamorphic block in such a shear zone. The metamorphic block is higher grade than the matrix or the surrounding “coherent” rocks. To the right (south) of the road one sees gentler, hummocky slopes with large blocks typical of melange. That area is underlain by melange with some large, blocks, many of which are of higher metamorphic grade than the matrix.

Where classic melange geomorphology is lacking, some rock type distributions may indicate the presence of melange in the Franciscan or similar subduction-related rock units. For example, sandstone (sometimes colloquially called graywacke) and shale comprise the largest proportion of Franciscan bedrock. If one maps in an area that comprises largely shale (probably does not crop out well, if at all) and sandstone (will commonly form decent outcrops), but finds a few outcrops of rocks such as chert and basalt, a melange may be suspected owing to the fact that the chert and basalt are not expected in a trench-fill depositional sequence (of sandstone and shale). This does not mean that if one encounters only sandstone
outcrops that one is not in a melange, for "broken" formation, derived from a bedded sandstone-shale sequence by deformation, may exhibit full block-in-matrix character without exotic blocks (ie rock types that did not belong in an original sedimentary sequence). Some rock types almost certainly signal melange in an otherwise sandstone-shale terrane. If one has outcrops of sandstone, but sees a few small scraps of serpentinite it certainly points to the presence of melange. The makers of the original cross section modified for Fig. 3 should have been aware of this, for the presence of serpentinite there nearly guarantees the presence of melange. Blocks of higher metamorphic grade than the surrounding rocks can also be a good indicator melange presence, such as the occurrence of blueschist, amphibolite, or eclogite blocks where surrounded by outcrops of sandstone that is prehnite-pumpellyite facies. The latter criteria will probably not prove useful for the vast majority of applied geologists who lack sufficient training to readily tell metamorphic grade contrasts but it underscores the potential value of metamorphic petrology, commonly thought of as purely an academic exercise by applied geologists.

Note that serpentinite by itself is not necessarily an indicator of melange as believed by many. Some serpentinite bodies consist of primarily massive rock, whereas others are both geologic and engineering melanges because they consist of exotic blocks (non serpentinite) in a sheared serpentinite matrix, and some are engineering but not geologic melanges because they may consist entirely of serpentinite (not geologic melange) but have an internal fabric of shear serpentinite enclosing stronger blocks of massive serpentinite [12,26].

ONCE A MELANGE IS IDENTIFIED: USEFUL FIELD DATA TO OBTAIN

Because empirical and experimental studies have determined a positive correlation between block proportions and melange strength, block proportions are a particularly important parameter to record [3,4,5,6]. Challenges come in selecting the appropriate scaling for determination of what constitutes a block versus matrix, as well as understanding the uncertainties inherent in interpolated between or extrapolating from surface or boring data [6,7,8,9,10,11,27]. For field mapping the non-predictive nature of internal contacts demands "saturation" mapping in which every last outcrop is recorded on the geologic map, in contrast to the traditionally taught "contact" mapping in which a few points on contacts may suffice to characterize the spatial distribution of units. Much has been written about the determination of appropriate block sizes for a given scale of interest and various techniques to determine block sizes for engineering purposes (the reader is referred to the references above), so I will not review them here; the remainder of this section will outline other field parameters that are not as well publicized, but are still potentially important.

Such field parameters include the external contacts of a melange, provided they occur within the study area. Although internally chaotic, the external contacts of a melange present nothing extraordinary in terms of geologic mapping. These external contacts may be "contact" mapped as one would a normal faulted or stratigraphic contact, although a gradational contact (many melanges have them) may represent an additional challenge. They are no more likely to change dramatically in strike and dip along their length as any other sort of contact.

The preferred orientation (foliation) of a melange matrix is commonly mappable and may contribute asymmetry to physical properties [28], so the geologist should record these orientations, if possible. Blocks commonly exhibit a preferred flattening plane parallel to this orientation and they may exhibit a collective lineation as well. Such block preferred orientation may also influence the physical anisotropy of the melange [27].

The lithologies of melange blocks should be recorded given that they can vary dramatically from melange to melange and locally within a given melange. Different block types may have vastly different strengths and hardnesses that may have a significant impact on how easily they may be excavated. In addition, although some melanges appear to exhibit a more or less random mixing of blocks, others appear to show systematic spatial distribution of block lithologies and block proportions, and this may be particularly the case along gradational contacts of melanges [12]. For example, a unit bordering a melange may be coherent sandstone and shale that grades increasingly disrupted toward the melange, to a broken formation (block-in-matrix fabric with only sandstone blocks), into the melange that will exhibit block-in-matrix fabric with exotic blocks. The field criteria discussed in this section are diagrammatically shown in Fig. 8.
IMPROVING FIELD INSTRUCTION IN UNDERGRADUATE GEOLOGY PROGRAMS AS ONE PART IN RAISING MELANGE AWARENESS

The value of field work has not diminished at all in professional practice, yet the amount of field work required of students in undergraduate geology programs has decreased alarmingly over the three decades that I have observed various academic programs. The cutback in field studies has many origins, including the comparatively high cost of field instruction and perceived liability risk, as well as the diminished role of detailed field mapping in many sectors of the academic geosciences. Even three decades ago, when students received far more field instruction than today, few students were taught the "saturation" mapping techniques necessary to surface map in melange terranes, for it was far easier (for the students and instructors) for field instruction to be conducted in areas of layercake stratigraphy and excellent exposure (this generally means somewhere in the desert in this part of the world). Unfortunately, the professional geologist in a place such as California commonly encounters poor exposure as well as the discontinuous structure and stratigraphy. While a student made to map in melange (even for a short time) with poor exposure will be able to map layercake stratigraphy with superb exposure with ease, the converse is not true. As much of a problem as this was a few decades ago, the problem has worsened as field time shrank in undergraduate programs. At Fresno State, I have tried to overcome some of the above problems by giving my advanced field methods
students a mapping exercise that includes mapping melange (Fig. 9), but I fear this may be unique among all the field mapping courses in this country. For the future I believe that there needs to be more dialogue between the applied geosciences and academia when it comes to the issues faced by professionals having to characterize melange. Professionals have a responsibility to update themselves with current understanding in geology rather than holding onto views abandoned more than 40 years ago by the academic community. In turn, academicians have a responsibility to learn more about what professional geologists do and what skills are important in the world of "real geology", so that they may better prepare their students, the vast majority of whom will become applied geoscientists rather than academicians. Finally, both academic and research communities need to establish better communication in order to bridge large gaps in understanding and knowledge.

Fig. 9. Fear not melange! Fresno State students mapping in Franciscan melange, Sunol Regional Wilderness, eastern San Francisco Bay area, spring 2006. Mapping layercake stratigraphy in the desert cannot prepare a geologist for this type of geology that is common in the California Coast Ranges, whereas these students would be able to map the former type of geology easily after mastering these initially intimidating field relationships.

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