

APPENDIX A

to

MELANGE AND FAULT ROCKS EXPOSED IN AND AROUND AN ABANDONED QUARRY AT THE SCHMIDT LANE RECYCLING CENTER, EL CERRITO, CALIFORNIA

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THE LARGER GEOLOGIC CONTEXT OF CALIFORNIA TECTONICS, BIMROCKS, AND FAULT ROCKS

California has some of the most diverse geology in the world. This complexity is partly a result of California having been assembled by a series of interactions along active plate boundaries for the last 500 million years. The basement rocks of California preserve multiple subduction zones, scraps of ocean crust, island arcs, and batholiths, and record many episodes of deformation. Because of this history of active tectonics, fault rocks and bimrocks are commonplace. Although bimrocks are most famous in the Franciscan Complex, older subduction complexes with similar structures occupy both the Sierra Nevada and Klamaths. Brittle fault zones formed and preserved in various parts of California range in age from several hundred million years old to Holocene.

The following is a brief chronology of geologic events recorded in a transect from the northeastern Sierra Nevada to the northern California coast (this is another version of "Assembling California" by John McPhee!). It should be kept in mind that this chronology is largely a two dimensional (cross sectional) analysis and that there is considerable variation of geology and tectonic history along the northwest-southeast strike of the orogenic belt.

The oldest subduction complex in the Sierra is the Shoo Fly Complex of Devonian age. Similar to the Franciscan, this subduction complex contains units of melange up to several km thick. The grade of metamorphism of this complex in the northern Sierra is lower greenschist, so the fault structures (including the melange matrix) are brittle. In the central Sierra Nevada the grade of metamorphism in this unit is generally upper greenschist facies or higher, so most of the melange matrix and shear zones have been annealed. Following a Devonian collision between the west-dipping Shoo Fly subduction zone and the continental margin, a volcanic arc developed across the amalgamated margin (e.g. Schweickert and Snyder, 1981). Subsequently the closure of a large ocean basin, possibly in the Triassic or early Jurassic, led to the emplacement of the Feather River peridotite belt, a unit that contains abundant serpentinite and locally serpentinite matrix melange, over an east-dipping subduction zone. Much of this unit was metamorphosed in the amphibolite facies, but the Feather River belt was likely affected by strain later in the Jurassic and possibly the Cretaceous (e.g. Sharp, 1988). The later deformation took place under low-temperature conditions in the northern Sierra and included the development of brittle shear zones and further deformation of existing serpentinite matrix melange, resulting in the development of brittle fabrics.

West of the Feather River belt are one or possibly two subduction complexes that have been juxtaposed by collisional tectonics (either a single west-dipping subduction zone or two subduction zones dipping away from each other; compare Schweickert and Cowan, 1975, and Moores and Day, 1984). These comprise part of the "Central Belt" of the northern Sierra Nevada and include the Calaveras Complex and other units that have a high proportion of chert and shale (Moores and Day, 1984). Significant parts of these units are composed of melange. The grade of metamorphism is greenschist or lower in the northern Sierra Nevada, so the shear zones and melanges exhibit brittle fabrics (there was higher grade metamorphism with ductile fabrics to the south). Fault rocks in the Sierran basement are by no means confined to subduction complexes; numerous brittle shear zones cut volcanic arc rocks

and slices of oceanic crust and mantle in the northern Sierra Nevada. The Paleozoic to Mesozoic terranes of the Klamath Mountains are similar to those of the Sierra Nevada in structural and lithologic character, although one-to-one correlation is not as straightforward as was once thought (e.g. Dilek and Moores, 1992).

During the most recent chapters of active plate margin history in California, the Coast Ranges have had the starring role. Following the mid-Jurassic collision in the Sierra Nevada that blocked one or more subduction zones (Schweickert and Cowan, 1975; Moores and Day, 1984), subduction stepped west and east-dipping Franciscan subduction began at 165-160 million years ago (Wakabayashi, 1992). All but the first few million years of Franciscan metamorphism took place at low temperatures (but high pressures), so most of the major fault zones in the Franciscan are brittle ones; these include melanges up to several kilometers thick. Franciscan subduction with intermittent accretion of various units took place continuously for over 140 million years and is still occurring north of the Mendocino Triple Junction (e.g. Wakabayashi, 1992).

The Franciscan in a gross sense can be viewed as a stack of thrust nappes, some of which are coherent, some of which are melanges (Wakabayashi, 1992; 1999b) (Fig. 4). Most of the coherent terranes are themselves imbricated, and the thrust faults within these coherent terranes range from discrete faults of centimeter width to melange zones up to several hundred meters in width. The stack of nappes is a consequence of progressive accretion (off scraping from the downgoing plate) of both trench sediments and far-traveled oceanic rocks. As a consequence of this progressive accretion, the incorporation ages of the nappes, and hence the ages of formation of melanges of the nappe stack, young progressively down structure (Wakabayashi, 1992).

Coeval with Franciscan subduction, deposition of the Great Valley Group took place in a forearc basin between the Franciscan subduction zone to the west and the Sierra Nevada magmatic arc to the east. The Great Valley Group consists of bedded siltstones, sandstones, and shales that underwent negligible burial metamorphism (in contrast to the common blueschist facies metamorphism in the Franciscan). The Great Valley Group is commonly seen as the well ordered mate to the chaotic Franciscan, but it is not altogether free of fault rocks or bimocks. In particular, a 1-km-thick serpentinite-matrix melange occurs at the base of the Great Valley Group in the northern Coast Ranges (Phipps, 1984). Unlike the melanges of the Franciscan Complex that have tectonic upper and lower contacts, the Great Valley Group melange is of depositional (olistostromal) origin with depositional upper and lower contacts. Despite having a different genesis than Franciscan melanges, from an engineering standpoint it is the same type of material, blocks in a weak matrix. In addition to the basal melange, the Great Valley Group does contain some fault rocks because it did not entirely escape deformation. Large-scale shortening resulting in fold and thrust belt development affected the Great Valley Group during both the subduction regime and the subsequent transform regime (e.g. Unruh et al., 1995). This has resulted in significant layer-parallel shearing generally hosted within the shale horizons.

During Franciscan subduction, additional deformation took place to the east in the Sierra Nevada, locally forming penetrative brittle fabrics and faults in the northern Sierra Nevada that locally cut across older lithologic boundaries. Among these later faults are the faults along which Mother Lode gold mineralization occurred (e.g. Böhlke, 1999).

The timing of the cessation of subduction along coastal California depended on latitude, with the earliest cessation starting at about 25 million years ago, and the San Andreas dextral transform system beginning at about 18 million years ago and lengthening with time (e.g. Atwater and Stock, 1998). This tectonic regime has led to the development of the major strike-slip faults and also fold and thrust belts that are related to both partitioning of a minor amount of compression across the plate boundary, and to local restraining bends in the strike-slip faults (e.g. Aydin and Page, 1984; Namson and Davis, 1988). The major strike-slip faults have developed zones of long-term displacement that are up to several km wide; the Holocene trace locally carries but a fraction of the total late Cenozoic displacement along many of the major dextral faults in the San Andreas system (Wakabayashi, 1999c). However, the broad zones of long-term strike-slip displacement are generally different from Franciscan melanges in character in that they are largely blocks with volumetrically subordinate shears between them. Nonetheless the mechanically weaker nature of the zones along strike slip faults is illustrated by the common occurrence of linear valleys (erroneously called "rift" valleys in some areas) that have formed as a consequence of preferential stream erosion along these faults.

In summary, 500 million years of active plate tectonics has created an abundance of fault rocks and bimrocks in California. Volumetrically, the most significant fault rocks or block in matrix rocks are melanges that are associated with subduction complexes. One major exception is the basal Great Valley Group, which is not a fault rock but has the same mechanical properties. However, as described above, fault rocks are present in non-melange settings, and the dimensions of these features (up to tens or even hundreds of meters in thickness) are such that they can be of engineering significance. Melanges and other bimrocks and fault rocks are common in many places of the world; they occur in essentially all orogenic belts, so the engineering problems associated with them are global in scope.