The Franciscan Complex, San Francisco Bay Area: A Record of Subduction Complex Processes

A Field Trip led by Dr. John Wakabayashi

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THE FRANCISCAN COMPLEX, SAN FRANCISCO BAY AREA: A RECORD OF SUBDUCTION COMPLEX PROCESSES

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INTRODUCTION

The Franciscan Complex of the California Coast Ranges records over 140 million years of uninterrupted east-dipping subduction, during which the Franciscan formed as an accretionary complex (Wakabayashi, 1992). Coeval with formation of the Franciscan subduction was the development of the corresponding volcanic arc, the roots of which are the Sierra Nevada batholith, and the forearc basin, represented by the sandstones and shales of the Great Valley Group, that crop out primarily on the margins of the Central Valley (e.g., Dickinson, 1970) (Fig. 1). Equivalents of the Franciscan are still being formed north of the Mendocino Triple junction, along an actively subducting plate margin. The Mendocino Triple junction migrated past the San Francisco Bay region about 15 million years ago, leaving in its wake to the south a transform plate margin now occupied by the San Andreas fault system (Engebretson et al., 1985).

The Franciscan is famous for the occurrence of high pressure-low temperature (such as blueschist facies) metamorphism (e.g., Coleman and Lee, 1962, 1963; Ernst, 1965; 1970; Brown and Ghent, 1983; Maruyama and Liou, 1988), a type of metamorphism that is now universally recognized as the signature of a subduction zone (e.g., Ernst, 1970; 1988), and for melanges, chaotic geologic units with a sheared matrix and a variety of included blocks (e.g., Hsu, 1968; Aalto, 1976; Cloos, 1982; Cowan, 1985).

The field trip takes us across part of a structural transect of part of the Franciscan Complex and San Andreas fault system in the San Francisco Bay region (see Fig. 2, 3). This transect is interesting because of the proportion of melange is comparatively small (see Figures 2,3). Because the Franciscan is so famous for its melange zones there is a misconception among many that most of the Franciscan is melange. In fact the proportion of melange is highly variable in the Franciscan, ranging from the comparatively coherent thrust sheets of the Bay region and the eastern Northern Coast Ranges, to a high proportion of melange in the central northern Coast Ranges (Fig. 4). One of the more recent developments in the study of Franciscan geology is the correlation of individual terranes to discrete structural horizons or thrust nappes (Blake et al., 1984; Wakabayashi, 1992). This concept is similar to that applied in the Alps for over a century and emphasizes a structural stacking order as opposed to stratigraphy (stratigraphy can be followed within each nappe sheet). This concept of structural stacking order can be applied to the entire Franciscan, including regions that have large proportions of melange (Fig. 4). The folding and subsequent erosion of the folded nappe stack resulted in the northwest-trending belts of rock that characterize the map pattern of the California Coast Ranges (see the Geologic Map of California, Jennings, 1977). Based on geochronologic data (both age of fossils and isotopic ages of metamorphic rocks), the ages of incorporation (or 'docking' in terrane parlance) of individual nappe sheets-young structurally downward in any given stack of nappes (Wakabayashi, 1992). This suggests that the nappes represent sequential offscraping or underplating of units in the subduction zone. The Franciscan units in Figures 2 and 3 apparently were offscraped in the subduction zone from 160 to 80 million years ago (to 60 million years ago if one includes the overthrusting of the Salinian block). The inverted accretion sequence is a key for recognition of subduction-related structures, for such a stacking order would be more randomized in age progression if the thrusting was a consequence of post-subduction shortening during the transform regime. It should be noted that late Cenozoic folding and thrusting during the transform regime is widespread (e.g., Page, 1981) and locally, particularly along the eastern margin of the Coast Ranges, shortening amounts can reach several km (e.g., Namson and Davis, 1988; Unruh et al., 1995), so criteria that distinguish subduction age structures are important.

Another aspect of Franciscan geology that can be seen in Figure 4 is that there is considerable along-strike variation in the Franciscan complex (Wakabayashi, 1992). This along strike variation is pronounced
no matter how one restores the faults of the San Andreas fault system (Fig. 5, 6). As can be seen in Fig. 4, 5 and 6 the 'classical' division of the Franciscan into 'Eastern, Central and Coastal Belts', applied to the northern Coast Ranges (e.g., Blake et al., 1988) is not very useful in the San Francisco Bay area and Diablo Range. For example, the 'belt' division follows the three-part metamorphic grade division (the zeolite, prehnite-pumpellyite, blueschist and higher grade division shown in Fig. 1, 5) in the northern Coast Ranges (if and only if tectonic outcrops are corrected for; but this is seldom done) but not elsewhere. The 'belt' division is consistent with structural stacking order or accretion age in the northern Coast Ranges, again, if and only if corrected for tectonic outciers. The belt division is not consistent with accretion age or structural stacking order south of the northern Coast Ranges. Many geologists have become confused trying to apply the three belt division of the Franciscan to areas other than the northern Coast Ranges. Alternative ways to subdivide the Franciscan would be on the basis of metamorphic grade (as done in Fig. 1) or relative accretionary timing or relative structural stacking order (done in Fig. 4).

The evolution of ideas on the Franciscan serves as an interesting illustration of the linkage between prevailing geologic paradigms and field mapping. For example, prior to the 1960's, many geologists tried to force the Franciscan into 'conventional' stratigraphic sequences (well stratified and younging upward). In that era, a field geologist would have tried to 'connect the dots' of scattered outcrops of similar lithology to form coherent 'beds' or strata-bound units (e.g., Taliaferro, 1943). In the 1960's, the concept of 'melange' was introduced as a model for the Franciscan (Hsu, 1968). Following the general acceptance of the melange concept, a geologist mapping the same terrane that had formerly been interpreted as a series of beds, would map each outcrop or group of outcrops as separate blocks in the inferred melange (the matrix of the melange is generally poorly exposed except in sea cliffs and other very steep exposures). Starting in the 1970's and extending to the present day, geologists found ways of identifying mappable units within the Franciscan, demonstrating that geologic detail could indeed be recognized within the supposedly chaotic Franciscan (e.g., Maxwell, 1974; Blake et al., 1982; 1984; 1988). Thus, the Franciscan has since been considered to consist of both 'coherent' (i.e., non-melange) and melange units. Field geologists starting work in the Franciscan today take to the field an entirely different set of ideas than their predecessors, and these ideas will directly influence how outcrops are interpreted in the field and how lines will be drawn on their maps. Today, there are an unfortunate number of theoretical, quantitative geoscientists that say that since the geology of every square meter of the Earth's crust is mapped, geologic mapping is obsolete, and new mapping is no longer needed for research. As illustrated in the above example, these individuals fail to recognize the strong interpretive aspect of field geology.

In addition to attracting much interest from the academic community, the Franciscan impacts the applied geosciences community in large way, primarily because rocks underlie much of the California Coast Ranges, including innumerable engineered and proposed structures. Understanding the geology of the Franciscan can aid greatly in evaluating the engineering properties of these rocks at a given site. The great complexity of the Franciscan gives rise to headaches in the engineering community. Changes in seemingly esoteric, academic viewpoints on the Franciscan can have a significant impact on applied geoscience problems. Recently-developed theories on the engineering properties of block-in-matrix materials (Bimrocks) were in part developed to help characterize Franciscan rocks (Medley, 1994; Lindquist, 1994). Franciscan structures have also been used as geologic markers to help unravel the evolution of the San Andreas fault system (Wakabayashia and Hengesh, 1995).

With this as a framework we will now examine the geology at and between the various stops. Other major issues in tectonics will be discussed in the descriptions of the various stops.
Figure 1: Distribution of Franciscan and other basement rocks of central and northern California, showing Franciscan of different metamorphic grades. Note variation of character of the Franciscan along strike, especially the distribution of schistose rocks and jadeite-bearing sandstones. Map derived from Jennings (1977) with modifications from Wakabayashi unpub. field data.
Figure 2. Franciscan Complex and related rocks, San Francisco Bay area and geologic relations of units on Fig. 3 modified from Wakabayashi and Henges (1992).

Explanation of units on Fig. 3: Magnetic and gravity anomaly in San Francisco Bay from Jacobs and Roberts (1974a,b).
Franciscan Units

KJm: Tiburon melange: shale and serpentininite matrix melange with numerous
'high-grade' blocks
KJm: Angel Island nappe; metavolcanic and metasedimentary rocks; blueschist grade;
incipiently foliated to schistose
Ka: Alcatraz terrane (nappe): arkosic sandstone and shale; Valanginian or younger;
prehnite-pumpellyite grade
KLp: Rocks of Point Bonita: basalts that differ from basalts of Marin Headlands proper
both chemically and by occurrence of inter-pillow limestone; possibly correlative to
Nicasio Reservoir terrane; prehnite-pumpellyite grade
KLm: Marin Headlands terrane (nappe): basalt, chert, sandstone, shale; detrital rocks
as young as Cenomanian; prehnite-pumpellyite grade

Kab: San Bruno Mtn. nappe (includes San Bruno Mtn. and Novato Quarry terranes):
K-feldspar-bearing arkosic sandstone and shale; Novato Quarry terrane yield
Campanian age, no fossils from San Bruno Mtn. terrane; prehnite-pumpellyite grade
KLp: Permanente terrane: basalt, sandstone, shale, limestone, chert; prehnite-pumpellyite
to blueschist grade
Hunters Point Shear Zone, City College Fault Zone, Hillside Fault Zone: these are major
melange zones that bound coherent nappes; shale and serpentininite matrix; high grade
blocks much less numerous than Tiburon melange
KJu: undifferentiated Franciscan rocks

Non-Franciscan Units

Jo: Coast Range ophiolite and related rocks; includes variably serpentinized ultramafic
rocks, gabbro, diabase, and quartz keratophyre
Kg: Plutonic rocks of the Salinian block
TK: Upper Cretaceous(? ) and Paleocene(? ) sandstones and shales of the Salinian block.
P: Paleocene sandstone and shale of the Salinian block
FS: Pre-Eocene Franciscan-Salinian contact
E: Eocene sandstones and shales of the San Francisco peninsula
T: Tertiary rocks undifferentiated

Figure 3: Cross sections along lines shown in Figure 2; no vertical exaggeration.
Figure 5A: San Andreas fault system slip restored according to model of Powell (1993). Even with strike-slip faulting restored, the along-strike variation in the character of the Franciscan is still pronounced. Note especially the distribution of schistose Franciscan and jadeite-bearing Franciscan sandstones. Abbreviations same as Figure 1.

Figure 5B: San Andreas fault system slip restored according to model similar to Wakabayashi and Hengsh (1995). As with the Powell (1993) restoration, along-strike variation in the character of the Franciscan is still pronounced. Note also, however, that the details and distribution of metamorphic grade in the Franciscan are very different in the Powell (1993) and Wakabayashi and Hengesh (1995) restorations. Restoration of McLaughlin et al. (1996) would produce a result intermediate between these two restorations but significantly different from either. Abbreviations same as Figure 1.
Figure 7: Upper left: Close up of shear zone at base of metagreywacke slab at Stop 1. Note shear bands indicating sinistral (tops to SW) sense of shear.

Lower left: Well bedded turbidites of the San Bruno Mtn. nappe as seen in an old quarry cut south of Geneva Avenue in San Francisco. At this location the beds dip to the NE. This is representative of the regional dip of this unit on San Bruno Mtn. and in San Francisco. This is the structurally lowest of the Franciscan units seen in our transect.

Upper right: Folding of ribbon cherts at the Marin Headlands (Stop 3).
DESCRIPTION OF STOPS AND GEOLOGY BETWEEN STOPS

STOP 1: Quarry, east end Schmidt Avenue, El Cerrito.
Directions to stop and comments about geology along the way

From Stop 1, continue eastbound on the Petaluma-Point Reyes Road and make a right turn (south) onto the Nicasio Valley Road after passing the reservoir. After 4 miles or so on this road, turn left (east) onto Lucas Valley Road and follow this winding road for 10 miles to intersect Highway 101. Enter Highway 101 southbound (toward San Francisco) and proceed to the Interstate Highway 580 junction, where you will take 580 eastbound (right hand exit).

The next stop in the hills to the east will be part of a panel or fold limb of the folded nappe stack that dips to the northeast (Fig. 2 and 3).

Take the Central Avenue exit off of Interstate 580, cross over east the freeway, continue east under Interstate 80, then turn left (northwest) on San Pablo Ave. After several blocks (approximately 0.6 miles) turn right (east-northeast) on Moezer Lane. After a few blocks the street steepens. Just past Portola Junior High (on the left or north side of the street) take a left (north) onto Navellier Street. Shortly, turn right (east) onto Schmidt Lane and drive to near the end of the road where the road terminates at a recycling center. There is ample parking along both sides of the road outside the recycling center.

Description of stop

At this stop we view one of the finest exposures of a major tectonic contact found anywhere in California. From where we park we can see the steep quarry walls. The upper part of the walls are tan and the lower part dark grey. This color change is not an artifact of differential weathering, it is a true lithologic break. The tan colored blocky outcrops are part of a coherent slab of jadite-bearing metagreywacke, a blueschist facies rock that probably formed at 30 km depth or more. The dark colored rocks below are a shale matrix melange with blocks of sandstone and green tuff. These units all dip to the northeast, or into the cliff face, and are structurally above the rocks cropping out on the north side of the road where we park. The sandstone and shale outcrops along Schmidt Avenue near where we park are prehnite-pumpellyte facies sandstones of the Alcatraz terrane. The thin melange zone exposed in lower part of the quarry walls is a shear zone that accommodated somewhere in the range of 15 km of differential vertical displacement, thrusting the deep seated jadite-bearing rocks southwestward over the lower grade sandstones of the Alcatraz terrane. To get a close up of the contact we will walk up a hiking trail that ascends from the north side of Schmidt Avenue and takes one to a point along northern margin of the quarry exposure that is at the level of the bottom of the jadite-bearing greywacke slab. As the hiking trail heads northward away from the quarry, look for a place where you can move eastward onto a bench in the quarry face. Here, on the quarry face, we are right at the base of the jadite-bearing metagreywacke slab. Good asymmetric fabrics (mostly shear bands) in the rocks record a movement sense of northeast over southwest (Fig. 7), consistent with the tectonic transport direction inferred from the juxtaposition of metamorphic grades and the dip of the contact. The nature of the tectonic contact exposed here places constraints on the inferred exhumation mechanisms that brought the jaditeic-bearing rock to the surface of the Earth from the deep crustal level at which it was metamorphosed (for some background into the various mechanisms of exhumation proposed in the Franciscan see Platt, 1986; and Wakabayashi and Unruh, 1995).

The metagreywacke has a pronounced foliation and jaditeic clinopyroxene comprises up to 50% of the rock volume. Other blueschist minerals such as lawsonite, glaucophane and aragonite occur in this rock. In hand specimen, this metagreywacke is certainly not obviously a blueschist facies rock; the diagnostic minerals are easily visible in thin section however.

STOP 2 Hunters Point Shear Zone at North Baker Beach
Directions to stop
From the south: Proceed north on 25th avenue through and north of Golden Gate Park (or turn north onto 25th avenue from Geary Blvd.). Drive north on 25th avenue until just short of its northern end, near the coast. At this point turn right (east) onto Lincoln Blvd. This street is called El Camino Del Mar to the west. Lincoln soon curves westward to a northerly direction. The Presidio is on your right and the Pacific is on your left as you continue to drive northward. As you near the south abutment of the Golden Gate Bridge, take a descending left (west) turn onto Merchant Road. There is no roadsign, but the road going right from the same intersection is signed Ralston Road. It is easy to miss this turn; if you find yourself passing under an overpass, you've gone too far on Lincoln. Merchant Road descends from the intersection, then curves right, and old concrete bunkers and a large dirt parking area are visible on the left side of the road. Park in the parking area and find a trail that leads down to the beach from the parking area.

The trail leads west between the two bunkers toward the sea, then turns right (north) along the edge of the cliffs. After descending some wooden stairs, branch left and take the steep path that heads straight down to the beach. This path exploits the only easy break in the cliffs in this area.

Description of stop

This stop examines shoreline exposures of the Hunters Point shear zone, a serpentinite and shale matrix melange zone that is one of several discrete melange horizons that separates coherent Franciscan nappes in the San Francisco Bay area. Based on inferred incorporation ages of units structurally above and below the melange zone, the Hunters Point shear zone probably formed about 100 million years ago. This zone is interesting because it is an example of a ultramafic-bearing structural horizon within the Franciscan in contrast to the Coast Range ophiolite that structurally overlies the Franciscan. The origin of ultramafic bodies structurally within the Franciscan is a problem that has not yet been addressed in detail.

Most of the exposures at the base of the cliff are not in place, having slid down the cliff face to some extent, but a few exposures appear to be relatively intact and are in place. Classic block-in-matrix structures can be seen.

We will walk south along the beach to a rocky point that is composed of several blocks of unusually high grade amphibolite. These blocks in the melange zone are clues to the early history of the Franciscan, a history we will explore further at Tiburon Peninsula. The amphibolites are locally garnet bearing and yield garnet-hornblende temperatures of about 700°C (Wakabayashi, 1987) and are overprinted with blueschist assemblages. Textures suggestive of partial melting are preserved in some samples. Quartz and garnet rich interlayers are found that are apparently metachert beds. The occurrence of metachert is critical because it ties the surrounding metabasaltic rocks to a setting in the top layer of the ocean crust. High temperature metamorphism in an ocean floor setting in fracture zone and deep hydrothermal settings but not as high in the ocean floor sequence as basalts or overlying cherts. The high temperature metamorphism of the metachert and metabasalt is probably a product of the early stages of subduction as will be explained more fully in the stop description for Tiburon Peninsula.

STOP 3: Marin Headlands

Directions to stop

From Stop 2, return to the intersection of Merchant Road and Lincoln Blvd. and turn left (north) driving under the underpass beneath Highway 101, then making a left turn, following signs to the Golden Gate Bridge. A major tectonic break in the Franciscan nappe stack is located beneath the Golden Gate Bridge. The age of this tectonic contact is not well constrained, but it postdates the incorporation of the Franciscan nappes on either side of the Golden Gate (~80 Ma) and, more importantly, post dates the folding of the nappe stack. The age of this folding may be Cenozoic and related to post-subduction transform tectonics and the relative rotation of the Marin Headlands may also be related to faults of the San Andreas fault system (Wakabayashi and Hengesh, 1995). The rotation of the Marin Headlands proper, based on structural grounds is consistent with paleomagnetic studies that indicate about 130° of clockwise rotation (Curry et al., 1984). The break in the nappe stack beneath the Golden Gate can be easily visualized by noting that all of the strata in San Francisco and the major shear zones dip northeasterly and strike northwesterly toward the Marin Headlands north of the Golden Gate. At the
Marin Headlands strata dips southward. Cross the bridge, then take the Alexander Avenue exit. After exiting, turn left (west) on Alexander avenue and pass underneath the freeway, then curve to a southward direction. Make a right (west) turn following the sign to the Marin Headlands and proceed up a steep hill with stunning views of the Golden Gate to the south (if it’s not foggy). Park in one of the parking lots on the left (south) side of the road overlooking the Golden Gate.

Description of stop

From our parking area we can look across the Golden Gate to San Francisco as long as there is no fog. The outcrops in the roadcuts across the road from the parking areas expose red chert and basalt. These cherts are intricately folded (Fig. 7). Many of the fold orientations seem to defy a coherent explanation in terms of single or multiple deformations. However there seems to be at least gross consistency in fold axis orientation and folds in several localities that exhibit a consistent sense of asymmetry suggestive of north-vergent thrusting (Wahrhaftig, 1984). The chert section of the Marin Headlands was deposited in the deep ocean over an incredibly long period of time. The chert section is probably less than 80 m thick (considerable imbrication complicates assessment of stratigraphic thickness) and spans a period of deposition from approximately 200 million to 100 million years ago, based on detailed studies of radiolarian fossils found in the cherts (Murchey, 1984). In the Marin Headlands terrane, cherts depositionally overlie basalt and greywacke depositionally rests upon the cherts. The history recorded in the Marin Headlands is one of deposition of cherts on basalt (the top igneous layer of the ocean crust) in the open ocean for 100 million years as the oceanic plate moved toward the Franciscan subduction zone, followed by deposition of greywacke on top of the chert at 95 million years ago or so as this particular piece of the ocean floor neared the Franciscan trench (Wahrhaftig, 1984). The sequence of basalt-chert-greywacke is repeated many times over at the Marin Headlands by thrust faults (Wahrhaftig, 1984), with the tectonic stratigraphic repetition (as opposed to an interbedded stratigraphic sequence) confirmed by repeated biostratigraphic horizons (Murchey, 1984). These faults probably formed during the underplating of the Marin Headlands unit and are examples of imbrication within a larger coherent nappe. Such internal imbrication may be a universal feature of coherent nappes, however, the lack of recognizable marker horizons in many of the nappes has precluded the identification of such structures in many cases.

On a clear day we may be able to see the point south along the coast where the San Andreas fault comes onshore onto the San Francisco Peninsula.

STOP 4: Tiburon Peninsula

Directions to stop

From Stop 3, drive back toward Highway 101, turn left (north) on Alexander Avenue, then curve right (east), pass under the freeway, then take the curving loop to the right that then loops onto the northbound Highway 101. Drive north on Highway 101 to Tiburon Blvd. and exit eastbound. Drive about 1-1/2 miles eastward on Tiburon Blvd., then make a left turn at Trestle Glen Blvd. at a stop light. Trestle Glen Blvd. is the only road that crosses the spine of the peninsula. A short drive takes us to the crest of the hill where we turns left on to Shepherd Way, marked by signs to Shepherd of the Hills Lutheran church. The parking lot of the church is at the end of the road. IMPORTANT NOTE: If you wish to revisit this place you must phone ahead (415-435-1528) for permission to park in the Shepherd of the Hills parking lot. You can alternatively reach the same geologic spots from the public streets on the north side of the peninsula, although the walk is slightly longer. From the Sheperd of the Hills parking lot we will take a trail that ascends northwesterly up the crest of the ridge.

Description of stop

For the metamorphic petrologist, or simply the lover of beautiful rocks, Tiburon peninsula may be considered the crown jewel of all of the California Coast Ranges. Rockhounds take heed: This stop is entirely on a protected natural preserve in which collecting of rocks is prohibited (one can gawk but not bash or take). With a little snooping around one can find some decent specimens outside the preserve boundaries, although we may not have the time for such collecting on our trip.
High grade blocks shown in the PT diagram.

Figure 8: Pressure-Temperature Paths of Franciscan metamorphism and schematic cartoons showing the tectonic setting of subduction section from 150-65 Ma.
Tiburon Peninsula may be the best locality for observing high grade metamorphic blocks in the Franciscan. Rocks such as these occur nearly universally as blocks in melange, as is the case here at Tiburon, although some small, intact thrust sheets of similar material have been found in a few scattered localities such as southern Oregon and the southern Diablo Range. The high grade blocks display individual metamorphic minerals of several mm to even several cm in size. High grade blocks include amphibolites, eclogites and blueschists that exhibit the highest grade of metamorphism of any rocks in the Franciscan. The high grade blocks constitute but a tiny fraction of Franciscan metamorphic rocks, but they are arresting in appearance and record an interesting tectonic history.

Mappable sheets of Franciscan metamorphic rocks, that are generally much finer grained (minerals generally tenths of mm and smaller) and of lower metamorphic grade, are commonly referred to 'coherent' blueschists or 'coherent' metamorphic rocks. Because of their fine grain size, most coherent blueschists, although making up a significant part of the Franciscan (all areas shaded as blueschist or higher grade in Fig. 1), are visually rather disappointing, particularly to geologists who come from areas outside of western California.

From the northwest corner of the church parking lot, take a hiking trail northwest for several hundred meters. After this short hike, you find yourself on the trail following the crest of the peninsula and we soon see the first of several rocky outcrops on our right. These rocks appear very dark colored and are your high grade block welcoming committee. This first outcrop we come to is typical of the high grade blocks found in the shale and serpentinite matrix melange that makes up the structurally highest nappe on Tiburon Peninsula. This nappe is the structurally highest unit in the Franciscan complex in the San Francisco Bay area (Fig. 2,3). The block we see is a garnet epidote amphibolite that preserves a record of progressive retrograde metamorphism as the rock cooled from the high temperature conditions that produced the garnet amphibolite assemblage. On the southeast side of the main boulder (that has been broken into several big blocks) the original garnet amphibolite assemblage is well preserved. As one walks along the side of this boulder one can see an increasing amount of metamorphic overprinting with green omphacite, both in veins and in the ground mass. This overprinting increases until the rock is essentially an eclogite, composed primarily of garnet and omphacite. Walking still further along this block the eclogite assemblages become overprinted with blueschist minerals, the most prominent being the dark blue-black glaucophane.

The petrography and mineral chemistry of this particular block is described in detail in Wakabayashi (1990, sample 'TIBB'). The type of progressive metamorphism preserved in this block is one indicative of decreasing geothermal gradient with time, a so-called 'counterclockwise' PT path of metamorphism (Wakabayashi, 1990) (this is 'counterclockwise' if pressure is plotted on the positive y-axis and temperature on the positive x-axis) (Fig.8). Such a metamorphic evolution is unusual for high pressure rocks in orogenic belts of the world. In many localities, such as the Alps, New Caledonia, or Japan, the high pressure rocks record metamorphism under low geothermal gradients followed by metamorphism under progressively higher thermal gradients, the opposite of what we observe in our Franciscan high grade blocks. The 'conventional' type of metamorphism that typifies high pressure metamorphic rocks such as those of the Alps is thought to record initial cold underthrusting (subduction) followed by heating up because subduction stops (usually attributed to continental collision or arc-continent collision). This is the so-called 'clockwise' P-T path.

Geochronologic data indicates that the high grade blocks are the oldest rocks in the Franciscan Complex, having been metamorphosed ~160 million years ago (see review of isotopic ages in Wakabayashi, 1992). This data also indicates that the thermal evolution recorded in the rocks took place quickly (<5 million years). The following explanation for the type of the metamorphism observed in the Franciscan high grade blocks is adapted from Wakabayashi (1990) (see Fig.8). The decreasing thermal gradients recorded in the Franciscan high grade blocks along with the geochronologic data support the premise that these rocks represent vestiges of the earliest episode of Franciscan subduction. At the initiation of subduction, the first rocks subducted were in contact with the hot upper mantle in the hanging
wall of the subduction zone and were metamorphosed under high temperature conditions. Heat conduction is slow relative to the tectonic transport speed, so this aureole was probably only a few hundred meters thick at most. This first unit of Franciscan metamorphic rocks was underplated, that is physically transferred to the upper plate as the first slice of the new subduction complex, as subduction continued beneath. This continuing subduction quickly refrigerated the subduction zone, including that first slice of rock that had been accreted. The thermal gradient and temperatures dropped rapidly so that new minerals formed in the accreted slice, consistent with the new gradient. These later metamorphic minerals formed eclogite, followed by blueschist assemblages. Younger Franciscan metamorphic rocks (the 'coherent' blueschists) do not exhibit the 'counterclockwise' PT paths because this type of metamorphic evolution is restricted to the very initial stages of subduction when the hanging wall of the subduction zone is still hot. The former aureole of the high grade block parent material has apparently been badly broken up by subsequent tectonism leaving behind few intact remnants of the former aureole sheet. Small sheetlike remnants of the original aureole are preserved near Panoche Pass in the Diablo Range, at Goat Mtn. in the northern Coast Ranges, and possibly some thrust sheets in southwestern Oregon, but the bulk of the high grade metamorphic material is now present as blocks in melange.

It is worth noting that elevated thermal gradients followed the late Cenozoic transition from subduction to transform tectonics (e.g., Furlong, 1984) in the California. At depth in the Coast Ranges (say 10 km or greater), rocks that were metamorphosed in the blueschist facies during the subduction regime have been overprinted with higher temperature assemblages at depth (Wakabayashi, 1996). The metamorphic P-T path of such rocks would be strongly clockwise and resemble P-T paths from many of the world's high P metamorphic belts. Subduction-transform transition is an underappreciated tectonic mechanism that has probably profoundly influenced the evolution of many mountain belts (Wakabayashi, 1996).

Geology along drive back to East Bay

From our last stop we proceed eastward over the Richmond-San Rafael Bridge. As we cross the bridge, you will see a reddish, rocky island on your right (south). This is Red Rock, composed of chert and basalt of the Marin Headlands terrane. The presence of these rocks at this position in the Bay and the southwesterly dip of the strata on the island are important to constraining the regional structure of the Franciscan in the area (Fig. 2 and 3). At the east end of the bridge, we see the rugged sandstone outcrops of Point Richmond. These rocks are part of the Novato Quarry terrane, a structurally low nappe that may occupy the same structural position as the rocks of San Bruno Mountain (Fig. 2 and 3). At Point Richmond the strata dips southwesterly, structurally beneath the Marin Headlands rocks at Red Rock (Fig. 2 and 3). After passing roadcuts through Point Richmond, we enter a topographically low area covered by mostly Quaternary alluvium that conceals a major discontinuity in Franciscan structure. An old strand of the San Andreas fault system, the Point Richmond fault, that may have as much as 40 km of dextral separation, passes through this area (Fig. 2) (Wakabayashi and Hengesh, 1995).

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