Field Exercise #2

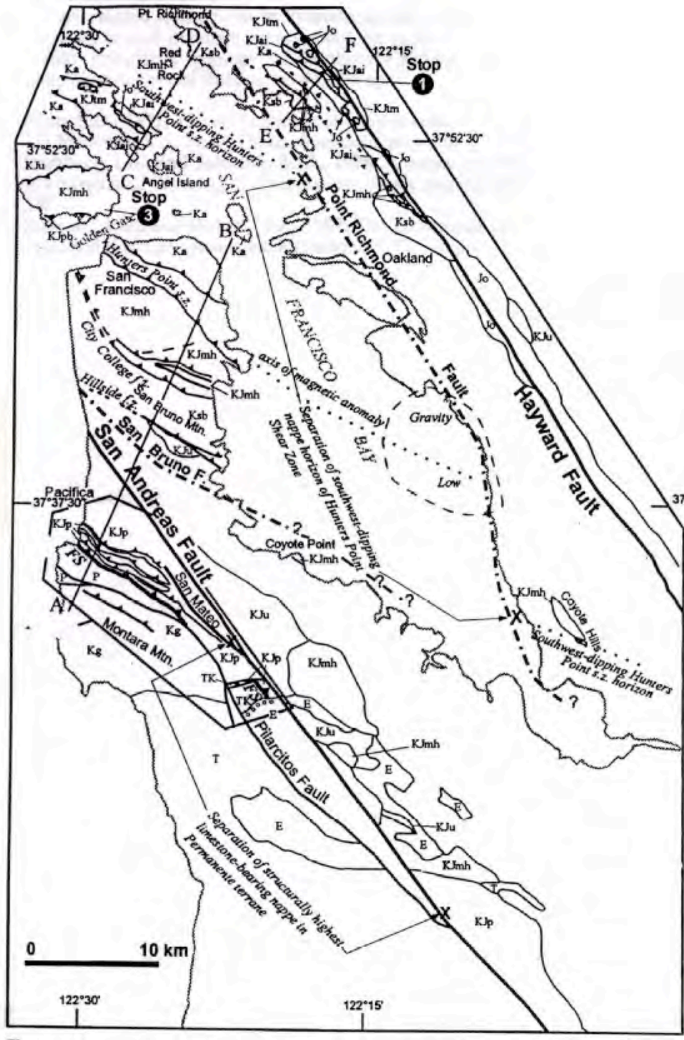
Deformation in the Franciscan Complex

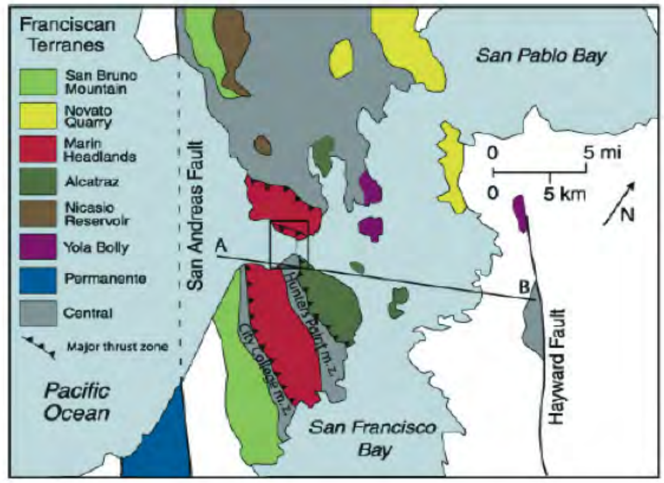
The Franciscan Complex is an **accretionary complex**, which records over 140 million years of east-dipping subduction. Coeval with the formation of the subduction complex was the development of a volcanic arc, whose roots are now exposed as the Sierra Nevada batholith. The Central Valley represents the **forearc basin** of this subduction system. North of the Mendocino triple junction, the equivalent to the Franciscan is still being formed along the active Cascadia subduction zone. In the Bay area Franciscan subduction made way for San Andreas fault strike-slip faulting with the passage of the triple junction ~15 Ma. The Franciscan complex is comprised of high pressure-low temperature metamorphic rocks, chaotically deformed **melanges**, oceanic lithosphere, and **greywacke** sandstones. All were offscraped or underplated during subduction. Much of the deformation and structures in the Franciscan Complex are quite chaotic. In this lab, we will try to make a bit more sense of the chaos.

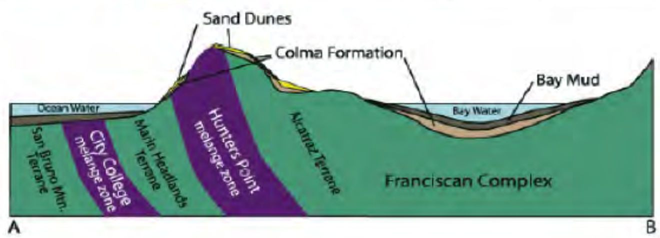
Stop 1: Quarry, at east end of Schmidt Lane, El Cerrito.
At this stop we view one of the finest exposures of a major tectonic contact found anywhere in California. From where we park we can see the steep quarry walls. The upper part of the walls are tan and the lower part dark grey. This color change 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 jadeite-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 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 Lane are prehnite-pumpellyite facies (metamorphic grade transitional between zeolite and greenschist facies representing a temperature range of 250 to 350 °C at 10 – 20 km depth) sandstones of the Alcatraz terrane. The thin melange zone exposed in the lower part of the quarry walls is a shear zone that accommodated somewhere in the range of 15 km differential vertical displacement, thrusting the deep seated jadeite-bearing rocks southwestward over the lower grade sandstones of the Alcatraz terrane. Asymmetric fabrics (shear bands etc., see figure) in the rocks record a movement sense of the northeast over southwest, consistent with the tectonic transport direction inferred from the juxtaposition of metamorphic grades and the dip of the contact. An unmetamorphosed block of Coast Range Ophiolite overlies the metagreywacke. The nature of the tectonic contact exposed here places constraints on the inferred exhumation mechanisms that brought the jadeite-bearing rock to the surface of the earth from the deep crustal level at which it was metamorphosed (on mechanisms of Franciscan exhumation see Wakabayashi and Unruh, Geology, v. 23, p. 85-88, 1995).

The metagreywacke has a pronounced foliation and jadeitic 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, the metagreywacke is certainly not obviously a blueschist facies rock. However the diagnostic minerals are easily visible in thin section (see figure).

<u>**For exercise:**</u> Take notes of your observations and make a sketch of the outcrop and structural relationships. What appears to be the dominant deformation geometry?







Left and top: Franciscan structures and terranes in San Francisco Bay area.
Bottom left: Outcrop picture of Schmidt Lane shear zone structures showing top-to-the left (SW) sense-of-shear. Bottom right: Thin section of jadeite (J) and glaucophane (G) bearing high-pressure metamorphic rocks found in the hanging wall of the shear zone. Both images from Wakabayashi (1999).

Marin Headlands: Deformation of Franciscan Subduction Complex

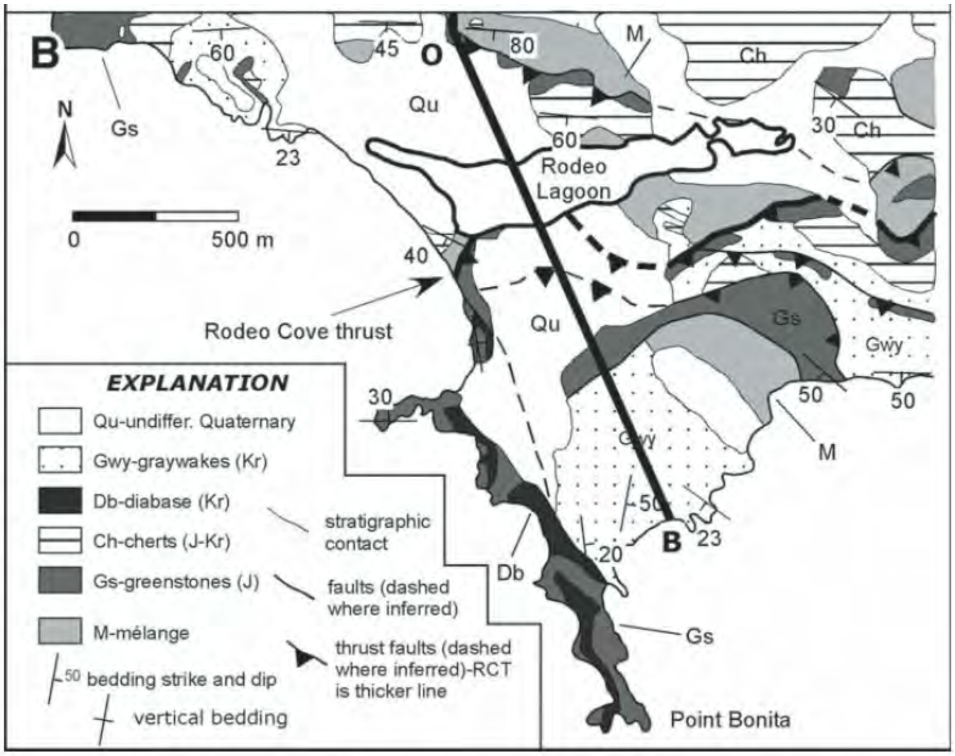
How to get there and geology along the way: We proceed westward towards the Richmond- San Rafael Bridge. Just before the bridge, we see the rugged sandstone outcrops of Point Richmond. These rocks are part of the Novato Quarry terrane, a structurally low **nappe** of the Franciscan that may occupy the same structural position as the rocks in San Bruno Mountain south of San Francisco. As we cross the bridge, you will see a reddish, rocky island on your left (south). This is Red Rock, composed of chert and basalt of the Marin Headlands terrane. The strata on the island dip southwesterly. The Point Richmond strata dip southwesterly, structurally beneath the Marin Headlands rocks at Red Rock. Driving towards the Golden Gate Bridge on Hwy. 101, you can admire the pillow basalts on your right before entering Waldo tunnel.

Coming from the North on Hwy. 101, take the Alexander Ave. exit and turn right. Proceed toward Sausalito on Alexander Avenue. Turn left toward Marin Headlands (this is Bunker Road, but there is no sign). Proceed through tunnel. First visible chert outcrops are on the left; views encompass coastal scrub plant community typical of the Marin Headlands. We continue on Bunker Road and take left on Mitchell Road to Rodeo Beach.

Stop 2 - Rodeo Cove Thrust

We stop near Rodeo Beach and hike across the beach to explore outcrops of the Rodeo Cove Thrust. The outcrop lies at the southern end of Rodeo Lagoon and is exceptionally well-exposed, with the exception of a landslide in the southeastern part of the outcrop, because the coastline runs at a high angle to the fault strike. Meneghini and Moore (2006 GSA Bulletin) provide a detailed analysis of this structure, on which this summary is based. The strike of the thrust fault is approximately ENE-WSW, with a N-NW vergence. The depth and temperature range of accretion inferred from the preserved metamorphic minerals along the Rodeo Cove Thrust falls within the seismogenic zone of subduction zone thrust faults, suggesting that the thrust was active at seismogenic depth or immediately below the shallow aseismic to seismic transition. The high percentage of veins in the fault core and widespread pressure solution phenomena show that deformation at the decollement zone of the accretionary prisms is associated with circulation of over-pressured fluids. The injection of over-pressured fluids caused hydrofracturing, increase permeability and mineralization. Overprinting co-planar events of veining and shearing indicate large changes in fluid pressure that may occur on the time interval of seismic cycles.

Return and turn right onto Bunker Road. Pull out into gravel parking area to left just before large warehouse building.



Close-up view of Rodeo Lagoon and Point Bonita.

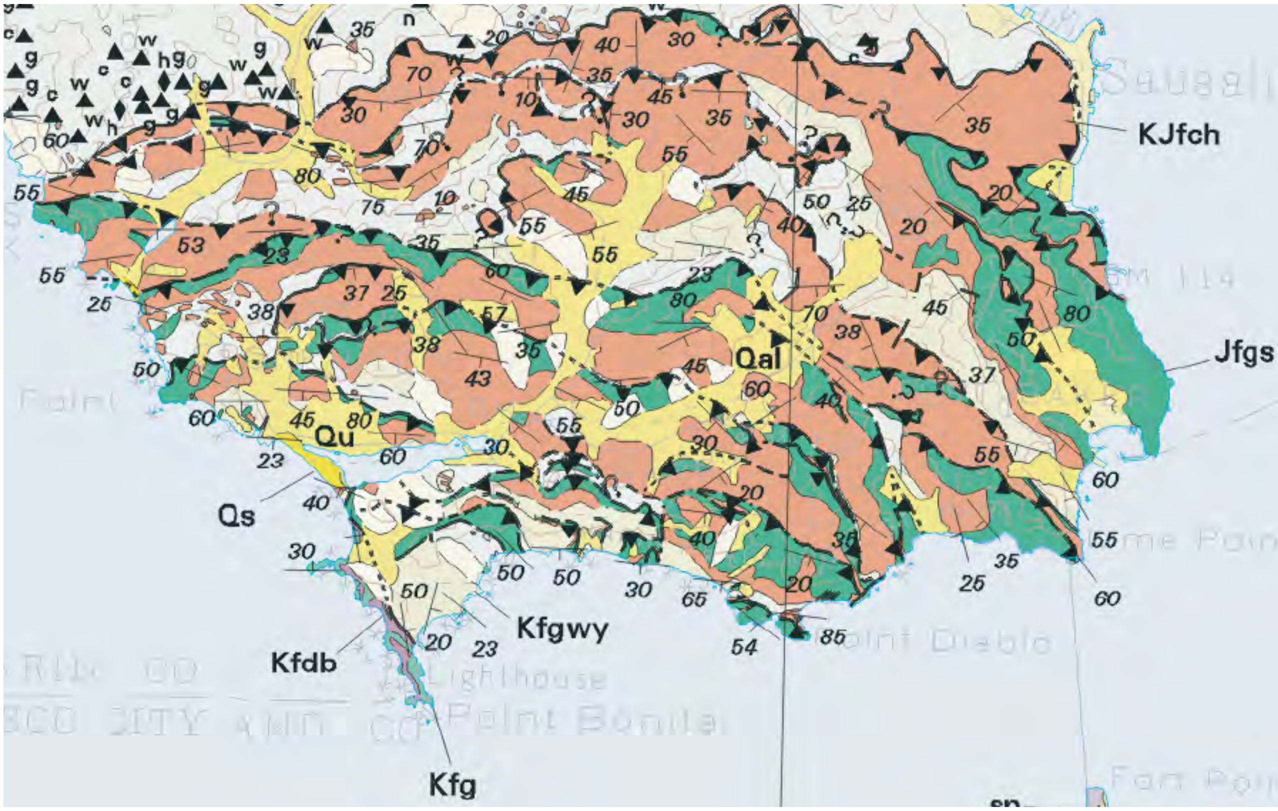
Stop 3 – Rodeo Beach Quarry

This abandoned quarry face shows excellent exposures of the radiolarian ribbon cherts characteristic of the Marin Headlands Terrane. The chert seen here displays dark steelygray manganese staining typically developed in rocks near the base of the chert section, probably reflecting manganese-rich hydrothermal and bottom waters associated with the mid-ocean ridge volcanism. The Calcite Compensation Depth (CCD), the depth below which the rate of supply of calcium carbonate lags behind the rate of dissolution, is such that no calcite is preserved. At the present time the CCD in the Pacific Ocean is about 4200 - 4500 m. Do you think it was at that depth in the Mesozoic?

Prominent chert and shale bedding rhythms also are evident. These sedimentary cycles, which have been enhanced by burial diagenesis, reflect either submarine landslides or cyclic changes in radiolarian productivity and/or clay input, such as due to global climate cycles. The shells of some Radiolaria can be seen on freshly broken surfaces with a hand lens.

Stop 4 – Point Bonita Lighthouse

Take Field Road to Point Bonita lighthouse. Proceed down Point Bonita Trail to locked tunnel. On the way down the trail, the first outcrop seen to your right is graywacke sandstone. A prominent fault and sheared zone can then be seen separating the graywacke from greenstone. **Greenstone** is the predominate rock the rest of the way to the tunnel, except for a small interval of serpentinite and shale just beyond the fault. Near the tunnel entrance, well-developed pillows are seen in the basalt of the cliff face. Pods of red chert are sometimes altered to jasper. The chert was deposited during periods between eruptions. Locally, in the Marin Headlands terrane, inter-pillow limestone pods also are found, indicating that the seafloor was above the CCD for at least a short time after forming. The best pillows are seen near the water line below Point Bonita lighthouse, where the waves have beautifully exposed them.



Geologic map of the Marin Headlands peninsula, north of San Francisco, after Blake et al. (2000).

Stop 5 - Folded Franciscan chert outcrops on Marin Headlands

The next stop is near the top of the Marin Headlands. We will drive up, do a U-turn at the top and park on right (ocean side across from the outcrop). Caution: Beware of traffic. Also, be prepared to give explanations for twisted rocks, earth upheavals, and California falling into the ocean to tourists passing by.

This portion of the lab involves the measurement, detailed description, and interpretation of the origin of small-scale folds developed in thin-bedded chert and argillite of the Franciscan complex. The chert section is probably less than 80 m thick and spans a period of deposition from approximately 200 million to 100 million years ago. We will spend some time along this stretch of outcrop, measuring as many of the folds we can. Please follow the instructions below.

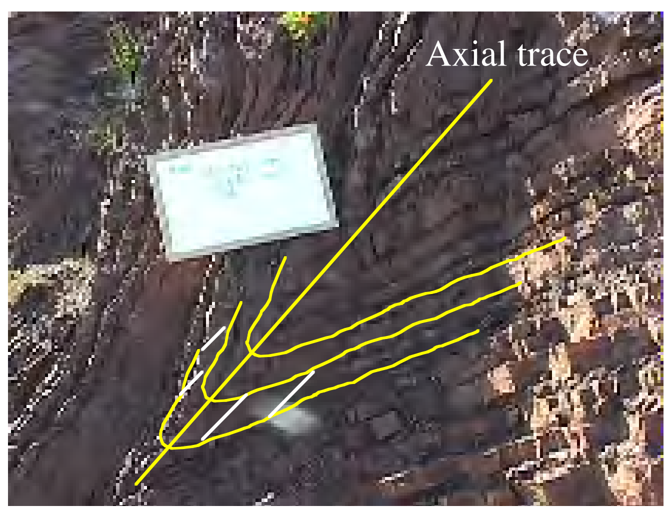
Begin by standing as far away from the outcrop as possible and sketch the outcrop and its folds. This may seem fairly difficult, but the most important aspect of doing so is to follow the traces of the axial planes of the folds in order to determine how the vergence, i.e. the sense of overturning, of folds change. Also, determine the length scales of folding (e.g. 10 cm folds on 1 m folds on 100 m folds). If subsidiary second order folds form on a large fold's limbs then the second order folds should show a reversal in asymmetry as you cross the axial plane of the larger fold: It is important that you establish the overall picture of what is going on before beginning. The sense of asymmetry is defined as you look down the plunge of the fold axis. Is it clockwise or counterclockwise?

Exercise: Working in small teams, measure strikes and dips of the limbs of several folds and locate your readings on your sketch of the outcrop. Your fold data should consist of:

-Fold description (size, length of limbs, shape, etc- here you should run through the range of descriptive terminology applied to folds and make sketches of key observations if necessary)
-Fold axes (you can abbreviate as F.A. in your notebook)
-Axial Trace (A.T.) or axial plane (A.P.). If you measure axial trace, leave a blank line for filling out later when you solve for the axial plane (fold axis and axial trace define the axial plane)
-Asymmetry
-Measurements of strikes and dips of bedding on the limbs of folds.

• Relate the sense of asymmetry to geographic coordinates. Are the folds overturned to the north or south?
• In the case of these folds, the orientation of the axial plane is best measured by first taking its trace and then measuring the fold axis orientation. The axial trace is the line formed by the intersection of the axial plane with the outcrop. Next solve for the orientation of the axial plane when you get back by plotting the fold axis and axial trace on a stereonet (two points), which define the axial plane.
• When you find a really nice-looking fold in cross-sectional view (one of the folds you measured and described in detail), take a close-up photograph that you will use when you get back to help you define the exact style of folding of the chert and shale.
• Consider how these folds came to be, and what supporting evidence you can cite for your interpretation. For instance, are they tectonic or soft-sediment slump folds? Were the rocks hard and brittle or soft when folded? In detail, how were strain and space problems accommodated during folding? What was the mechanism of folding?

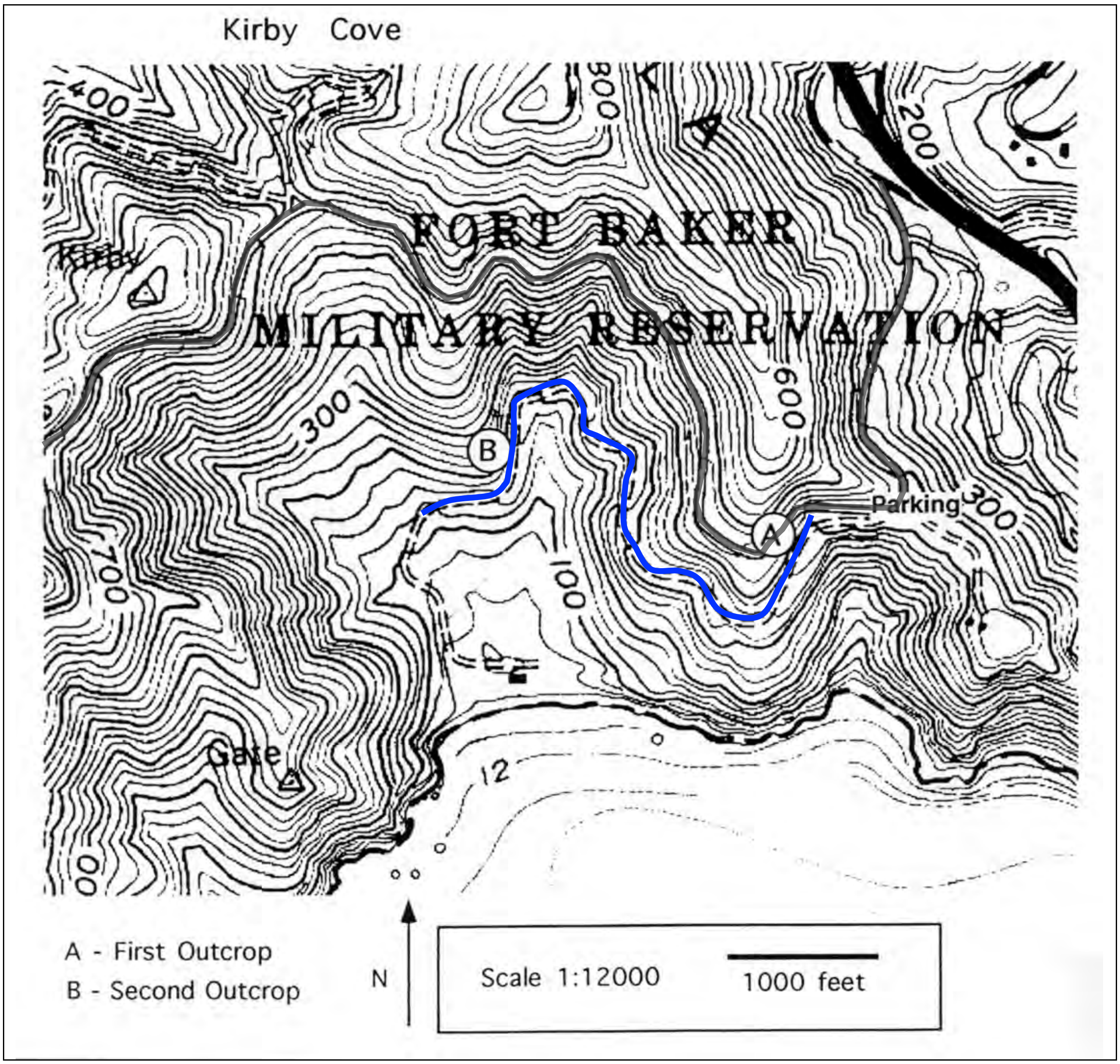
Outcrop of folded cherts at Marin Headlands.



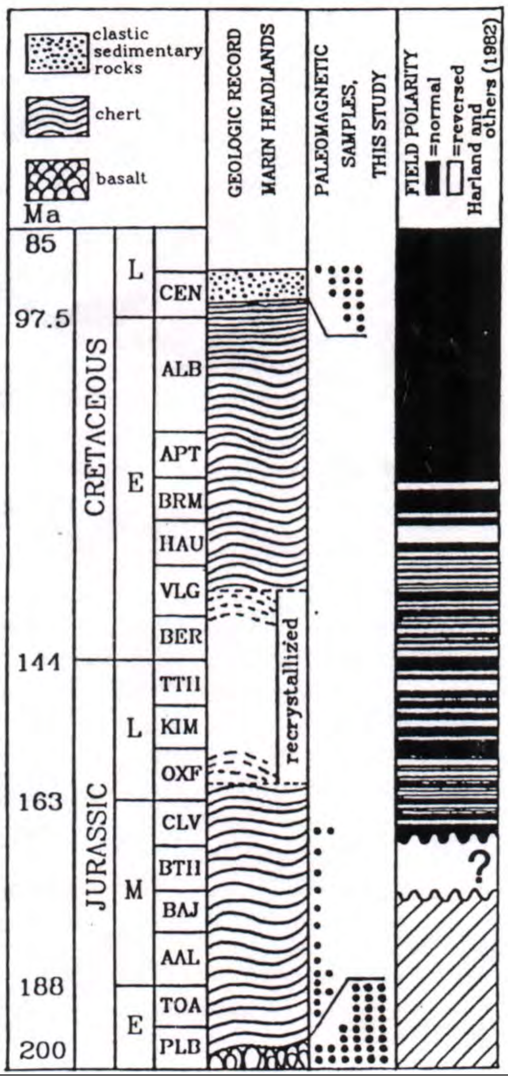
Example of fold close-up for follow-up analysis.

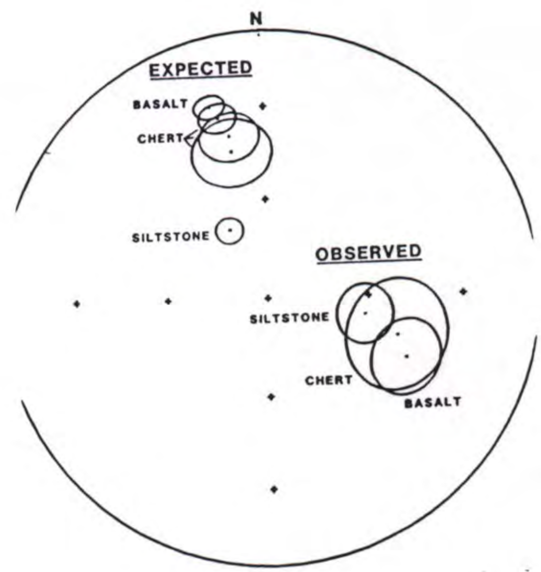
Stop 6: Geology along Kirby Cove Road

We will park near the gate to Kirby cove and study the geology along the road down to the ocean. Fill in the topographic map with the geology you observe (rock types etc.). On the way back up the road, carefully check your locations on the map and mark wherever you see a change in the bedrock. Label the type of bedrock and indicate areas with vegetation or soils. Draw dashed lines, if you cannot see the contact. Use colored pencils to indicate different rock and cover. Describe the rocks located near points A and B on the map in more detail in your field notes. Document any structures and natures of lithologic contacts you found in your field notes.



The stereonet below shows the paleomagnetic directions from Marin Headlands cherts, basalts, and sandstones after correction for tilt (Curry et al., 1984). The circle indicates the mean preferred orientations based on a large number of samples. The expected orientations are those predicted for cratonal North America.





Exercise: Make sure your map is complete. As part of this exercise you will hand in your finalized map and notes together with a short description of the structures and their formation.

What appears to be the dominant deformation geometry and kinematics?

What can we infer from the paleomagnetic data?

Marin Headlands Field Report (200 Points)

Please Note: The reports need to be complete, neat, and well produced.

Overall Expectation

Your report summarizing this field exercise should be comprehensive and professional looking. It should also be concise.

Field Notes (40 pts)

Please turn in a copy of your field notes. In some disciplines, field notes are considered legal documents and modifying them after you leave the field renders them inadmissible in a court of law, so please do not make any attempts to "improve" your field notes now.

Fill out the checklist for your field notes that is on the last page of this document. I will assign grades in the end, but I want you to look critically at your own work.

Schmidt Quarry (10 pts)

Make a sketch of the outcrop and/or any key structural relationships. Describe all kinematic indicators you observe that allow you to constrain the tectonic history represented in this outcrop. What is the geometry of deformation? How is this deformation related to your observations at the Marin Headlands and the overall tectonic setting?

Kirby Cove (20 pts)

Finalize or redraw your map of Kirby Cove. Your report should include a textual description of the lithology and deformation features you observed here. What appears to be the dominant deformation geometry? What can we infer from the paleomagnetic data?

Fold Analysis (50 pts)

From your data collected at the Headlands folds outcrop (Coordinate your field measurements and use everybody's data).

1. Plot your Headland fold measurements on a stereonet. Use the Stereonet program to accomplish this task. Plot the fold axes and poles to fold-axial planes on one steronet. Add labels that refer to a designated fold or location. Can you make out representative sets of bedding orientations that can be related to the geometry of folding? What is the sense of asymmetry of the folding at this site?
2. Add a second stereonet layer and plot the data from Kirby Cove (as 3 different symbols).
3. Measure bedding thickness on the outcrop photos along different segments of your folds, parallel to the axial plane of each fold and perpendicular to bedding. Draw dip isogons on each sketch. Determine the classification of your fold (See Ramsey's fold classification scheme in T&M). Do the chert layers behave differently than do the interbedded shales? Why? In order to do the above project more easily, you may want to enlarge the photo of the fold in a program like Powerpoint or Photoshop. What is the regional sense of shear implied by these folds? (Remember that when you are discussing the folds formally, you should say overturned to the southwest or northeast, not "Z" or "S" or clockwise or counterclockwise). How does your special fold compare to other folds around it and the regional deformation field?
4. Discuss any evidence that bears on the mechanisms for folding and/or the physical conditions or rheology of the strata during folding.

One Page Report (80 pts)

A. Provide a general overview of the timing and sequence of events in the Bay Area that are relevant to your observations on this trip. What appears to be the dominant deformation geometry of Franciscan structures in the Bay area (from stop 1, description of other outcrops, and generalized structure of the Franciscan subduction complex)?

B. Write a couple of sentences on purpose of this study and the type of data collected.

C. Discuss the mesoscale structures in the chert beds:

- Describe concisely the style and geometry of the folds measured. Use your dip isogon study here to document in more detail the geometry of the folds in the chert and shale.
- Concisely describe the orientation data of folds from your stereonets, i.e. average and spread of fold axes, average and spread of axial planes.
- What is the regional sense of shear implied by these folds? How does this inferred shear relate to the direction of underthrusting inferred for the Marin Headlands during Franciscan subduction? (Remember that when you are discussing the folds formally, you should say overturned to the southwest or northeast, not just clockwise or counterclockwise).

D. Discuss the mechanisms for folding and/or the physical conditions or rheology of the strata during folding.

E. Discuss the relationship of the geometry of folding, as well as the mapped relationships on the Kirby Cove road, to plate margin tectonics: If one assumes that the continental margin was parallel to the trend of the Sierra Nevada and Great Valley during the time of Franciscan deformation, and that subduction was directed eastward under this margin, is the attitude and sense of asymmetry of Marin chert folds compatible with this scenario? What can we infer from the paleomagnetic data? Could you have predicted these data?

Use YES, NO, ONCE, or SOME to indicate whether or not your field notes include the following crucial items:

General	
Page Numbers	
Beginning of Day comments	
End of Day summary	
Locations	
General Location Sketch	
Station Numbers (on sketch)	
Orientation (North Arrow, Direction of X-Section)	
Scale bar (approximate)	
Description of location (optional if map is excellent)	
Times Visited (optional)	
Use of Standard Mapping Symbols	
Lithology	
Individual Units	
Individual Unit Names (granite, gneiss, sandstone...)	
Color	
Compositon (minerals or clasts)	
Grain/Clast Size	
Structure (ie: massive, cross-bedded, sorting)	
Structural Observations (Joints)	
Thickness, where appropriate	
Stratigraphy/Structural Observations	
Sketches	
Measured the orientations of contacts	
Description of what orientation is (ie: strike and dip are useless without comments about what you took the strike and dip of!)	
Nature of contact (unconformity, bedding, etc.)	

Grade:

Completeness	/10
Neatness / Organization	/10
Scale Bar & Orientation	/10
Station Locations/Spatial Control	/10