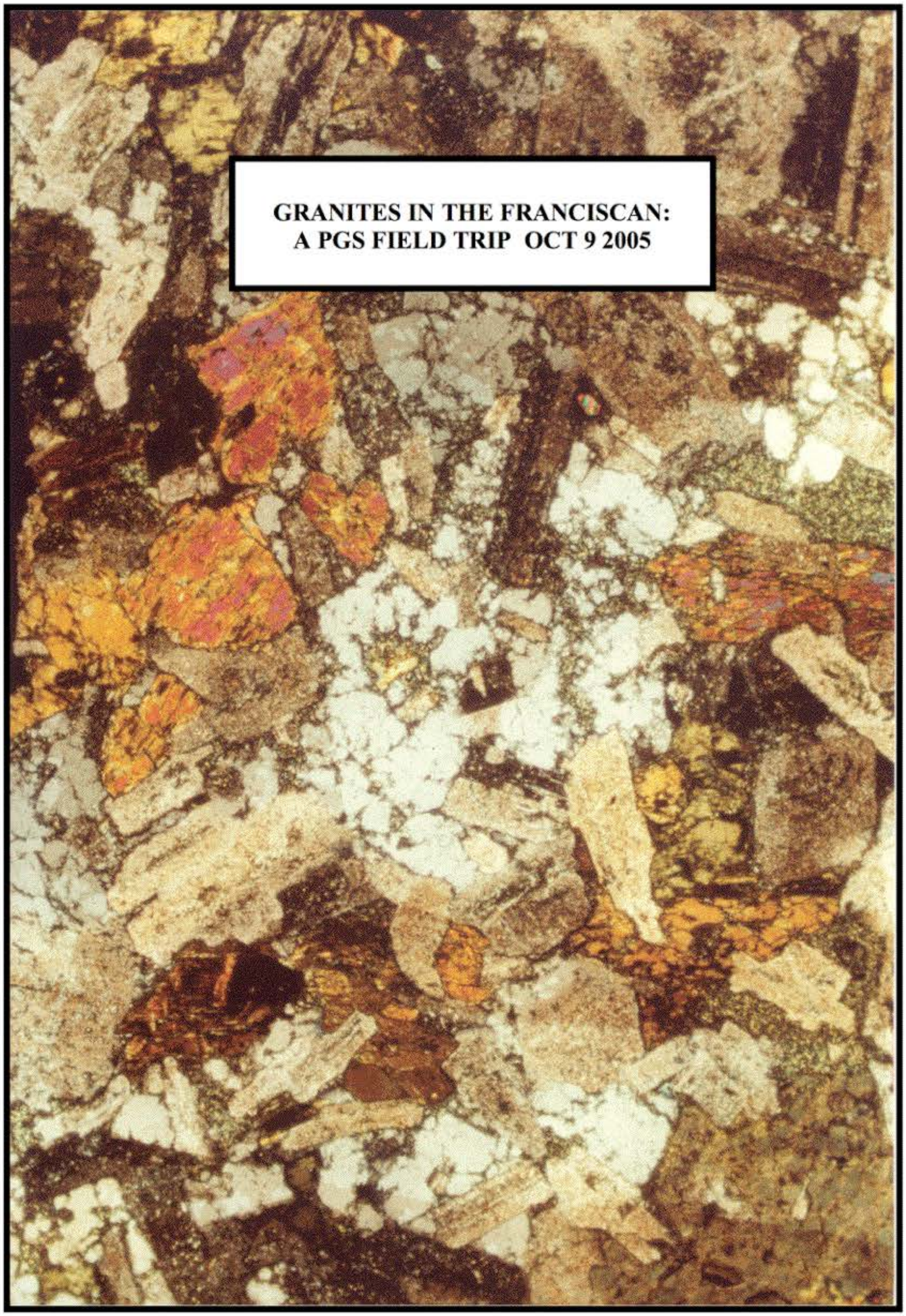
GRANITES IN THE FRANCISCAN: A PGS FIELD TRIP OCT 9 2005



GRANITES IN THE FRANCISCAN: FIELD EXAMINATION OF GRANITOID AND OTHER COMPONENTS OF THE FRANCISCAN COMPLEX IN THE CAZADERO-WARD CREEK AREA, CA

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A field trip for the Peninsula Geological Society (PGS)
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Introduction: The chief purpose of this field trip is to visit two 'granitoid' components of the Franciscan Complex near Cazadero, CA. One of these components is a multiply metamorphosed quartz diorite exotic block in the King (formerly Kings) Ridge Road olistostrome. The other is an intraFranciscan rhyolite stock, a plutonic body. We will also examine the classic Ward Creek blueschist locale and look at two other interesting exotic blocks in the olistostrome, as well as the olistostrome matrix. My main theme will be field and geochemical evidence for a second, oceanic arc in the Franciscan Complex.

Mileage for Stop 1 is measured from the Cazadero turnoff from River road; all other Stop mileage is measured from the Cazadero store. UTM coordinates are provided for all stops; be sure to use the 1927 Datum. Figure 1 shows where the stops are located.

Appendix I contains an overview article on the Franciscan geology of the area and provides background information on the units visited, and a bibliography of most references cited. Appendix II provides a short history of Cazadero. Appendix III contains copies of GSA Meeting abstracts of presentations by the author and Sonoma State University Geology department students on some of the geologic features discussed. Appendix IV contains relevant geochemical diagrams keyed to the stops. Appendix V contains the chemical data on previously unpublished samples. References not found in Appendix I are given in the short form used in GSA abstracts.

Stop 1: Examination of the King Ridge Road olistostrome melange

Location: UTM 10 S 0492732E 4263286N 1927 CONUS Datum

Go North on Highway 101 from Larkspur or the Golden Gate bridge; pass through Rohnert Park and Santa Rosa. Take the River Road exit from Highway 101, head west, and **set your trip odometer to 0** miles. At 16.0 miles pass through the center of Guerneville, and at 20.3 mi find yourself under the hanging sign in Monte Rio; take the right-hand fork, Highway 116, of the Y intersection here. Continue along 116 to the Cazadero Highway marker at 23.8 mi. **Reset your trip odometer to 0**. Drive 5.0 miles roughly north on the Cazadero highway to stop #1. Here the highway builders and

Austin Creek have cut a vertical cliff in the Franciscan rocks. Pull off on the LEFT on the grassy edge of the road, which is just wide enough for one vehicle, watching for oncoming traffic. While inspecting the outcrop, keep a sharp eye on the traffic flow; the locals drive very fast.

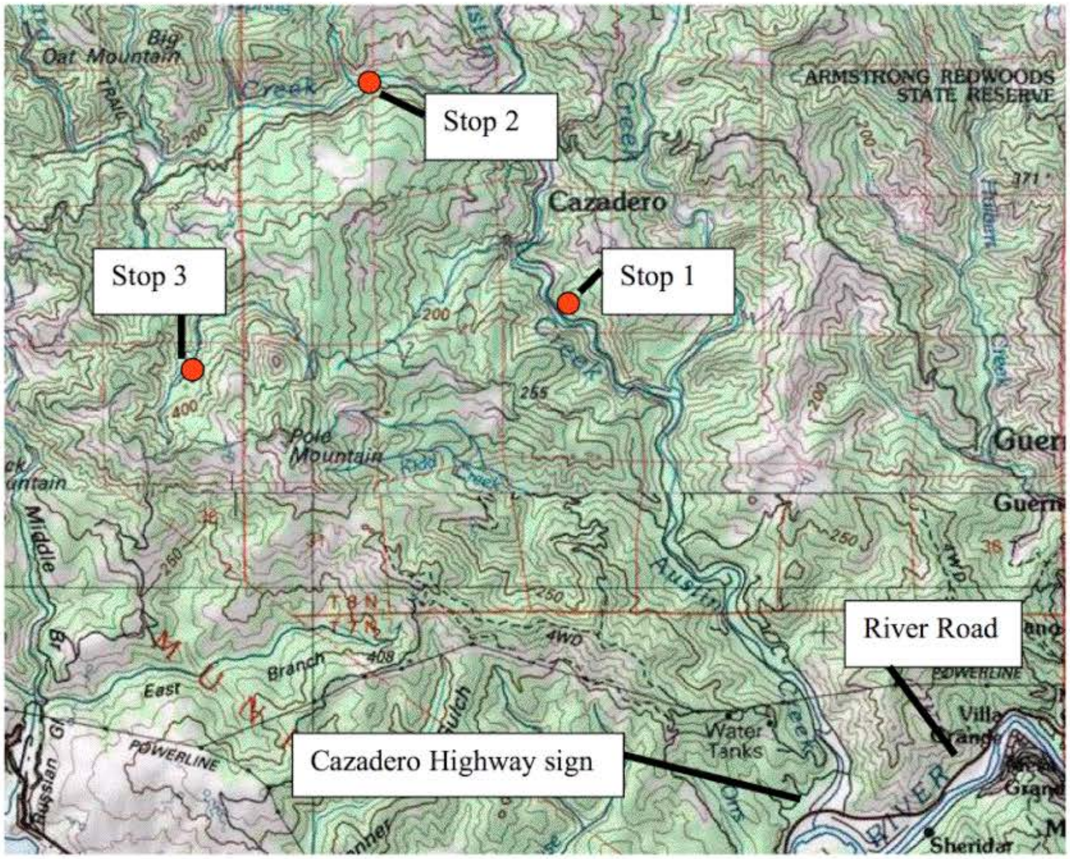


Figure 1: Stop Location Map

Geology: Here a very large chert block sits in the sandstone matrix of the King (formerly Kings) Ridge Road melange, and the contact and the matrix may be examined closely. The chief feature of the exposure is that the sandstone matrix is well-jointed but unsheared; this means that the melange is not tectonic but an <u>olistostrome</u>, and the chert block is an <u>olistolith</u>. Part of the block outcrops on the west side of Austin Creek across from our stop; the creek has cut down through it.

The author has mapped 14 sections around Cazadero (Appendix I); about half the area is underlain by this melange (Appendix I, figure 2). 249 exotic blocks of great petrographic variety and greater than 3m maximum dimension were mapped in it. Reconnaissance suggests this melange unit extends far beyond the area mapped. The melange matrix here is massive medium-grained sandstone, typical of the King Ridge Road olistiostrome. The sandstone by Pettijohn's classification is generally a <u>litharenite</u>

and **not** a classic "greywacke". The sandstone has little matrix and most of its clasts are quartz, feldspar, mica, and metamorphic rock fragments (Sucha, 1995; an unpublished senior project at SSU). The sandstone is recrystallized, with zero porosity. It is strongly jointed, but again not sheared. Some joints show weak slickensides.

The sandstone is not an accumulation of turbidites. It lacks turbidite structures, such as graded beds or Bouma sequences. Locally the sandstone shows planar bedding which fades out quickly in all directions; we'll see an example at stop 3. The attitudes of this bedding are random across the field area, and cannot be resolved into intelligible folds. My conclusion is that the sand from which the matrix is made originated from multiple gravity flows into the trench, and the beds are inherited from the original deposits; in most exposures the sand was stirred up enough in the flow to lose all traces of its original beds.

The contact between the block and its matrix can be closely examined at ~2m above road level at UTM 10 S 0492726E 4263279N. The sandstone matrix and the chert can be traced to within a few cm of each other; two faults are in the chert but I think the exact contact is unfaulted, which fits the olistostrome model; the chert block is a giant boulder in the olistostrome. This is one of two exposed contacts in the entire map area!

After leaving Stop 1 we will pass through the village of **Cazadero at 6.30 miles. Set your trip odometers to 0 at the Cazadero store**. See Appendix II for a brief description of Cazadero history.

Stop 2: The classic Ward Creek metabasalt - metachert sequence.

Location: UTM 10 S 0490351E 4265531N 1927 CONUS datum (entrance of dirt road going down to the cabin at the Ward Creek site).

UTM readings are chancy in the redwood forest; sometimes a unit will pick them up and sometimes not, probably depending on the GPS satellite positions. I include two ways to find the right driveway to the cabin at Ward Creek.

The driveway that I use to reach the cabin at Ward Creek T's into the Fort Ross Road at 2.70 miles from the Cazadero store. A second driveway which we will use for this trip but perhaps not afterward is at 10 S 0490712E 4265753N, 1.45 miles from the store. Parking is more abundant at this more easterly driveway. Parking consists of several pullouts along the narrow Fort Ross Road which can take 1-4 vehicles.

As you leave Cazadero and head for the driveway to Ward Creek, in 0.4 miles you come to a triple (road) junction at the Trosper monument. Take the Fort Ross road, which goes uphill steeply to the left. Follow the road to the given UTM coordinates and/or mileage, where on the North side of the road a dirt road with a chain across it leads down to the exposures. There is space to park three vans/cars about 100 m E of the road's entrance and space for two more another 100 m E from there, and there are more pullouts to the W and E from here. When planning trips, be aware that more than 30 people will crowd the outcrop on the creek, and crowd the parking. As at stop #1, watch the cars! If you have old boots or sandals to wade in the creek with, bring them along. It is difficult to move about the creek freely and keep your feet dry! Bring water and lunch, we will eat at the creek.

The owner of the property has asked us to **sign lawsuit waivers**, and I will pass these out and then collect them at this time. Anyone wishing to visit Ward Creek needs to contact the owner for permission and sign a waiver. The present owner, Mr. Kent Look, is quite supportive of scientific study of this exceptional exposure. However, much of the best exposures form the wall of his swimming hole, and he does not want hammer marks there! **This is a no-hammer, no-collect stop!**

Geology: Appendix I contains a review of the geology, especially the mineralogy, of the Ward Creek assemblage. Some high points are that it was here that Coleman and Lee, in their classic Journal of Petrology paper (Appendix I), showed that glaucophane schists were not odd metasomatic rocks with an unusual, high Na chemistry due to alteration by sodic fluids from serpentinites, but were isochemically metamorphosed normal basalts. It was here that Bob Coleman discovered metamorphic aragonite, which led to its recognition as one of the characteristic high-pressure metamorphic minerals. It was here that labels were applied to the four main textural types of glaucophane metamorphites. It was here that the mineralogy of these rocks was studied in 2 groups of papers, first by Coleman and Lee and their colleagues in the 1960's and then by Maruyama and Liou (Appendix I) and their colleagues in the 1980's. Work continues on various aspects of the complex; one recent contribution from a Sonoma State student is discussed below.

At least 30 refereed papers and several guidebook articles have been published on this small exposure, and I believe it is the most intensively studied body of metamorphic rocks in the world, certainly in terms of papers/m^2!

Some ongoing or future projects remain. One continuing problem at Ward Creek is that we don't know the age of the protolith or its metamorphism. Another thing which has not been done is a detailed structural study building on Coleman and Lee's original observations ~45 years ago.

After examining the classic sequence, we will walk downstream in Ward Creek about 250m to examine the Big Oat Creek metabasalt unit which lies north of it and discuss whether the Ward Creek and Big Oat Creek units should be considered one unit or two.

<u>Geochemistry of the basalt protolith at Ward Creek</u>. In a 2004 GSA poster session (Appendix III) study by Swanson, Erickson, and Plummer, the authors showed that the Ward Creek metabasalt protolith had <u>arc trace element geochemistry</u>, as showed especially by Pearce spidergrams, superimposed on N-MORB rare earth patterns (Appendix III and IV). This best models a back-arc supra-subduction zone environment. The classic view of the Franciscan is that it is a subduction complex/accretionary wedge, whose matching (single) arc is the Sierras. The probability that these rocks at Ward Creek were originally backarc basalts requires a <u>second arc</u>, probably an M-type oceanic arc, to have existed in the Franciscan system somewhere. Data from the granite block we will visit this afternoon also supports this new model, as does data by Basu and Wakabayashi (2005) and Shervais (2005).

Another question discussed by Swanson et al (Appendix III) is the areal extent of the Ward Creek metamorphites. Coleman and Lee (Appendix I) considered the Ward Creek sequence to be a small body about 300 m long. Maruyama and Liou (Appendix I) alternatively, presented the Ward Creek block as a part of a much larger metabasalt unit, earlier called the Big Oat Creek metabasalt by Erickson (Appendix I). Swanson et al disagree, and suggest restricting the Ward Creek name to the body defined by Coleman and Lee. They point to the absence of relict pillows and vesicular zones in the Ward Creek rocks and the absence of metachert in the Big Oat Creek unit. Additionally, trace element geochemistry in Pearce spidergrams and REE diagrams (Appendix IV) show great contrast between the two units. 3 of 4 samples of the Big Oat Creek unit taken over several kilometers show a fertile/OIB pattern typical of oceanic islands/seamounts in both Pearce spidergrams and REE diagrams; the sample nearest the classic Ward Creek rocks does still retain an arc Pearce pattern. Maruyama and Liou (Appendix I) applied the seamount model to both the Big Oat Creek unit and the Ward Creek rocks. Swanson et al think that the Ward Creek classic section and Big Oat Creek metabasalt unit are separated by a fault (Appendix I, Figure 2) with considerable movement.

Stop 3(a:) A metamorphosed and brecciated granitoid block in the King Ridge Road melange

Location: UTM 10 S 0488635N 4262558N 1927 CONUS Datum

On departing the Ward Creek stop, drive west 2.15 miles (3.60 miles from Cazadero) on the Fort Ross Road to the intersection with Dawona (formerly Pole Mountain) Road, newly signed. Go south up Dawona road, being careful as you almost immediately cross a one-lane wooden bridge with no guard rails and in deep shade (!). At 1.1 miles (4.70 miles from Cazadero) Dawona road ends in a 3-way split; go sharp right (SE) and immediately cross a bridge (again, no guard rails!); immediately after the bridge there is another 3-way road split; take the center road, running S40W, and in about 100m find a chain gate, normally locked. For access contact the landowner, presently Mr. Jack Hart, on whose property we will be working this afternoon. Mr. Hart has generously offered to let us tromp around on his land all afternoon, and I hope we will all thank him as the occasion arises.

From the chain gate go 0.55 miles (5.25 miles from Cazadero) to Mr. Hart's house and parking area. If you have 4WD, lock it in; if your vehicle is not a 4WD drive vigorously! Park in the meadow next to Mr. Hart's home; we will access our last 3 stops from here. Collecting is OK here. Rattlesnakes are common here, and Mr. Hart saw a juvenile mountain lion on the road about a month ago, so take normal field precautions.

The granite block we will examine for the first of three stops here lies just north of Mr. Hart's house. Walk back down Mr. Hart's road about 100 m to where an old road T's to the west from the road, at UTM 10 S 0488650E 4262662N. Cross here and go up this road to a cut at 10 S 0488581E 4262714N; this cut is in the granitoid we have come to examine and the best samples are obtained here.

Geology: This ~100 m block is a partially exhumed olistolith in the King Ridge Road olistostrome. Details of its petrology, mineralogy and isotope geochemistry are in a GSA abstract by Erickson, Mattinson, Dumitru, and Sharp (Appendix III) and in a pending article; highlights are given here.

Walk up the cut to the natural exposure. The rock is a medium-grained plutonic-textured rock with obvious plagioclase and amphibole in roughly equal proportions; quartz is not obvious, and it might easily be identified as a gabbro. It is, instead, a multiply metamorphosed and brecciated granitoid olistolith, perhaps the first one ever described from the Franciscan melanges. A thin section photomicrograph of the rock is the cover of this field guidebook. Because of its combination of the accessory minerals zircon and apatite and the isotopes they contain, and abundant relict minerals and textures from its protolith and metamorphic and brecciated phases, this block provides a great deal of quantitative information about its history, perhaps more than found in any other single location in the Franciscan.

The **protolith** was a hornblende biotite quartz diorite (IUGS), with 10% modal quartz, accessory zircon and coarse separable apatite. The pluton crystallized in an oceanic island arc (M-type) at about 800°C and 1.4 kb at 165 Ma (zircon U/Pb), cooling to perhaps 400°C by 160 Ma (apatite U/Pb). The pluton was subducted and underwent a major but incomplete **first metamorphism** generating albite, ferrorichterite (a blue amphibole) and chlorite at 300±50°C and 4±1 kb. It was then cooled and brecciated by hydrofracturing, which developed innumerable irregular breccia veins a few mm wide, which then recrystallized so the rock was as solid as before.

(In **hydrofracturing**, the fluid (probably an H_2O/CO_2 mixture) exerts such a pressure that the rock breaks from it and the fluid moves along the break, continuously breaking the rock as it advances. In section the breccia veins in the granite follow an irregular winding course and show no link to tectonic fractures. Fragments of minerals have been **fluidized** and transported along the veins).

Some fragment of the quartz diorite then moved to a higher P and T environment, and in a **second metamorphism** was cut by abundant veins of pumpelleyite at 250±50°C and 5±2 kb. A fragment roughly the size of the present block was then carried to the surface and rolled or slid into the trench, where it was covered by accumulating grain flows of sand as the King Ridge Road olistostrome developed. Fossils nearby in probably equivalent sandstone date the formation of the melange matrix at 147±3 Ma (Tithonian). The whole olistostrome was then moderately folded and metamorphosed, the block for the **third time**, at 250±50°C and 2±1 kb, marked by the formation of laumontite veins. Intrusion of the Little Black Mountain stock at >100 Ma occurred at about this time; it was affected by only one weak metamorphic event. The block then sat in the melange for ~100 Ma while it was slowly isostatically uplifted; apatite fission track dating of the block and its sandstone matrix show that at 36±2 Ma the melange T dropped below ~100°C. Recently the block reached the surface and is now breaking up, mostly due to root wedging. Fragments of it can be found in Ward Creek up to 2 km downstream. Several other quartz diorites, tonalites, and diorites with similar histories are present in the melange in other locations (see for example Mangel and Erickson, 2004).

The massive sandstone matrix of the melange is exposed at UTM 0488650E 4262662N at the T-intersection to the block. A sample is an arkosic arenite by Pettijohn's classification and is essentially disintegrated granite. It is not a greywacke.

As we walk along Jack's road, at UTM 10 S 0488656E 42632759N a small gully lies west of the road. In it is a local well-exposed bedded sequence in the matrix of the

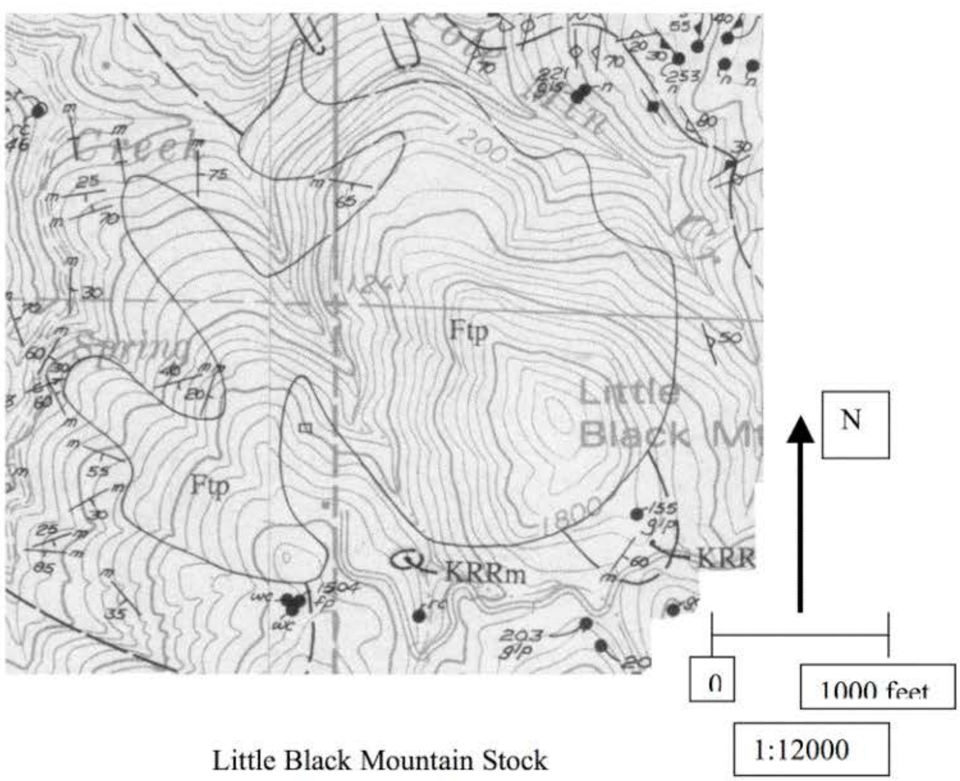
King Ridge Road melange, with strike and dip N65E at 65S. Laumontite veins from the **third metamorphism** are present cutting the beds.

The arc into which this quartz diorite intruded was an oceanic M-type formed where one oceanic plate subducts below another. Isotopic data (Appendix III) support this model. A good modern analog is the Mariana Islands in the western Pacific. This is a new arc, not contained in the classic model of the Franciscan, and requires that the Farallon Plate be two plates for part of its existence. It is not clear at present whether the oceanic arc in which the Ward Creek basalts formed is the same as this one or not.

Stop 3(b): The Little Black Mountain rhyolite stock

Location: UTM 10 S 0488772E 4262693N

Walk back to the road to Jack's house, to the point where the old road to the granite block T's with it. To the east lies hilly terrain underlain by the Little Black Mountain stock, a ~1/4 km^2 rhyolite body, also a 'granitoid' in that it is a plutonic body formed from a felsic magma, although at this level it is dominately aphanitic. We will climb up the slope to the east roughly 300m, following pink streamers, to an old quarry in the stock where we can examine it. We will be on property of the Sonoma Land Trust, and they want us to sign **lawsuit releases**, so we will do that before we go up.



Little Black Mountain Stock

Geology: The original study of this pluton was done by Charles Stuart, an SSU Geology major, as a senior research project, and published in a 1992 NAGT field trip guidebook (Appendix I). The unit has a whole-rock K-Ar date of 101 ± 7 Ma which is certainly too young due to Ar loss, but the age places it in the Franciscan Complex; it is an intraFranciscan felsic pluton, perhaps the only one known to date.

The pluton is a green aphanitic to porphyritic rock with circa 10% 1-5 mm tabular blocky euhedral white to pink feldspar phenocrysts. Some feldspars are plagioclase and some are Kspar; some of the plagioclase crystals are pink, the only case with which I am familiar. Local blue arfvedsonite, an alkali amphibole, is visible in section as small phenocrysts. Local vesiculation indicates the pluton intruded to a shallow depth. No surface flows or tuffs associated with the pluton are known to have survived.

The magmatic arc associated with the Franciscan in our standard model is the Sierra Nevada, and the Franciscan is modeled as its accretionary wedge above the subduction zone. I interpret the Little Black Mountain stock as a pluton that originated by partial melting of the base of that accretionary wedge, and was therefore intruded well to the west of the main Sierran arc. Trace element geochemistry plotted in an REE diagram and a Pearce spidergram (Appendix V) show chemical similarities to granitoid plutons, such as the Skaergaard pluton, that have intruded thickened continental crust. In the Aleutian accretionary wedge there is just such a line of plutons circa 100 km to the south of the main magmatic arc (Hudson et al 1979).

Stop 3(c): A multiply-metamorphosed and brecciated lawsonite-glaucophane fels metabasalt block from the King Ridge Road melange.

Location: UTM 10 S 0488531E 4262312N

Return to the cars. From our parking area at Jack Hart's house, walk to the south across his property and along the jeep trail that parallels the dominant but nameless creek running from the south. In a short distance we cross a downed gate and fence onto another property, whose owners have given us permission to cross their land. It is possible they will join us; if so, please express your thanks to them. We will walk ~500 m along the jeep trail onto a small partially wooded plateau and then go cross-country to the site of this block. A series of pink streamers hanging from trees show the way. If looking for the block after the streamers are gone, stay south of the small creek initially to your N to avoid most brush-crashing. At the UTM coordinates above you will be 10m S of the block.

Geology: The block is about 5m wide and 3 high, and sits on/in a landslide. In 2001 Pearce and Erickson (see Appendix III) did a GSA poster presentation at the Cordilleran section meeting at Universal City on this block. The block is an unfoliated metabasalt breccia whose minerals are dominantly lawsonite, glaucophane, and albite; it has aragonite veins as well.

Pearce and Erickson found that the protolith was an arc basalt; the abundance of LILE elements suggested an arc source, perhaps the Sierras. A REE diagram suggests a magma source in MORB mantle modified by LILE addition, and perhaps indicates a backarc environment. A block of that arc was transported to the Franciscan trench, subducted, and metamorphosed to a lawsonite-glaucophane fels. (a fels is a phaneritic but unfoliated metamorphic rock).

The fels was then shattered, probably by hydrofracturing by water escaping the subducting plate. To repeat, in **hydrofracturing** the fluid exerts such a pressure that the rock breaks from it and the fluid moves along the break, continuously breaking the rock as it advances. In this case, the finer-grained fragments then recrystallized, also to a lawsonite-glaucophane fels of finer grain than the first. Metamorphic conditions were about 300^{o}C and 7 kb, and did not change during the brecciation and recrystallization of the rock. The rock later underwent a second metamorphism which produced pumpelleyite veins in it, and a block of it was then moved to the surface and incorporated in the developing King Ridge Road melange. This melange then underwent burial metamorphism marked by the formation of laumontite. This breccia block has had the same metamorphic and brecciation history as the granite block we looked at earlier, with the exception that the first metamorphic mineral assemblage was different! The breccia block, lacks zircons or apatite and cannot provide as much information on its history as the former quartz diorite block did.

The **brecciation** which is a minor but persistent feature of the granite block just visited is the dominant textural feature of this block. Quite a number of exotic blocks in the melanges exposed around Cazadero are breccias or have brecciated zones. Brecciation, presumably by hydrofracturing by water/CO2 escaping the subducting slab, is probably a major physical process in the subducting plate and the overlying mantle wedge. Once brecciation has occured, fluids can travel along these paths easily.

Another process related to brecciation and the production of innumerable fragments of many sizes is **fluidization**. The moving fluid will fluidize the smaller fragments and carry them to other parts of the system. In the granite earlier visited, the breccia veins are full of fragments which obviously don't match the vein walls; fluidized transport of mineral fragments occurred there. I speculate that fluidized transport of fragments of the rock through which dewatering/decarbonation fluids pass is an excellent mechanism for mixing and transporting materials, and must have some influence on processes in subduction zones.

This concludes the field trip.

Appendix I:

An Overview of the Franciscan geology of the Ward Creek-Cazadero area

The Geology of the Franciscan Complex in the Ward Creek-Cazadero Area, Sonoma County, California

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INTRODUCTION

In 1963, Coleman and Lee published their classic study of the **glaucophane***-bearing metamorphic rocks in a small exposure in the channel of Ward Creek, about 1 mile (2 km) west of Cazadero, Sonoma County, California (Photo 1; Figure 1). These rocks are glaucophane, **lawsonite**, **aragonite**, and sodic **(jadeitic)** pyroxene-bearing metabasalts, with associated **stilpnomelane** metachert. The presence of sodic pyroxene makes it clear that these are unusually high-pressure metamorphic rocks (Newton and Smith, 1967).

Coleman and Lee's 1963 paper on Ward Creek was the foundation for many others in the 1960s and 1970s. In 1988, Maruyama and Liou published an exhaustive study of mineral composition and stability relationships in the metabasalts and metacherts, which was in turn the foundation for many other papers. At least 32 articles on **petrology**, mineralogy, **oxygen isotopes**, and **geochronology**, including three field guides, have been published on this exceptional sequence (Erickson, 1992a). Possibly the most intensely studied body of metamorphic rocks in the world, Ward Creek's small outcrop is the American standard for glaucophane-bearing metamorphic rocks.

In contrast, the geology of the area surrounding the Ward Creek rocks is poorly known. To learn the larger-scale setting of the Ward Creek rocks, I mapped about 14 square miles (35 km^2) of the Franciscan Complex centered on the Ward Creek locale (see page 164 for map ordering information).

In this article, I combine my studies of the geology surrounding Ward Creek

Photo 1. Type III metabasalt in Ward Creek. Type III metabasalt dominated by green sodic pyroxene, blue glaucophane, and bands of foliated white aragonite. *Photos by Rolfe Erickson.*

(Figure 2) and those of many others on the classic exposure itself into an overview of the areal geology. Wakabayashi (1992) provides a good modern overview of the whole Franciscan Complex. Any recent physical geology text should provide a good discussion of the basic plate-tectonic model, including the trench – accretionary wedge – volcanic arc structure of subduction zones.

THE CLASSIC WARD CREEK EXPOSURES

Ward Creek is a very youthful stream, with high angle-of-repose, vegetation-covered canyon walls and no flood plain, vigorously cutting its channel through competent rocks. The outcrops are superb, but restricted to the active channel of the stream. The classic exposure studied by Coleman and Lee (1963) is about 1,000 feet long and 30 feet wide (300 m x 10 m) (Figure 3); contacts with surrounding units are covered.

The Ward Creek sequence is probably a fault-bounded block lying along the major fault separating the Big Oat Creek metabasalt to the north from the Cazadero **phyllite** mélange to the south (Figure 2).

Some Major Discoveries at Ward Creek

Whole-rock Chemistry of the Metabasalts. Coleman and Lee (1963) and Coleman, Lee, Beatty, and Brannock

*Minerals and terms in **boldface** type are defined on page163.

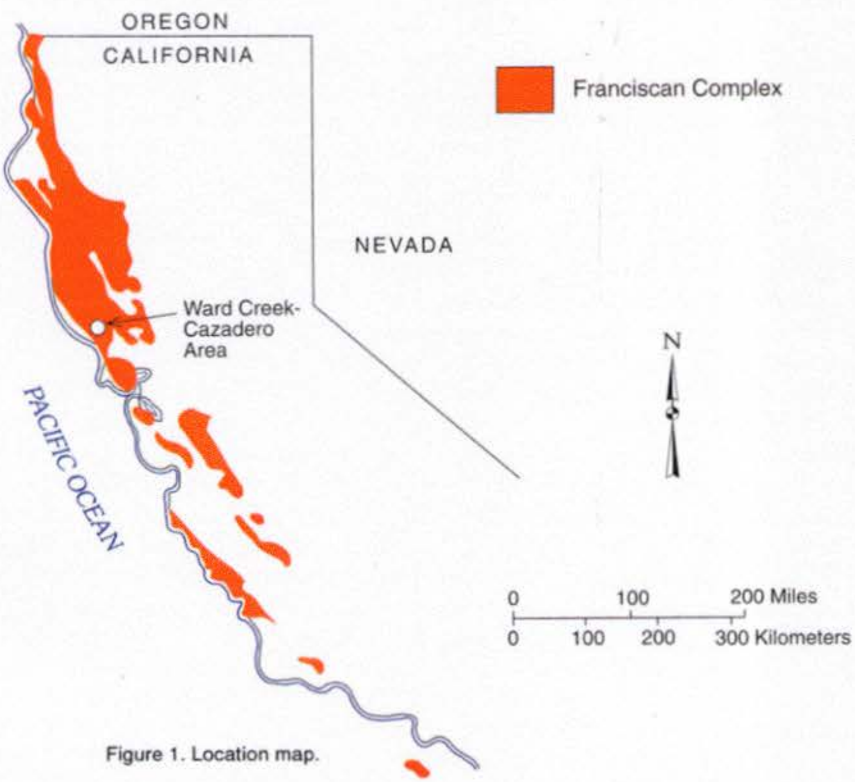

Figure 1. Location map.

(1965) provided 17 whole-rock chemical analyses of Ward Creek metabasalts. The data show the metabasalts are the same in composition as typical oceanic island **tholeiites** or oceanic island **alkali basalts**, like those in Hawaii.

In 1963 the long-standing hypothesis for the origin of glaucophane **schists** was that they were **metasomatic** rocks, normal basalts altered by sodium metasomatism from nearby **mafic** bodies (Coleman and Lee, 1963). Coleman and Lee (1963) effectively show instead that glaucophane schists at Ward Creek and elsewhere result from nearly **isochemical** metamorphism of a normal oceanic basalt type.

Types I, II, III, and IV Metabasalts. Coleman and Lee (1963) subdivided the metabasalts into four textural/mineralogical types. Type I, unmetamorphosed basalts and other rock types, show no **foliation** or field evidence of high-pressure metamorphism, that is, they lack glaucophane. At least some Type I rocks have undergone **burial metamorphism**, however.

Type II metabasalts are incipiently metamorphosed. They are fine-grained, <0.3 mm, lack foliation, but contain glaucophane. Garnet is not present. They have abundant outcrop-scale **relict** textures such as vesicles and pillows, and are commonly cut by bright purple veins or patches of glaucophane.

Type III metabasalts are strongly metamorphosed (Photo 1). These rocks are texturally schists or phyllites with strong foliation, and include both metasediments and metabasalts. Type III metabasalts are much coarser-grained than Type II, typically >1 mm. They have glaucophane plus red garnet. **Protolith** textures are obliterated.

Type IV metabasalts are very strongly metamorphosed and are usually sodic (jadeitic) pyroxene garnet **gneisses**.

Details of the Mineralogy of Type II and III Metabasalts in Ward Creek. Metamorphic rocks are, in general, much more complex mineralogically than igneous rocks. Part of their fascination lies in this complexity, in determining what the minerals are, what the parent rock was, when and how metamorphism happened, and so forth. The metamorphic petrology at Ward Creek is one of the best understood examples of this complexity, so it is worthwhile to provide the following review.

Field studies usually include establishing linear map boundaries called *isograds* which, in the direction from unmetamorphosed to most-metamorphosed rocks, mark the first appearance of any particular mineral. Each isograd is named after the mineral whose appearance it marks, such as **epidote**-in isograd. The area between two isograds may be labelled as a mineral zone characterized by a particular mineral, for example, *epidote zone*.

Maruyama and Liou (1988) defined the set of isograds at Ward Creek and the mineral zones between them, and expanded the original study area roughly a half mile (a kilometer) north, west, and east into the Big Oat Creek metabasalt, which they believe is virtually continuous with the Ward Creek rocks (Figures 2 and 3).

The lowest **grade** metabasalts of the lawsonite zone lie farthest north in the Big Oat Creek metabasalt. Lawsonite-zone rocks are lower-grade Type II, and carry glaucophane as the only **prograde** amphibole, along with a single low-Na clinopyroxene, lawsonite, and aragonite. In the central lawsonite zone, the single sodic clinopyroxene of lowest-grade rocks is replaced by two, which are both high-Na but vary in their Fe/Al ratio. At the high-grade end of the lawsonite zone, however, only one sodic clinopyroxene is stable. The lawsonite-zone rocks commonly also contain relict igneous clinopyroxene, hence three types may be present in one sample.

At the southern limit of the lawsonite zone, **pumpelleyite** appears in the metabasalts, defining the *pumpelleyite-in isograd* (Figure 2). Although these rocks carry pumpelleyite, they are otherwise mineralogically unchanged from high lawsonite-zone rocks, and are medium-grade Type II rocks.

A short distance south of the pumpelleyite-in isograd, **actinolite**

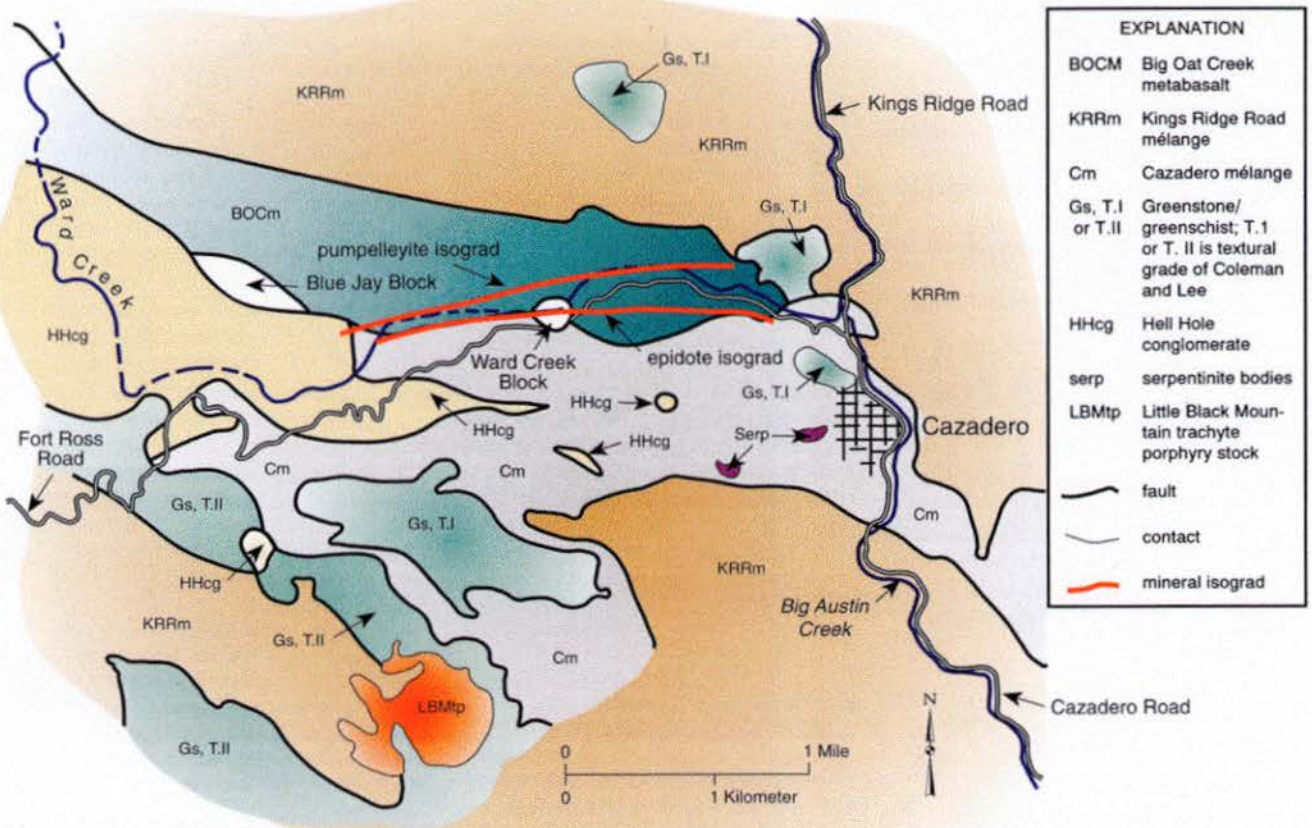

Figure 2. Geology of the Franciscan Complex surrounding the Ward Creek locality. *Isograds from Maruyama and Liou, 1988, Figure 2.*

appears for the first time, marking the *actinolite-in isograd*. (Maruyama and Liou [1988] did not map it, so it is not shown in Figure 2). The actinolite-in isograd defines the northern, lower-grade boundary of the *upper* pumpelleyite zone and splits the pumpelleyite zone in two. With the appearance of Ca-rich actinolite, actinolite and glaucophane coexist as stable amphiboles. It is common in these rocks to find single amphibole crystals with different sections of green actinolite and blue glaucophane, with no indication one is replacing the other. In these rocks two amphiboles and a Na clinopyroxene coexist stably.

At the southern border of the pumpelleyite zone, the first appearance of **epidote** locates the *epidote-in isograd* (Figures 2 and 3). Here epidote is part of all stable assemblages. This is also the boundary between lower-grade Type II rocks to the north and higher-grade Type III rocks to the south, where most of the classic Ward Creek rocks lie (Figure 3).

In this zone, epidote, sodic clinopyroxene, glaucophane, actinolite, lawsonite, and aragonite are all stable together. At highest epidote-zone conditions the Na-Ca blue amphibole **winchite** replaces glaucophane and actinolite.

Eclogites are usually encountered only in loose small blocks in mélanges, geological units composed of separate blocks in a matrix. *In situ* eclogitic zones exist in Type III rocks in Ward Creek, an interesting detail shown by Oh, Liou, and Maruyama (1991). These unusual eclogites develop in thin manganese-rich zones and contain almandine-rich garnet, sodic clinopyroxene, and rutile. Their minerals are compositionally different from those of the normal eclogite of the Type IV blocks and develop under typical Type III conditions. They are the only eclogites in California found in place. Blocks of this Type III eclogite with a local source are in Ward Creek.

Type IV Metabasalts in Loose Blocks. In Ward Creek, Coleman and Lee (1963) observed loose, metabasalt blocks up to 65 feet (20 m) across (Figure 3). Called Type IV rocks, these mineralogically banded, coarsely crystalline gneissic schists are generally much more strongly metamorposed than the bedrock metabasalts. Type IV rocks are found only in loose blocks. Eclogites and glaucophane-epidote-rutile schists predominate here. They contain epidote in place of lawsonite as a calcium silicate, and rutile in place of sphene as the Ti mineral. Some eclogite blocks contain the blue Na- and Al-rich amphibole **barroisite**, which is found in them only.

The Type IV blocks found in the valley of Ward Creek are exotic blocks that have slid or rolled into the creek

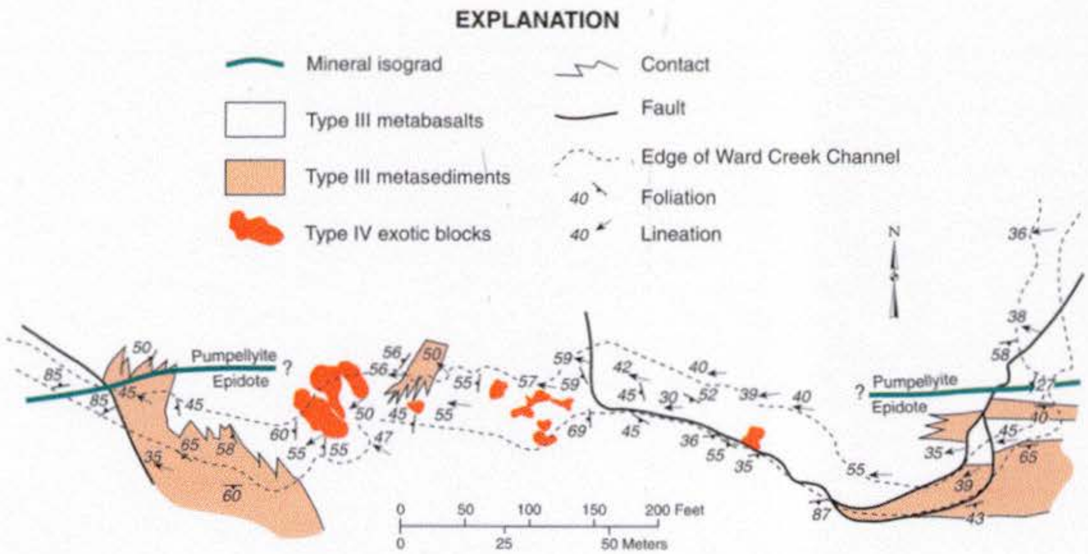

Figure 3. Geology of the Ward Creek exposures. *Modified from Coleman and Lee, 1963, Figure 2, and Maruyama and Liou, 1988, Figure 2.*

from the Cazadero mélange south of the creek (Figure 2). As it happens, the petrographic variety of all the large exotic blocks in the Cazadero area is much greater than that of the original sampled set found at the Ward Creek locality. It is only by chance the original block population studied in Ward Creek did not include cherts, breccias, or felsic textured rocks, for example. Many of these other units would not be called Type IV by the original criteria of Coleman and Lee (1963).

Metasediments. The metasediments found with the metabasalts at Ward Creek are restricted in composition (Coleman and Lee, 1963). Metacherts are the dominant rock type, with minor meta-ironstones and ferruginous shales (Photo 2). Metamorphosed equivalents of the immature sandstones that greatly dominate regional Franciscan lithologies are not found. Carbonates are found as interpillow material and a few thin layers. The metacherts typically show strong compositional, and hence mineralogical, layering, with bands of greatly varying color. These rocks are commonly strongly deformed, showing abundant, typically discontinuous folds. Metacherts in Ward Creek are always Type III rocks. Their typical mineralogy is glaucophane, epidote, garnet, and stilpnomelane in different proportions in different beds. Recrystallized relict quartz is usually dominant.

Structure of the Exposures. Coleman and Lee (1963) determined that the rocks along Ward Creek are folded into an anticline with an axis trending N85°W and plunging 40°W (Figure 3). Glaucophane orientation lineations and linear elongation of aragonite pods parallel this trend. Two faults of unknown displacement cut the sequence in the creek.

Metamorphic Conditions at Ward Creek

Discovery of Metamorphic Aragonite and Proof of the High-Pressure Character of the Metabasalts. During their study of the Ward Creek rocks, Coleman and Lee (1962) discovered the carbonate mineral in Type III rocks was aragonite, a mineral previously found in nature only in mollusc shells and cave deposits. This was the first time aragonite was recognized as an essential component of glaucophane-bearing high-pressure rocks. Here it is common, found in lenses, layers, and veins in the metabasalts (Photo 1). Coleman and Lee (1962) showed the aragonite and other metamorphic minerals had texturally developed together, sharing, for example, a lineation with amphiboles. For perhaps a century, the carbonate mineral in glaucophane-bearing metamorphic rocks was misidentified as calcite. This is understandable because the two minerals look nearly identical in thin section, and both fizz with dilute HCl.

Photo 2. Metachert in Ward Creek.

As it happened, experimental studies a decade earlier had established aragonite as the high-pressure **polymorph** of $CaCO_3$, and determined precise values for the minimum pressure for aragonite stability at different temperatures. These data showed the Type III rocks of Ward Creek were high-pressure rocks indeed. For example, at only 570°F (300°C) the pressure would have to be a minimum of 6,900 atmospheres (7 kb), equivalent to pressure at a depth of perhaps 12 miles (20 km), roughly the depth of the base of the crust. This was the first good quantitative estimate of the pressures at which these rocks form.

Before the development of the plate-tectonic model with its subduction zones, it was difficult to imagine how rocks could reach such great depths, let alone ever return to the surface. Now we know they are carried down subduction zones, and perhaps return to the surface by faulting through the accretionary wedge or by counterflow up subduction zones. This latter topic of the mechanism of return is very controversial.

Metamorphic Temperatures and Pressures. Type II and III rocks formed over a range of conditions. Lawsonite-zone temperatures were less than 400°F (200°C), with pressures of 3,950 to 6,400 atmospheres (4-6.5 kb). Pumpelleyite-zone rocks ranged from 400 to 550°F (200-290°C); and epidote-zone rocks, including the unique Type III eclogite bands, developed at greater than 550°F (290°C) and pressures of 6,400 to 8,880 atmospheres (6.5-9 kb) (Maruyama and Liou, 1988). Oh, Liou, and Maruyama (1991) determined loose Type IV eclogite blocks formed at 930 to 1,000°F (500-540°C) and pressures above 9,870 to 11,350 atmospheres (10-11.5 kb).

Fluid Phase Composition. In general, fluids in metamorphic rocks are predominantly H_2O and CO_2 mixtures. The presence of lawsonite defines the proportions of these two compounds in the fluid at Ward Creek. Brown and Bradshaw (1979) pointed out that lawsonite is unstable in metabasalts unless the fluid phase is nearly pure water; it cannot tolerate any significant CO_2. This is surprising at Ward Creek in view of the common presence of aragonite veins and pods in these rocks. It is also surprising that the fractures in which the aragonite was deposited must have remained open at rock pressures of up to 8,880 atmospheres (9 kb), equivalent to pressures at perhaps 18 miles' (30 km) depth, at which the rock should have been too plastic to have sustained fractures. They could have remained open only if fluids were sealed within them, so the fluid pressure equalled or exceeded lithostatic pressure.

A striking and unusual feature of all the Ward Creek rocks is the absence of iron oxide phases; no magnetite or hematite is present. The iron sulfide, pyrite, however, is usually abundant. In summary, the fluid in the rocks during metamorphism must have been water with a high concentration of dissolved sulfur and little dissolved oxygen or CO_2.

Dates of Metamorphism

Wakabayashi and Deino (1989) report an Ar-Ar date of 142.7 ± 0.5 Ma (millions of years ago) for white mica from a Type III metachert at Ward Creek (Figure 3). This is the most precise and oldest age obtained among several dating studies of the in-place Type III rocks (Erickson, 1992a). The most recently determined and oldest date on a Type IV block from Ward Creek is that of Coleman and Lanphere (1971) who obtained 150 ± 7.5 Ma on white mica, by K-Ar. Like all argon ages, these two date cooling of the rocks below the dated mineral's **closure temperature**, and it is possible the dated units are somewhat older than the dates obtained. Ross and Sharp (1988), for example, used the Ar-Ar technique on Type IV blocks elsewhere and obtained dates of 158-163 Ma.

A Plate-Tectonic Model for Formation of the Ward Creek Rocks

Maruyama and Liou (1988) agreed with Coleman and Lee (1963) that the bulk chemical and mineralogical features of the Ward Creek metabasalts were consistent with an origin as oceanic island basalts and not as mid-ocean ridge basalts. They provided a plate-tectonic model for formation of these metabasalts in a subducted **seamount**, deformed and metamorphosed under the conditions described above. Presumably the rocks reached the surface through a combination of erosion and tectonic activity once subduction had stopped.

UNITS SURROUNDING THE WARD CREEK LOCALITY

Kings Ridge Road Mélange

This unit underlies slightly more than half of the mapped area, in three separate exposure areas (Figure 2). It is named after the road going north from Cazadero, which crosses the largest exposure area. Clearly a *mélange*, it consists of a generally massive sandstone matrix with exotic blocks in and on it (Raymond, 1981).

There are two fundamental types of mélange. A *tectonic mélange* is formed by extreme stretching of, for example, interlayered sandstone and shale. The competent sandstone layers pull apart and separate into individual ovoid blocks (phacoids), while the shale becomes a sheared fluid matrix. An excellent example is described by Erickson (1992b).

A *sedimentary mélange*, or *olistostrome*, has blocks that are essentially boulders in a sedimentary matrix, typically sandstone or shale or interbeds of the two. The blocks are called *olistoliths* and, if they are compositionally very unlike the matrix, are often called *exotic blocks*. The Kings Ridge Road mélange is this type.

The Mélange Matrix. Over 95 percent of matrix outcrops are massive unbedded sandstone (Photo 3). A typical specimen is a medium-to-coarse-grained texturally immature but well-sorted litharenite. Dominantly composed of small rock fragments, this sandstone shows strong compaction, with a small amount of secondary matrix. The age of the sandstone is unknown.

Bedding is visible in local outcrops, usually marked by shale interlayers and sometimes by planar beds; conglomerate interbeds are rare. These bedded zones are rarely extensive. The sandstones contain no evidence of turbidity current deposition, no cross-bedding, no

Photo 3. Massive sandstone matrix of the Kings Ridge Road mélange. Massive well-sorted sandstone with a thin zone of planar beds in upper right. Exposure 33 feet (10 m) high.

pebbles, and no fossils, and are remarkably homogenous. The well sorted character of the sand, together with the absence of shale or pebbles, suggests initial deposition in a beach or bar system. The rarity of bedding structures, and their apparently random attitudes, suggest resedimentation of the initial deposits on the forearc side of the trench by a combination of sediment flow and slumping (Middleton and Hampton, 1973).

In typical individual outcrops, the matrix sandstone is unsheared and shows no deformation except jointing, which shows the mélange cannot have a tectonic origin. The matrix is a Type I unit of Coleman and Lee (1963), but local veinlets and patches of **laumontite** show the unit has undergone burial metamorphism at depths of several miles.

Exotic Blocks of the Kings Ridge Road Mélange. The outcrop area for the Kings Ridge Road mélange contains 249 mapped exotic blocks greater than about 10 feet (3 m) (Photo 4). One of them, a 330-foot (100-m) red chert clast, has a visible unfaulted contact with its unsheared sandstone matrix in a cliff exposure where the Cazadero road cuts through it (Erickson, 1992b). This is the only primary block-matrix contact exposed in the map area.

The blocks exhibit great petrographic variety. Most are **greenstones** (including sparse pillowed blocks), greenschists, or simple glaucophane-bearing schists, phyllites, **hornfelses**, or **felses**, but many are of uncommon or unique petrography. Three examples are: 1) two blocks of arc-type quartz diorite; 2) a block of garnet + epidote + hornblende fels with small patches of glaucophane in the hornblende; and 3) a block of hornblende-albite **granulite** fels with extensive metamorphic epidote. Many blocks are radiolarian chert of several colors and degrees of recrystallization. No blocks of conglomerate, sandstone, shale, or carbonate rocks are present. The exotic blocks range in size from 10 feet to half a mile (3 m to 1 km); most are 15 to 65 feet (5-20 m) in maximum dimension. The abundant chert blocks and the quartz diorite blocks are found only in this mélange unit, lending support to the idea that mélange units can be differentiated by their block content (Gucwa, 1975).

The blocks that can be observed in three dimensions are generally equant and often rounded (Photo 4). They seldom show much weathering, and rounding seems to have occurred by abrasion in some earlier sedimentary or tectonic environment. The blocks are not uniformly distributed by any means, and are often widely separated. Large areas of the mélange are nearly devoid of blocks, while other parts contain dozens of blocks in a small area.

The great petrographic variety and presence of so many unique types and the wide spacing of blocks in many areas, coupled with the contact evidence mentioned above and the generally unsheared sandstone matrix, make it impossible for the blocks in the Kings Ridge Road mélange to be phacoids produced by shearing or extension of competent units. Rather, the evidence shows that the sandstone and blocks together constitute an olistostrome mélange with a sandstone matrix and a highly varied olistolith population.

The exotic blocks of all sizes are interpreted here as giant clasts, which presumably came down the paleoslope of the accretionary wedge into the depositional setting by individually sliding or rolling or in sediment flows. The source of the blocks is unknown.

Cazadero Phyllite Mélange

This unit underlies the central part of the map area, and is named for the village of Cazadero, which is built on it (Figure 2). Diverse exotic blocks usually constitute surface exposures; the matrix is rarely exposed. The age of the unit is unknown.

The Mélange Matrix. Matrix exposures are mostly in stream bottoms and road cuts, or on ridge crests. They are almost entirely sericite phyllite, but rarer glaucophane phyllite occurs (Photo 5). The original rock was probably a shale. Typical phyllite is composed of alternating quartz-rich and sericite-rich laminae 1 to 2 mm wide; in outcrop small quartz veinlets parallel to foliation are abundant. Glaucophane and lawsonite are present. Map data show the phyllite is strongly deformed in complex patterns. The Cazadero mélange is a Type III unit.

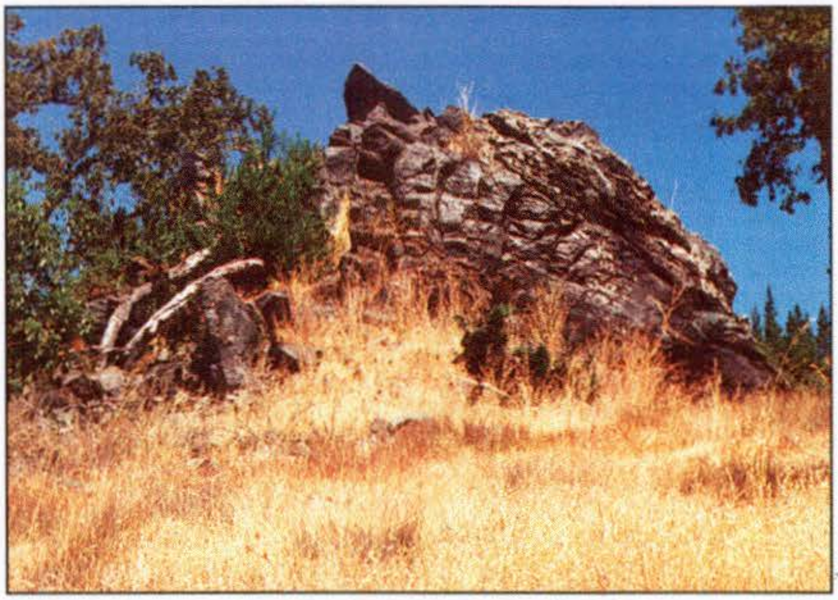

Photo 4. Typical exotic block exposure. A 20-foot (6-m) equant block of garnet-glaucophane schist protrudes from meadow soil.

Exotic Blocks of the Cazadero Phyllite Mélange. There are 341 exotic blocks measuring 10 to 195 feet (3-60 m) cropping out in this mélange unit, at a higher distribution density than in the Kings Ridge Road mélange. Blocks are typically equant, rounded, and separated from one another by tens to hundreds of yards. In general they are little weathered. Many glaucophane-bearing blocks have actinolite and/or chlorite-rich rinds about an inch (3 cm) thick. No blocks of conglomerate, sandstone, shale, or carbonate rocks are present, just as in the Kings Ridge Road mélange.

The proportion of lithologies in the block population is different from that in the Kings Ridge Road mélange. For example, only three chert blocks were found in the Cazadero mélange as opposed to 80 in the other. The Cazadero mélange also contains unique blocks, such as a block whose upper half is a metamorphosed silicic lava with albite and clinopyroxene **phenocrysts** in a very fine-grained quartzofeldspathic groundmass, containing glaucophane, lawsonite, and green stilpnomelane in patches. Blocks in this mélange show great lithologic variety, just as in the Kings Ridge Road mélange.

The great number of blocks and the markedly different proportions of block types in the phyllite, compared to the population in the Kings Ridge Road mélange, strongly suggest the phyllite terrane is the source of these blocks and that they are clasts in the phyllite. Their great petrographic variety in turn suggests the phyllite-clast assemblage is a metamorphosed olistostrome mélange.

A simple model for formation of the protolith mélange is similar to that proposed for the Kings Ridge Road mélange above, except that the matrix in which the blocks were deposited was mud rather than sand, presumably abyssal (deep ocean) mud far from shore. Metamorphism has destroyed the original textures of the matrix, including bedding, so there are no data on which to base more detailed models.

Coleman and Lee (1963) and Maruyama and Liou (1988) suggested that the Type IV exotic blocks in the Ward Creek area were tectonically emplaced upward along the unit-bounding faults. This study strongly supports the alternate hypothesis that the blocks in both mélanges were brought to the area by sedimentary processes.

The metamorphic mineralogy suggests initial formation of a relatively mature low grade sericite + chlorite + quartz mineralogy, followed by the patchy development of local glauco-

Photo 5. Matrix of the Cazadero mélange. Glaucophane-lawsonite-muscovite-quartz phyllite, cut by dolomite veins.

phane and/or lawsonite during a brief episode of subduction into a high-pressure environment, followed by rapid uplift to low pressures and temperatures. It is perhaps during the early low-grade interval that many glaucophane-bearing blocks acquired their rinds of actinolite/chlorite, superimposed on the earlier metamorphic mineralogy acquired before they became blocks.

Big Oat Creek Metabasalt

This distinctive unit has a protolith of pillow basalt with minor interlayered sediments and is named after its excellent exposures in Big Oat Creek (Figure 2). Texturally, the pillow structure has undergone marked flattening and the pillow ellipsoids define a flattening plane. Foliation is not common. Relict amygdules are commonly preserved.

The metamorphic mineralogy is complex, as described above (Maruyama and Liou, 1988). The pillows are green because many of the major minerals are green, but they typically have a band of purple glaucophane 0.5 to 1 inch (1-2 cm) thick at their edges, which effectively outlines their forms in the rock. From a distance the pattern of purple ovoids in stream exposures is quite striking. The original pillow outlines have been deformed enough that no tops could be determined. Masses of aragonite between the relict pillows may represent metamorphosed calcareous ooze in the protolith.

Unlike the other units so far described, this metabasalt has a simple structure. The flattening plane of the relict pillows is roughly parallel to the long axis of the metabasalt exposure and no folds are visible. The metamorphic grade is Type II of Coleman and Lee (1963).

Blue Jay Ridge Type III Block

The Ward Creek block lies along the fault zone between the Big Oat Creek metabasalt and the Cazadero mélange (Figure 2). About 1 mile (2 km) west of it, in and east of Blue Jay Ridge, lies a second Type III block of similar size, containing similar metabasalts and stilpnomelane metacherts. It has not been studied.

Hell Hole Conglomerate

This unit is named for its excellent exposures in the northern portion of the Ward Creek drainage, called the Hell Hole (Figure 2). The dominant rock is unbedded and ungraded pebble to cobble conglomerate characterized by well-rounded, round to elliptical pebbles and cobbles as much as 4 inches (10 cm) in diameter, with rare larger clasts, of many rock types. No detailed petrographic information was gathered on clast types, although many silicic volcanic rock clasts and some plutonic clasts were observed. The rock is usually clast-supported, and elliptical clasts show a marked planar parallelism but no imbrication. The unit contains no exotic blocks. It is an unmetamorphosed Type I unit of Coleman and Lee (1963). It is not a Franciscan unit, but related to the Great Valley Series of the eastern Coast Range.

The clasts lie in a matrix of coarse-grained sandstone. There are rare pure sandstone lenses up to 10 feet long by 4 to 12 inches wide (3 m x 10-30 cm), that lack internal bedding and are often deformed. No turbidites are present. Edward Bailey (oral communication, 1976) found Valanginian (~125 Ma) fossils in the matrix.

The unit was probably emplaced as a sediment flow (Middleton and Hampton, 1973). This suggests deposition on a fairly steep slope, probably on the forearc side of the Mesozoic trench. The conglomerate in the main body is quite deformed, in what appear to be large-scale complex folds, perhaps due to slumping after redeposition on the trench slope.

Serpentinite

There are small serpentinite bodies in the map area, the two largest of which are shown in Figure 2. Workers in the Franciscan Complex have suggested exotic blocks like these at Cazadero were brought to the surface within serpentinite bodies. However, this is not the case with the Cazadero blocks since the serpentinites available are far too small to do the job, and in any case do not contain any significant blocks of metamorphic rock at this level of exposure.

Felsic Pluton of Little Black Mountain

In Figure 2 (south center) is a polylobate body of metatrachyte to rhyolite porphyry, the eastern half of which underlies Little Black Mountain (Stuart, 1992). In hand specimen, the rock is 0 to 20 percent 1-to-5-mm tabular red to white feldspar and rare blue amphibole phenocrysts in a medium green aphanitic groundmass. Chemical analysis shows the blue amphibole is the igneous alkali amphibole **arfvedsonite**; it is a primary phenocryst phase. The rock is an arfvedsonite albite **trachyte porphyry**. The trachyte is a Type I unit of the Franciscan Complex with a whole-rock K-Ar date of 101 ± 7 Ma (Stuart, 1992). Polylobate contacts often dip steeply to vertically, and show that the body is a small stock; local **vesiculation** shows it intruded to a shallow depth. It is the first felsic pluton to be described from the Franciscan Complex. I interpret the pluton as one which intruded the forearc well west of the main Sierran magmatic arc.

The pluton cuts the faults separating metabasalts from sandstones of the Kings Ridge Road mélange, and must postdate the assembly of the fault-bounded blocks in this area. In plate-tectonic nomenclature, it is a *stitching pluton*, gluing the faulted fragments together.

ACKNOWLEDGMENTS

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GLOSSARY

Alkali basalt: A basalt that contains nepheline.

Burial metamorphisn Low temperature metamorphism caused by shallow burial.

Closure temperature: In K-Ar dating, the temperature below which a mineral quantitatively retains argon.

Eclogite: A very high-pressure metamorphic rock composed of MgAl garnet and Na-rich pyroxene.

Fels: A coarse-grained metamorphic rock without foliation.

Foliation: A texture produced by intense shearing during metamorphism, in which all the platy minerals lie parallel to a common plane.

Geochronology: The study involving determination of absolute ages in rocks using radioactive decay schemes. In K-Ar, for example, radioactive K^{40} breaks down at a known rate to form Ar^{40}; in gas-tight minerals age is calculated from the K^{40}-Ar^{40} ratio.

Gneiss: A metamorphic rock in which minerals are arranged in bands or lenses.

Grade: Qualitative estimation of the general level of intensity of pressure and/or temperature in metamorphism (high, medium, or low).

Granulite: A high-grade metamorphic rock characterized by an absence of good crystal form in the minerals.

Greenstone: Low-grade metabasalt without foliation.

Hornfels: A fine-grained metamorphic rock without foliation.

Isochemical: Having no compositional change during a given process.

Mafic: Descriptive term for igneous rocks with high iron and magnesium content.

Metasomatic Here, refers to chemical components moving in and/or out of rocks during metamorphism.

Oxygen isotopes: Oxygen has two stable isotopes, O^{16} and O^{18}; the ratio of the two in a mineral is affected by temperature of formation.

Petrology: The study of rocks and their genesis.

Phenocrysts: Visible crystals in a fine-grained igneous matrix.

Phyllite: A foliated, fine grained, and mineralogically homogenous metamorphic rock.

Polymorph: One of two or more atomic structures of a particular chemical composition, determined by pressure and temperature during crystallization.

Prograde: Referring to changes during increasingly intense metamorphic conditions.

Protolith: Parent rock before metamorphism.

Relict: Mineral, structure, or feature surviving destructive processes.

Schist: A foliated, coarse grained, and mineralogically homogenous metamorphic rock.

Seamount: A rise in the seafloor formed by a submerged extinct volcano.

Tholeiite: A basalt that contains quartz.

Trachyte porphyry: A dominantly fine-grained igneous rock with only potash feldspar crystals (phenocrysts) visible.

Vesiculation: Formation of cavities in igneous rock by bubbling and frothing of rising magma as pressure drops and gases escape.

MINERAL FORMULAS

Actinolite	$Ca_2Fe_5[Si_8O_{22}](OH)_2$	Jadeite	$NaAl[Si_2O_6]$
Aragonite	$CaCO_3$	Laumontite	$Ca[Al_2Si_4O_{12}] \cdot 4H_2O$
Arfvedsonite	$Na_3Mg_2Fe_2Al[Si_8O_{22}](OH)_2$	Lawsonite	$CaAl_2(OH)_2[Si_2O_7]H_2O$
Barroisite	$NaCaMg_3Al_2[Si_7AlO_{22}](OH)_2$	Pumpelleyite	$Ca_4MgAl_5O(OH)_3[Si_2O_7]_2[SiO_4]_2 \cdot 2H_2O$
Epidote	$CaFeAl_2O \cdot OH[Si_2O_7][SiO_4]$	Stilpnomelane	$(K,Na)(Fe_3Mg_3)[Si_8O_{20}](OH)_4(OH)$
Glaucophane	$Na_2Mg_3Al_2[Si_8O_{22}](OH)_2$	Winchite	$NaCaMg_4Al[Si_8O_{22}](OH)_2$

FIELD TRIP GUIDES TO THE AREA

The list of references contains field trip guidebooks that include stops in the Cazadero area. These are Erickson (1978, 1992b) and Liou, Maruyama, Coleman, and Gilbert (1986). The stops are different and each guidebook has information on Ward Creek area geology. Many stops are in roadcuts or other public domain locations, but some are on private land and require the landowner's permission.

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Geology of the Cazadero-Ward Creek Area, Sonoma County, California, scale 1:12,000, is available from the author:

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Appendix II: Cazadero town

The small village of Cazadero is the hub of the surrounding area; the store is an excellent source of resupply for the wandering geologist, as it sells a little of everything.

Cazadero began life in 1869 as a town called Ingrams, named after its founder Silas Ingram. Ingram sold the town in 1888 to George Montgomery, who renamed it Cazadero, supposedly Spanish for "hunting place". In 1886 the North Pacific Coast Railroad extended to Cazadero and the town prospered as a vacation spot, with a number of hotels caring for the visitors. In the 1930's tourist train travel declined with the widespread ownership of the automobile, and the train was abandoned in 1933. In 1941 Berry's sawmill started up in the center of town; the sawmill was moved to the mouth of Austin Creek in 1979, and the center of town has had a big hole in it since then.

Cazadero is famous for having perhaps the wettest weather in California;
It has a Mediterranean climate, wet in winter and dry in summer. Average yearly rainfall is ~ 70" lately; the recent record of 143" (nearly 12'!) was in 1936.

Logging has sustained Cazadero's economy for decades. Life in the woods has a downside, however, in periodic large forest fires that ravage parts of the area. The most recent was the Creighton Ridge fire in 1978, which burned 12,000 acres, including the area of Stop 3. Here and there along the roads in the area you will notice on power poles shiny metal pots circa 1' in diameter; these are fire sirens installed after the fire.
(much of this information is taken from a local Cazadero website, whose address is: http://oredezac.tripod.com. The name oredezac comes from a local monument called the Oredezac Oracle; if you know where it is then you know Cazadero well!

Appendix III: Abstracts of recent work in the Cazadero area by Sonoma State University Geology students and faculty

Trace element geochemistry of the Ward Creek metamorphic sequence and Big Oat Creek Metabasalt, Cazadero, CA, ***Swanson, Nathan*** (Sonoma State University, Geology, Rohnert Park, CA, United States); Erickson, Rolfe C., Plummer, Erica In: Abstracts with Programs - Geological Society of America, April 2004, Vol. 36, Issue 4, pp.39 Published by: Geological Society of America (GSA) : Boulder, CO, United States.

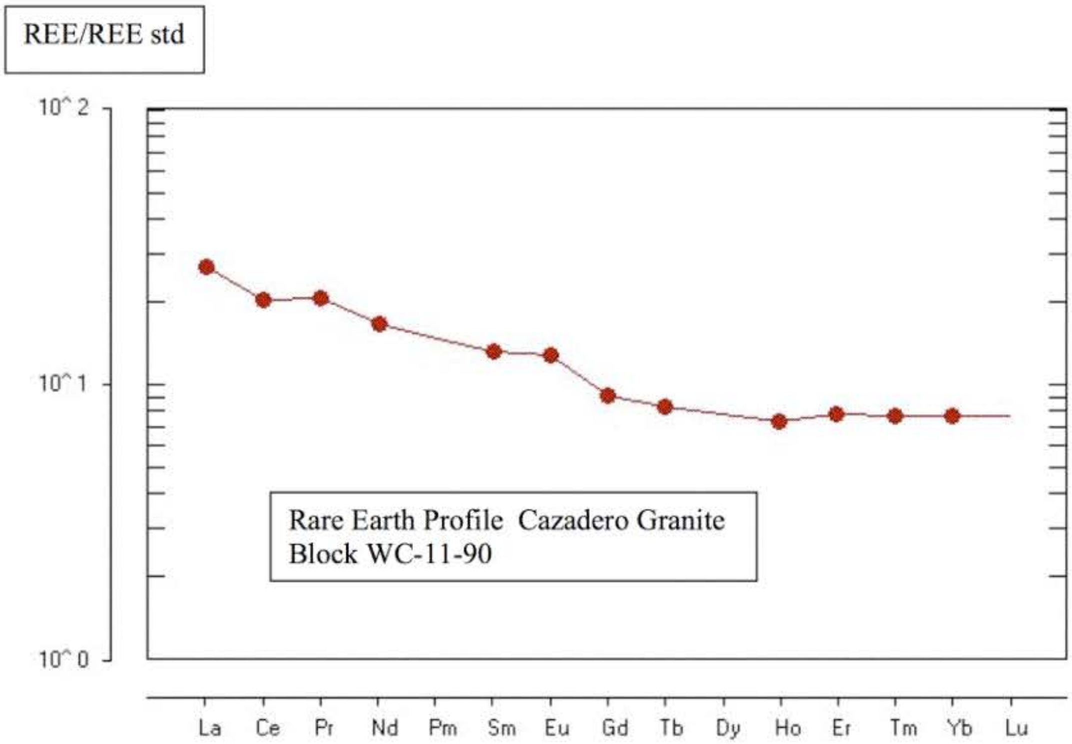
Abstract: One of the most intensely studied metamorphic complexes in the world is exposed in Ward Creek, Sonoma County, California (Erickson, 1995). The Ward Creek (WC) metamorphic sequence is composed primarily of glaucophane and sodic pyroxene blueschist metabasalt with aragonite stringers, and abundant metachert. Protolith textures have been completely obliterated. In contrast, Big Oat Creek (BOC) metabasalts adjacent to the WC sequence across an unexposed contact have green flattened relict pillows with blue glaucophane margins. BOC metabasalts have interpillow aragonite and no metachert. Aragonite in WC and BOC is from pre-metamorphism interpillow pelagic carbonate, suggesting a pillowed WC protolith. Three samples from the WC sequence and two samples from the BOC sequence were analyzed for major and trace elements. WC REE diagrams show N-MORB patterns with a weak positive Eu anomaly. WC samples show enrichment in water soluble elements (Sr, K, Rb, Ba) and deficiencies in Ta, Nb, and Ti on spidergrams (Pearce, 1983), indicating an arc origin. Ti-V plots (Shervais, 1982) place WC samples in the N-MORB field and Cr-Y plots (Pearce et al, 1981) place them within the SSZ-MORB boundary. WC samples plot in the supra-subduction zone (SSZ) field on a Ta-Th-Hf diagram (Wood, 1980) and in the MORB field on a [Zr-Y]-Zr diagram (Pearce, 1983). The BOC sample nearest WC has a similar REE plot and Pearce spidergram to the WC samples, though 1.5X enriched. It also plots MORB on a [Zr-Y]-Zr diagram. The second, more distant BOC sample is, alternatively, enriched in LREE (La/Sm=1.9) and its Pearce spidergram shows an OIB signature. Both BOC samples plot separately from WC on Ti-V and Cr-Y graphs. Contrasting outcrop textures in BOC and WC and absence of metachert in BOC also suggest separate units. All evidence suggests for WC an N-MORB source modified by water soluble elements from the subducting plate in an SSZ environment. Part of BOC has the same type of source as WC, but part has an OIB source.

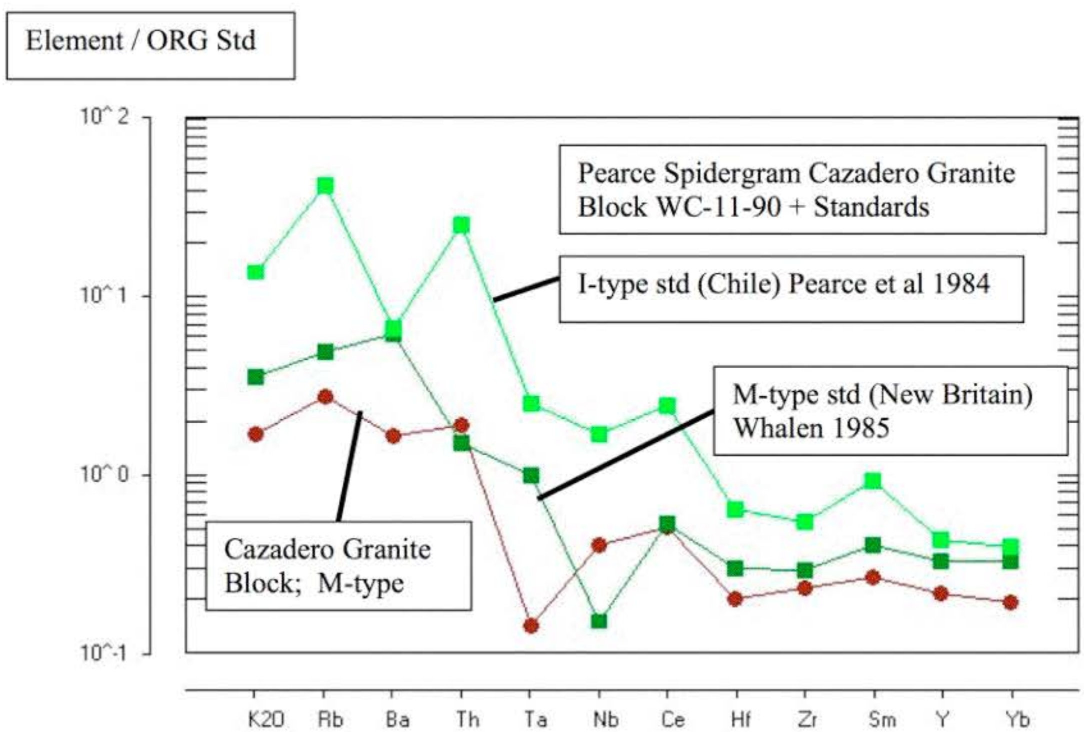
Petrology of a brecciated glaucophane-lawsonite meta-arc basalt block, Franciscan Complex, Sonoma County, CA, Pearce, L. Sara (Sonoma State University, Department of Geology, Rohnert Park, CA, United States); Erickson, Rolfe C. In: Abstracts with Programs - Geological Society of America, April 2001, Vol. 33, Issue 3, pp.47 Published by: Geological Society of America (GSA) : Boulder, CO, United States. Abstract: The block is an albite - Kspar - aragonite - chlorite - jadeitic pyroxene - lawsonite - glaucophane fels ***breccia***. Aragonite is only present in sparse veins. The ***breccia*** is composed of fragments of coarse-grained glaucophane - lawsonite fels in a recrystallized fine-grained glaucophane - lawsonite fels matrix. A late dike, now metamorphosed to a fine-grained chlorite - lawsonite fels, cuts the block. Aragonite, glaucophane and albite were stable at maximum prograde conditions, circa 300 degrees C and 7 + or - 1 kb, based on Figure 6 of Evans (1990). The alumina in glaucophane geobarometer gives a minimum pressure of 7.8 kb and the chlorite geothermometer used on chlorite in the dike gives a temperature of 275 degrees C. Jadeitic clinopyroxene was forming from glaucophane and lawsonite in the coarse-grained fragments. Veins of retrograde pumpelleyite are present. The gas phase had very low X (sub CO2) . Later, in an olistostrome, the block went to <3 kb pressure and <300 degrees C, forming laumontite veins in the matrix. The protolith was a basaltic andesite (52.4% SiO (sub 2)) of probable continental arc origin. A REE profile matches NMORB while a Pearce spidergram has arc-typical low Ta - Nb anomaly and high K, Rb, and Ba peaks, modified by low Ce, Sm,and Yb values. ***Brecciation*** and recrystallization of the primary fels occurred at approximately 7 kb pressure in a single event, by hydrofracturing caused by water escaping the recrystallizing subducting plate. Our model is that (1) a subducting oceanic (Farallon?) plate released water into a wedge of depleted mantle forming the protolith basaltic andesite magma, which erupted in a continental arc, probably the ancestral Sierras; (2) a portion of a flow was carried into the trench and subducted to approximately 7.5 kb pressure; (3) the protolith was metamorphosed to glaucophane - lawsonite fels, ***brecciated*** by hydrofracturing, and recrystallized; (4) the block of metabreccia was transported to the surface, perhaps by a diapir; (5) the block was deposited in an olistostrome; (6) the olistostrome was subducted to < 3 kb pressure and <300 degrees C, forming laumontite veins.

Petrology, isotope geochemistry, and geochronology of a multiply metamorphosed granitoid exotic block in a Franciscan olistostrome melange, Cazadero, California, Erickson, Rolfe C. (Sonoma State University, Geology, Rohnert Park, CA, United States); Mattinson, Jim, Dumitru, Trevor A., Sharp, Warren In: Abstracts with Programs - Geological Society of America, April 2004, Vol. 36, Issue 4, pp.39 Published by: Geological Society of America (GSA) : Boulder, CO, United States. Abstract: The block protolith was an M-type biotite-hornblende quartz diorite pluton. Igneous crystallization and cooling is dated by U/Pb on zircon at 165+ or -1 Ma, by Ar40/Ar39 on relict magnesiohornblende at 162+ or -2 Ma, and by U/Pb on apatite at 160+ or -1 Ma. Amphibole Pb206/204=18.66 and Pb207/Pb204=15.62, which plots with arcs. Apatite Sr87/Sr86=0.703537+ or -20; apatite Sm147/Nd144=0.130 and Nd143/Nd144=0.512904+ or -7; epsilon Nd is +6.6, and epsilon Sr is -13.8. On an epsilon diagram the pluton plots with primitive oceanic arcs like the Marianas. The pluton was subducted at <160Ma and partially metamorphosed to a ferrorichterite-albite-clinochlore fels at unknown T and 4+ or -1 kb. It cooled (<200 degrees C) and was fragmented by many thin breccia veins, which then recrystallized. Metamorphism occurred a second time, forming abundant pumpelleyite and chlorite at approximately 250+ or -50 degrees C and 5+ or -2 kb. A approximately 100m block of this metamorphite was then transported to the surface and incorporated into the Kings Ridge Road olistostrome melange (Erickson, 1995) by approximately 147+ or -3 Ma (Tithonian). The melange was next weakly subducted, and a third metamorphism at approximately 250+ or -50 degrees C and 2+ or -1 kb produced abundant laumontite veins in its sandstone matrix. Metamorphism ended by 135+ or -3 Ma (Valanginian); local faulting ended by 103 Ma. Block apatite yielded a poor quality fission track age of 36+ or -11 Ma. Block sandstone matrix yielded high-quality apatite fission track ages of 36+ or -2 and 38+ or -2 Ma with slow-cooling track length distributions. These data suggest that the melange and block were exhumed to the surface over a protracted period, cooling below approximately 100 degrees C in early Tertiary time. Block location is UTM 10 S 0488568E 4262693N NAD 27 datum.

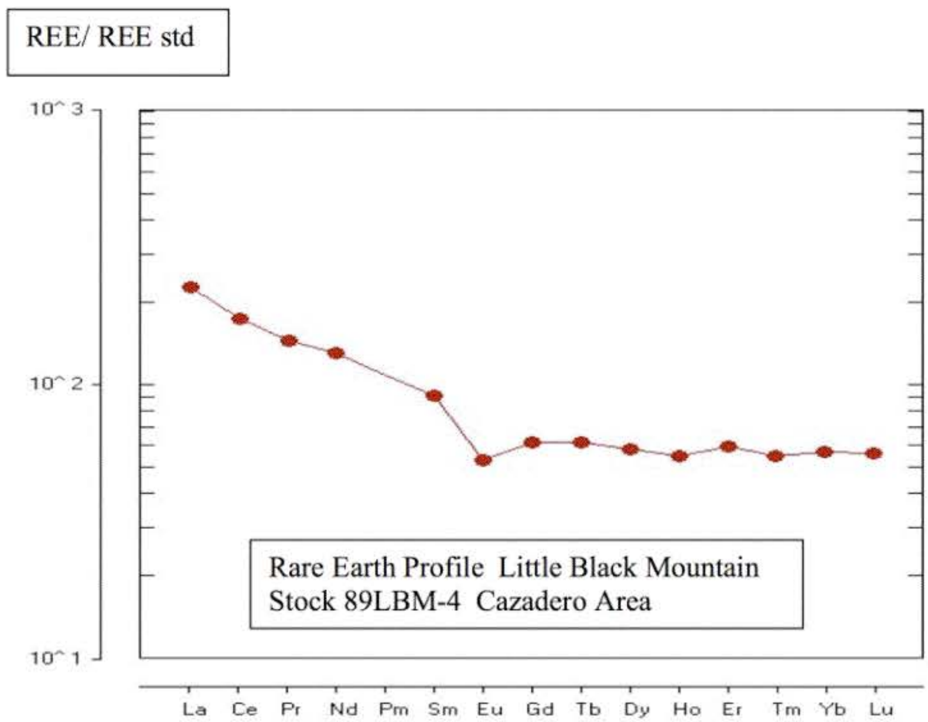
Appendix IV:

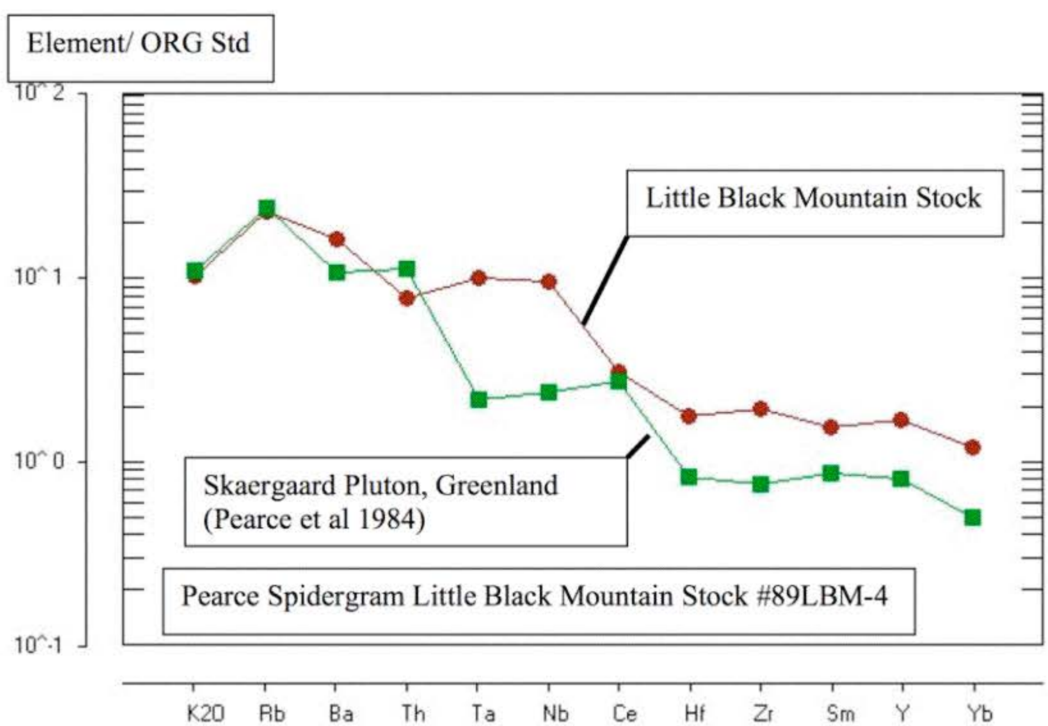
Rare Earth Profile Diagrams and Pearce Spidergrams for the Units Discussed



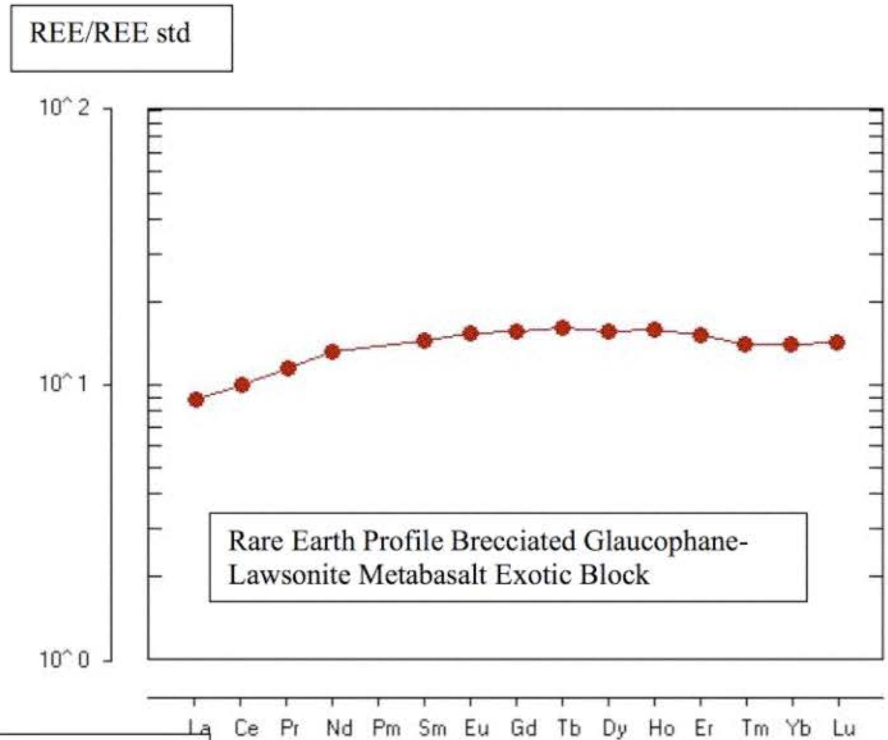


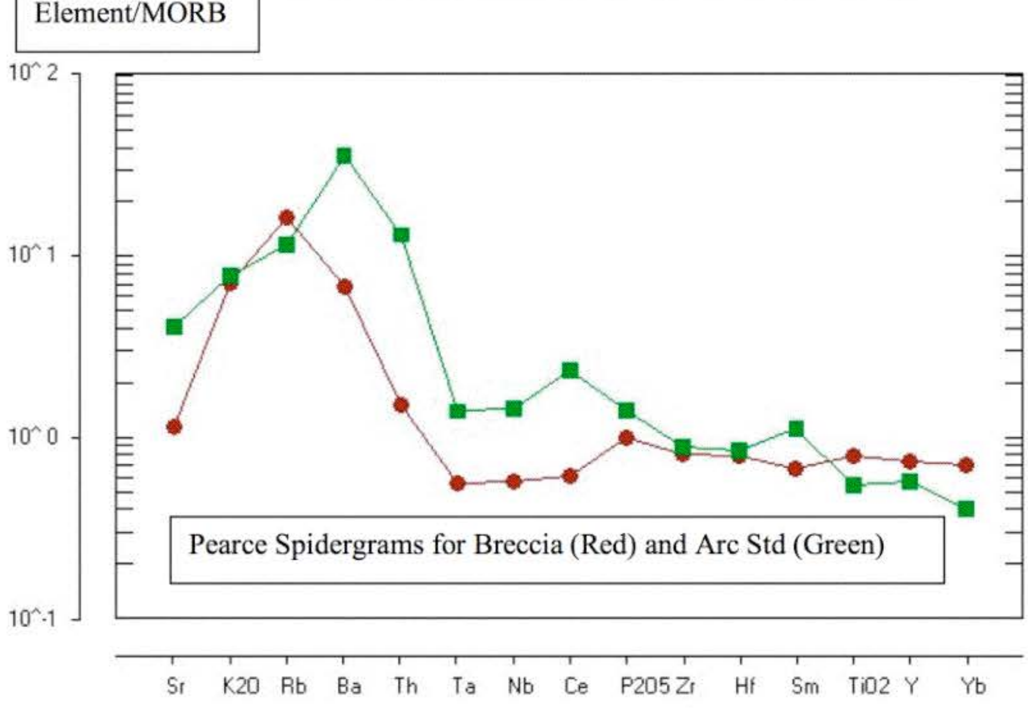
A. Geochemical Diagrams for the Cazadero Granite Exotic Block



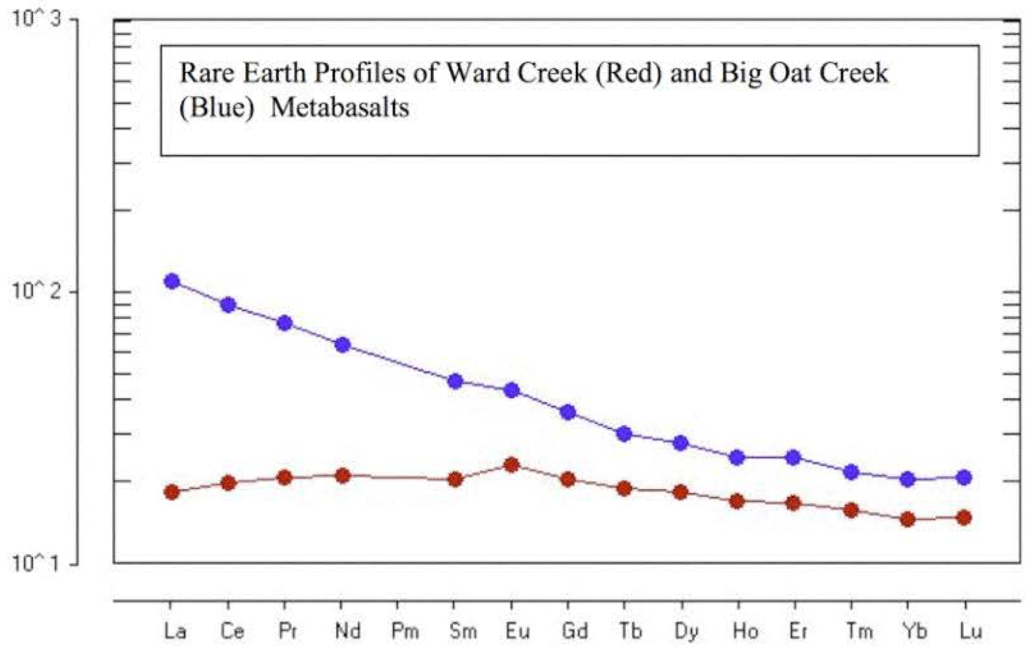


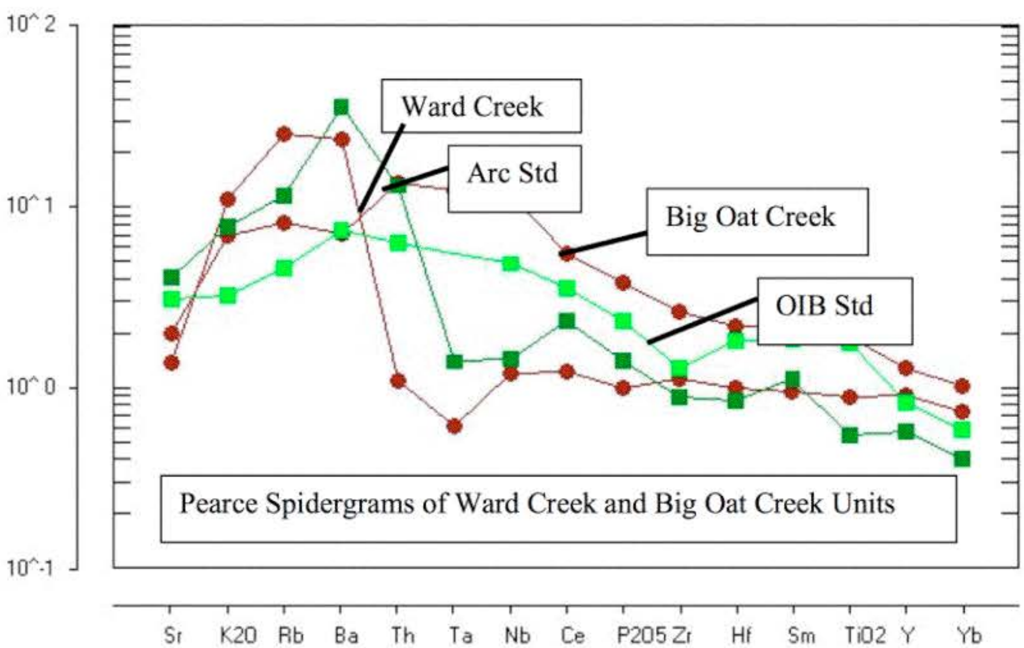
B. Geochemical Diagrams for the Little Black Mountain Stock





C. Geochemical Diagrams for Brecciated Glaucophane-Lawsonite Fels Exotic Block





D. Geochemical Diagrams for the Ward Creek - Big Oat Creek Area

Appendix V: Unpublished Chemical Data on Units Discussed

sample element	SiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI
Quartz diorite WC-11-90	60.15	16.67	2.51	4.16	0.13	2.74	3.65	6.58	0.67	0.567	0.21	2.32
LBM Rhy 89LBM-4	69	14.7	3.5		0.13	0.53	0.47	6.81	4.12	0.27	0.01	0.54
Sarah Breccia SPCA 2962	52.38	13.41	11.79		0.148	7.45	3.73	5.06	1.06	1.17	0.12	3.88
Nathan Ward Creek EP-02-1-WC	47.06	14.89	9.71		0.18	8.2	10.78	2.05	1.64	1.33	0.12	4.11
Nathan Big Oat Creek EP-02-1-PB©	44.75	17.38	11.71		0.19	5.44	7.91	3.47	1.04	2.84	0.46	5.28

Note: FeO in WC-11-90 determined by titration

sample element	Ba	Sr	Y	Zr	Rb	Nb	Ta	Th	Hf	La	Ce	Pr
Quartz diorite WC-11-90	82	72	15	78	11	4	0.1	1.51	1.8	8.87	17.9	2.31
LBM Rhy 89LBM-4	811	43	119	660	92	96	7	6.3	16	54.1	107	13.7
Sarah Breccia SPCA 2962	137	136	22	73	33	2	0.1	0.3	1.9	2.1	6.1	1.09
Nathan Ward Creek EP-02-1-WC	480	164	27.42	101.06	50.95	4.22	0.11	0.22	2.4	4.36	12.14	1.95
Nathan Big Oat Creek EP-02-1-PB©	144	241	38.83	235	16.41	41.43	2.22	2.74	5.27	26.12	55.23	7.26

sample element	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Quartz diorite WC-11-90	10	2.38	0.882	2.27	0.39	2.43	0.51	1.56	0.23	1.54 -	
LBM Rhy 89LBM-4	61.1	13.9	3.07	12.6	2.3	14.7	3.11	9.8	1.4	9.6	1.42
Sarah Breccia SPCA 2962	6.2	2.2	0.9	3.2	0.6	4	0.9	2.5	0.36	2.4	0.36
Nathan Ward Creek EP-02-1-WC	9.79	3.13	1.33	4.19	0.71	4.66	0.96	2.75	0.4	2.48	0.372
Nathan Big Oat Creek EP-02-1-PB©	30.03	7.12	2.51	7.45	1.12	7.08	1.38	4.06	0.55	3.44	0.526

Note: Data on Standards from Pearce (1983), Pearce et al (1984), and Wilson (1989)