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

ROLFE C. ERICKSON
Sonoma State University Geology Department
Rohnert Park, California

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.

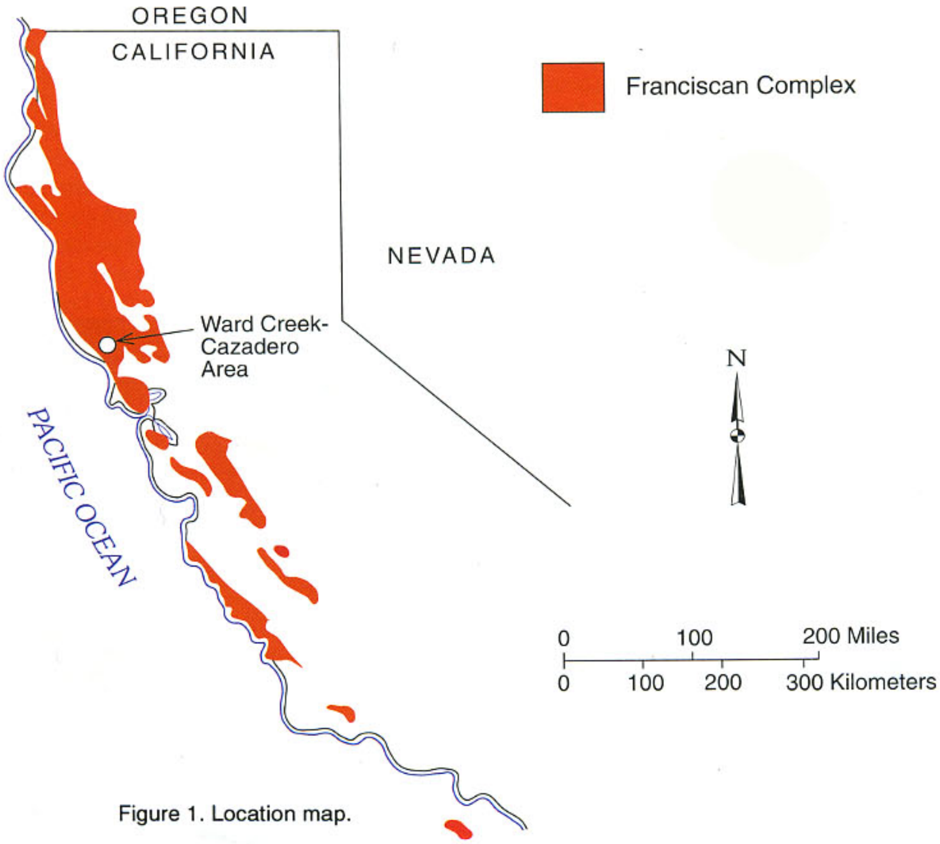

Figure 1. Location map.

(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**

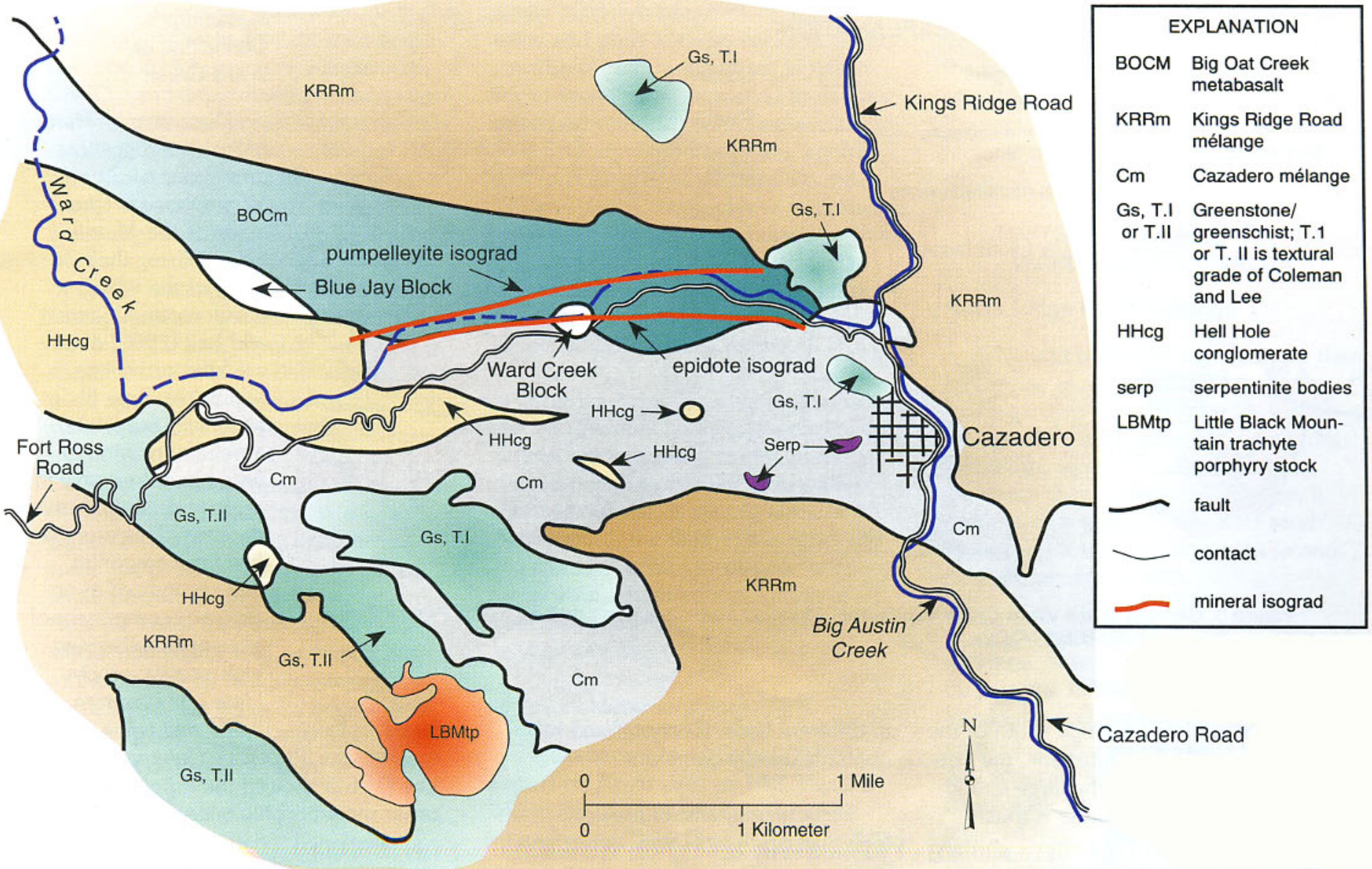

Figure 2. Geology of the Franciscan Complex surrounding the Ward Creek locality. *Isograds from Maruyama and Liou, 1988, Figure 2.*

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

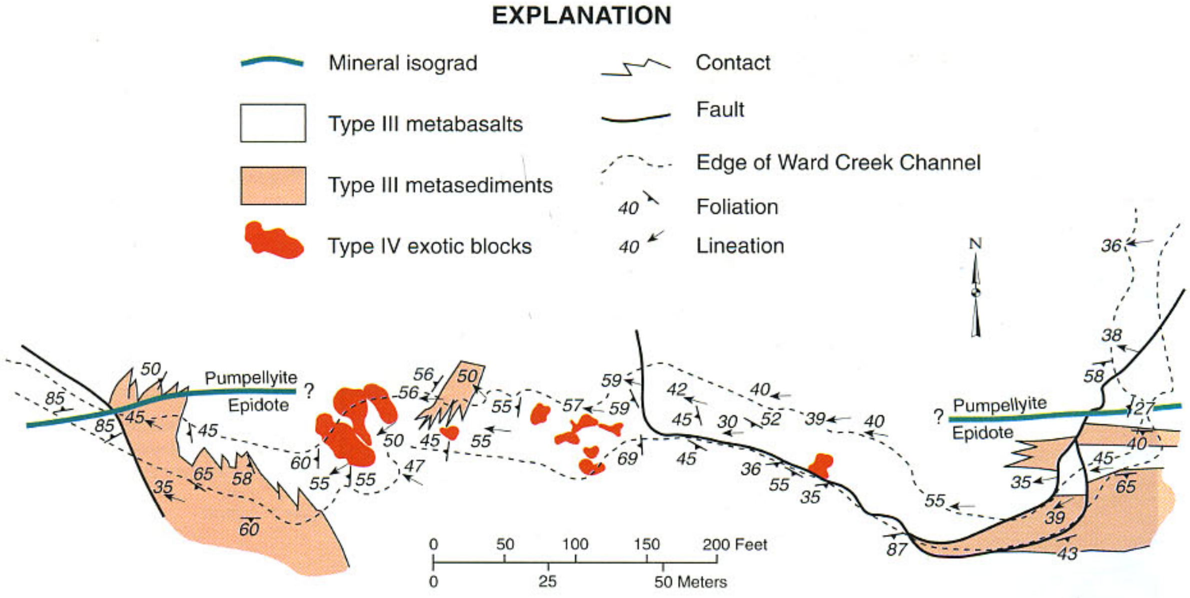

Figure 3. Geology of the Ward Creek exposures. *Modified from Coleman and Lee, 1963, Figure 2, and Maruyama and Liou, 1988, Figure 2.*

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.

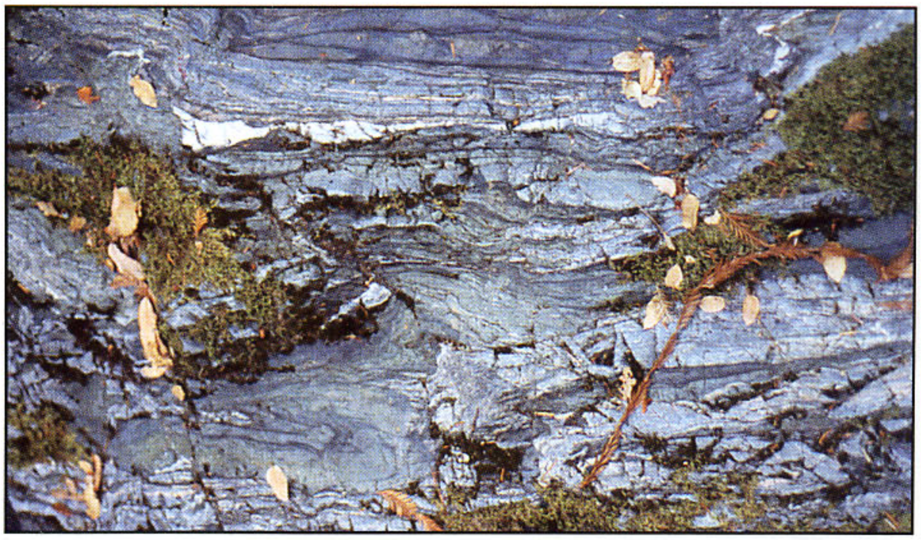

Photo 2. Metachert in Ward Creek.

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.

Note: this picture was left out of the original printing by mistake. This picture is correct—! R.

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 metamorphism: 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	$Ca[Al_2Si_40_{12}]\cdot 4H_2O$
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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Rolfe Erickson teaches petrology, geochemistry, field studies, and computer applications in Sonoma State University's geology department. He does research in the Franciscan Complex, in intrusive volcanic breccias, and on the stratigraphy and metamorphic conditions in the Precambrian of Arizona. His hobbies are playing the banjo and the stock market.

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

Rolfe Erickson
Geology Department
Sonoma State University
1801 East Cotati Avenue
Rohnert Park, CA 94928
(707) 664-2334