Geology

Key to understanding all of the McLaughlin Reserve's natural features is its rich and complex geology. The reserve captures much of the geological diversity of the California Coast Ranges, which are internationally famous for spectacular exposures of rocks deposited or modied by plate tectonic processes over the past 140 million years. In this chapter we begin by describing the geologic history of the Coast Ranges in the vicinity of the reserve. We then describe some of the reserve's most important and easily seen physical features: the serpentine and related rocks of the Coast Range Ophiolite, the sedimentary strata of the Great Valley Sequence, the Clear Lake Volcanics and other features formed by recent faulting and volcanism, and finally the soils formed from these diverse parent materials.

Geology has been well studied at McLaughlin because of the reserve's unusual history as a mine, and a good summary of this technical work can be found in the volume edited by J. J. Rytuba (1993) in the *Guidebook Series of the Society of Economic Geologists*. Accounts of Coast Range geology for non-specialists can be found in *Assembling California* by John MacPhee (1993), *California Geology* by Deborah Harden (1999), and *Roadside Geology of Northern andCentral California* by D. D. Alt and D. W. Hyndman (2000). Our description of the reserve's geologic history owes much to eld trip lectures by Dean Enderlin (Senior Environmental Engineer, Homestake Mining Company). Our geologic map, Map 2, comes from the 1982 D'Appolonia report, revised somewhat to reflect updated information, but still much in need of improvement. Important resources for future studies include an extensive collection of rocks and minerals from the mine pit, now located in the UC Davis Geology Department, and the exploration drill core, presently housed in the Core Shed at the reserve.

Geologic History

Plate Convergence and Subduction

The geologic history of the reserve begins with the series of plate convergence and subduction events that added California to the western edge of North America. The formation and movement of the earth's lithospheric plates begins at mid-ocean spreading centers, where hot partially molten rock rises from the Earth's interior and partially extrudes to form new lithosphere (oceanic crust and upper mantle). As the molten rock crystallizes at these spreading centers, it forms an ordered series of rocks that include peridotite (which may later metamorphose to serpentinite), gabbro, and basalt. This series is collectively known as an ophiolite. As this new lithosphere forms, older crust migrates away from the spreading centers, and this movement inevitably leads to the convergence of separate lithospheric plates. Subduction is the disappearance of one plate beneath another during convergence.

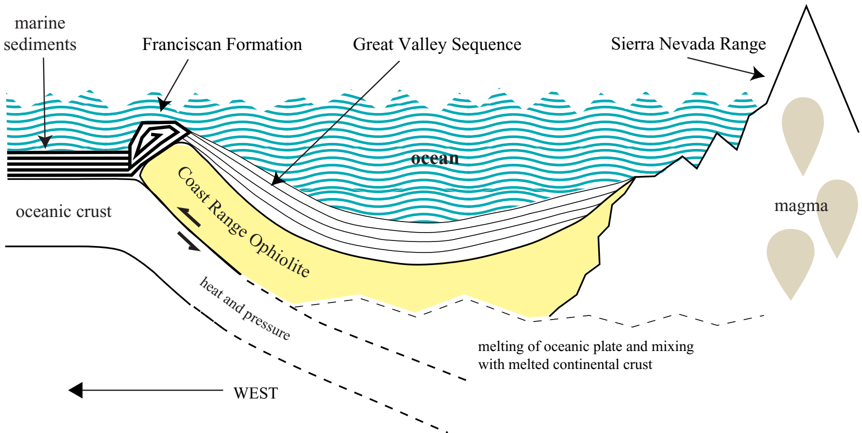

Figure 3-1. Subduction of the Farllon Plate beneath the North American continental margin, 140-100 million years ago.

One continent-building convergence of plates occurred in the late Jurassic and Cretaceous periods (about 140 to 100 million years ago), when the oceanic Farallon plate, coming from the west, subducted beneath the North American continental margin (see Figure 3-1). This process was instrumental in creating both the Coast Ranges and the Sierra Nevada. As the Farallon plate descended beneath the North American continent, hot uids derived from the downgoing plate caused melting in the overriding continental plate, producing a chain of volcanoes on the continent that were very similar to the present-day Cascade volcanoes. The molten rock remaining beneath the earth cooled to become the Sierra Nevada Batholith, the characteristic black and white granitic rock of that mountain range.

Sediments derived from the ancient Sierra Nevada settled in the ocean basin just beyond the edge of the continent, and became the Great Valley Sequence that forms much of California's eastern (inner) Coast Range. The material on the downgoing Farallon plate, mostly marine sediments, were scraped off against the leading edge of the continental plate to create a complex of diverse rocks known as the "Franciscan melange" or complex. The Franciscan melange makes up most of the western (outer) Coast Range. Unlike the orderly strata of the Great Valley Sequence, the Franciscan complex became so badly deformed that it contains little decipherable structure and few fossils.

The Coast Range Ophiolite lies between the Great Valley and Franciscan rocks, and represents the oceanic crust on which the Great Valley sediments were deposited; it was later pushed to the surface in the fault zone between the two former plates. The Coast Range Ophiolite consists largely of serpentinite, partly serpentinized peridotite, gabbro, and basalt.

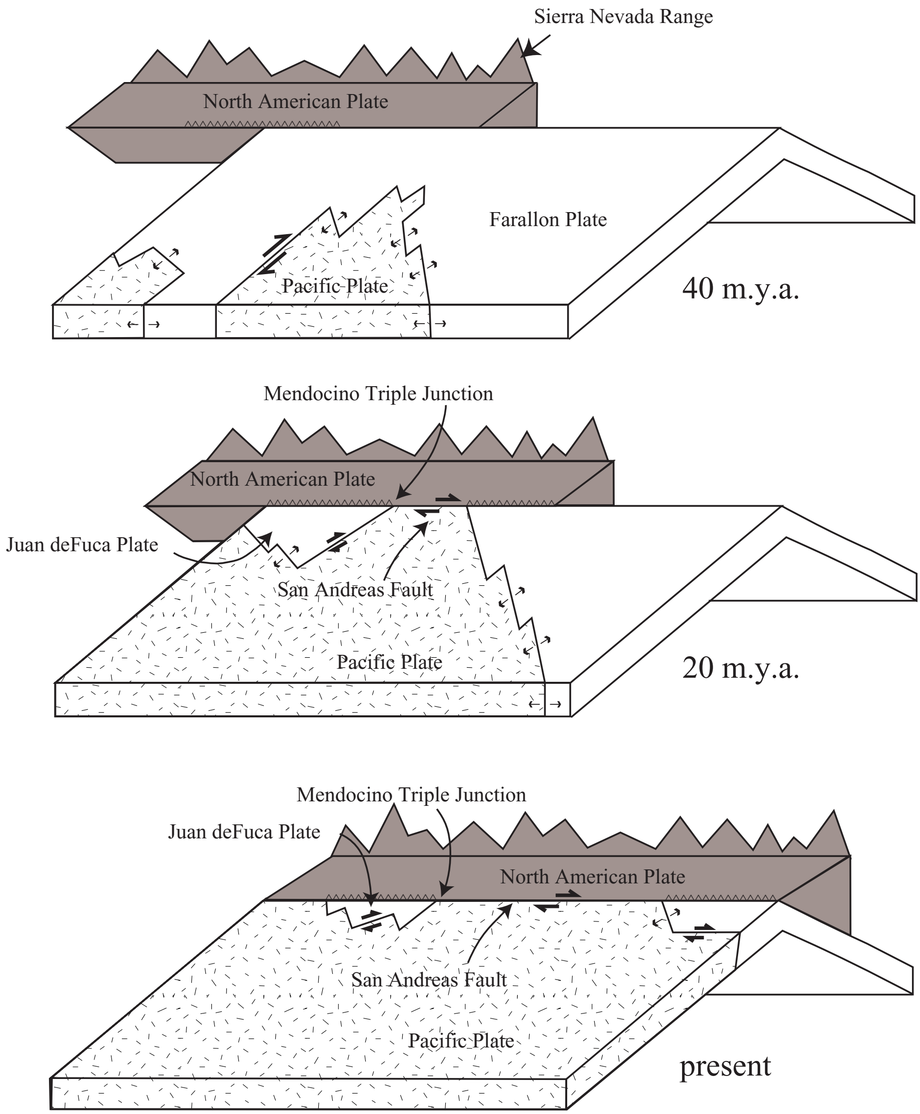

Figure 3-2. Collision of the Eastern Pacific Rise and the subduction zone and formation of the Mendocino Triple Junction, 40 - 20 million years ago.

Transform Movement on the San Andreas Fault System

About 30 million years ago, the spreading center behind the Farallon plate (the East Pacic Rise) collided with the subduction zone (Figure 3-2). This brought the Pacic plate, west of the Farallon plate, into contact with the North American plate.

In turn, this created the Mendocino triple junction, the meeting point of the Pacic, North American, and Juan de Fuca (a remnant of the Farallon) plates. North of the Mendocino triple junction, subduction continues, and as the Juan de Fuca plate disappears, the triple junction moves northwest along the continental margin like a closing zipper. As it does so, the direction of relative plate movement along the western edge of the continent changed, with the Pacic plate moving northwest relative to the North American plate in transform or strike-slip movement. This movement takes place along the formerly convergent plate boundary, which became the San Andreas Fault system that is so familiar to residents of California.

This change from convergent to transform plate motion caused the uplift of the Coast Ranges, which began about 5 million years ago at the latitude of the McLaughlin Reserve and still continues today. As the Pacific plate slides past the North American plate, localized centers of compression and extension develop at the jagged edges of former plate boundaries. Extension centers, or pull-apart basins, became the elongated northwest-southeast valleys of the Coast Ranges, and in places these also became the centers of volcanic activity (e.g. Clear Lake Volcanics, Sonoma Volcanics). Compression centers are characterized by reverse or thrust faulting and associated folding. Such faulting and folding (deformation) uplifted the Great Valley and Franciscan rocks, and brought the oceanic crustal rocks of the Coast Range Ophiolite to the surface.

The Stony Creek Fault crosses the McLaughlin Reserve from northwest to southeast, passing through the McLaughlin mine pit and Knoxville, and separating the Great Valley Sequence from the Coast Range Ophiolite. Several miles to the west, the Coast Range Fault separates the Coast Range Ophiolite from the Franciscan melange. The Stony Creek Fault may have originated as a north-trending thrust fault along which Great Valley rocks were thrust eastward over the Coast Range ophiolite during early Cretaceous time (100-140 million years ago). In the reserve area, this fault was folded subsequently and is now active as a part of the San Andreas fault system. The Stony Creek fault is described as an oblique strike-slip fault with components of normal and reverse slip. The complex tectonics of this region are still poorly understood and have been the subject of several research projects in the UC Davis Geology Department (e.g. Unruh et al. 1995, Unruh and Moores 1992).

Volcanic and Hydrothermal Activity

Roughly 2 million to 10,000 years ago, volcanic activity occurred in a region extending from Lake Berryessa to Clear Lake, known as the Clear Lake volcanic field. This Quaternary volcanism has tracked the northwestward movement of the Mendocino triple junction, and may be related to the shift from plate convergence to transform faulting. Rytuba (1993) argues that the volcanism resulted from molten mantle material moving into open portions of the earth’s crust (“slab windows”) that had been occupied by the previously subducting Farallon plate. Around the area of the reserve, volcanic activity occurred about 2 million years ago.

Another result of the shift to transform movement along the Stony Creek Fault was the creation of hydrothermal systems. Volcanic vents and dikes opened up along the fault, providing passage for flows of molten rock and geothermal waters, leading in turn to mineral deposits. The very wet Pleistocene climate, about 1 million years ago, may have helped give rise to this hydrothermal activity. During the Pleistocene era, Morgan Valley is believed to have been a lake.

Fluids moving in the hydrothermal system along the Stony Creek Fault, about 1 million years ago, included gold-depositing, mercury-depositing, and "barren" water that deposited neither gold nor mercury. These fluids may have been from different sources, or the mercury-depositing and "barren" waters may have been diluted and cooler forms of the gold-depositing waters. In either case, it is agreed that much of the gold-depositing water was Cretaceous seawater trapped in the Great Valley sediments. These waters are isotopically heavy and contain high concentrations of petroleum, carbon dioxide, gold, mercury, antimony, and arsenic.

The hydrothermal waters deposited gold in the veins of opal, chalcedony, and quartz that were created during the silica-carbonate serpentine alteration process. The highest concentrations of gold typically occurred in amber-colored (petroleum-bearing) opal veins, sometimes occurring as very fine, dendritic (branching) veins of gold. Most of the gold occurred as microscopic grains, and were much less spectacular than the coarse-grained gold that was mined from quartz veins in the Sierra Nevada foothills. Homestake's McLaughlin mine remains the only attempt to exploit the low-concentration hydrothermal gold deposits of the Coast Range.

Geologic Features of the McLaughlin Reserve

Serpentinite and related rocks

Serpentinite, commonly called serpentine, is rock composed of minerals from the serpentine mineral group (lizardite, chrysotile and antigorite). These three minerals are hydrated magnesian silicates that differ only in the spatial arrangements of their component ions. Relative to most rocks of the continental crust, serpentinite is rich in magnesium and iron, sometimes rich in nickel, cobalt and chromium, and poor in calcium, silica, potassium and sodium. Serpentinite forms when peridotite comes into contact with seawater or groundwater at low pressures and temperatures (< 500°C). This process of hydration, called serpentinization, probably occurred at varying times and places: in the ocean, during subduction, and perhaps even under modern-day conditions.

Antigorite and lizardite, both lamellar (sheeted) minerals, are the most common forms of serpentine in the reserve. They appear waxy and shiny green when freshly exposed. Peridotites that are only partly serpentinized weather to red or brown at the surface, and tend to occur in more massive outcrops compared to the scaly serpentinites.

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Another form of serpentine found in minor amounts is chrysotile, an asbestos mineral with a fibrous, silky appearance. Freshly exposed serpentine is visible in recent road cuts, such as along Morgan Valley Road in the south part of the reserve, and on the north and west sides of Research Hill.

Outcrops of serpentine characteristically display seeps and springs. Where alkali springs occur on serpentine, the rocks may become coated during summer with white precipitates of magnesium sulfate (epsom) left behind as the spring water evaporates. Stream drainages commonly follow the edges of serpentine blocks, which may correspond to faults and are weak and easily eroded.

Detrital serpentine is an unusual form that occurs as lenses of broken rock, interlayered with Great Valley sediments and lying slightly farther east than "normal" (massive) serpentine. Little Blue Ridge, at the north end of Davis Creek Reservoir, is an example of detrital serpentine. Probably because of its structural instability, it tends to support less chaparral and more open grassland than normal serpentine. The origins of detrital serpentine are not fully understood, but it may be derived from cold submarine "volcanoes" that rose to the ocean floor as serpentinization caused the rock to expand.

Gabbro is a dark coarse-grained rock that weathers to a bright-red soil. It is a part of the Coast Range Ophiolite, where it typically overlies the serpentine. Geologic maps, including those of the reserve, generally do not distinguish gabbro from serpentine. However, gabbro is more calcium-rich than serpentine, and patches of gabbro may be identified from a distance by the nearly pure stands of chamise (*Adenostoma fasciculatum*), a shrub that is not abundant on serpentine. A good place to see such a gabbro exposure is at the southwestern end of Research Hill.

Greenstone is basalt that has been slightly metamorphosed under low temperature and pressure. Where it is present in the Coast Range Ophiolite, it overlies the serpentinite and gabbro. It is more resistant to erosion than serpentine, and forms knobby brown boulders that protrude from the serpentine landscape. Greenstone is also more calcium-rich than serpentine, and buckeye (*Aesculus californica*) trees may be strikingly apparent at the bases of greenstone boulders. Good places to see greenstone outcrops are at the southwest end of Research Hill, and along Morgan Valley Road and Hunting Creek canyon, just south of the Napa-Lake county line.

Silica-carbonate rock is a distinctive feature along structures such as the Stony Creek Fault where serpentine has been hydrothermally altered. Soft serpentine is replaced with hard fine grained silica (quartz and opal) and carbonate minerals. Subsequent erosion leaves these rocks exposed high above the surrounding landscape. The dramatic buttes west of Davis Creek Reservoir ("the pinnacles") are an example of these "frozen hot springs." At the base of these buttes is a tunnel dug by mercury prospectors. Silica-carbonate rock is often associated with cinnabar, or mercury ore, which is likewise deposited by geothermal action. At Knoxville, the silica-carbonate outcrop was almost completely removed by mercury mining.

Sedimentary Rocks

The Great Valley Sequence consists of numerous well-stratified marine sedimentary units, including mudstone, siltstone, sandstone, shale, and conglomerates, that have been extensively faulted, tilted and folded. The McLaughlin Reserve primarily contains the two oldest and westernmost formations in the Great Valley Sequence, the Knoxville formation (Jurassic) and the Crack Canyon formation (Cretaceous). (Our geologic map distinguishes the Knoxville formation, but lumps the Crack Canyon formation together with other Cretaceous members of the Great Valley Sequence.) Because of the tilting of these rocks as the Coast Ranges were uplifted, the younger, more recently deposited units are found to the east of older ones. Traveling east along the Reiff-Rayhouse road from the Davis Creek Reservoir toward Cache Creek provides a cross-section through successively younger formations of the Great Valley Sequence.

The Knoxville formation consists largely of mudstones that weather to a soil high in silt content, and that typically support oak woodland and grassland. The Crack Canyon formation consists largely of sandstones that weather to well-drained soils supporting chaparral. Knife-sharp boundaries often separate these two sedimentary formations and the plant communities they host. One excellent place to examine such a boundary is on the dirt road between Knoxville and Clover Valley, just east of the Putah-Cache watershed divide.

Volcanic features

The Clear Lake volcanic activity about 2 million years ago produced a series of rocky hilltops composed of andesite, an igneous rock that weathers to a reddish color, roughly following the line of the Stony Creek Fault. Grizzly Peak, north of the tailings pond, is one of these volcanic exposures. Another one was found at the present location of the McLaughlin mine pit, and remaining parts of it can be seen in the pit wall and in a roadcut along the ridge just north of the pit. Chunks of volcanic rock are often found mixed with serpentine and other rocks in the cobbles along Hunting Creek, and are distinctive for being red on the surface and coal-black inside.

Travertine terraces, or white deposits of calcium carbonate left by alkaline streams emanating from hot springs, are visible on the hillside above the Berryessa-Knoxville Road between Knoxville and the Homestake mine. These were produced by the geothermal system that created the gold deposit. The gold and mercury mines themselves are, of course, the most conspicuous features related to the volcanic era. Several small geothermal springs are still active near the Knoxville and Harrison mines and in the bottom of the open pit lake at the McLaughlin mine. They give off a sulfurous smell that can sometimes be detected when the air is still in winter.

Soils

Most of the soils formed from serpentine parent materials at the reserve are mapped as the Henneke soil series, with smaller amounts of the Montara and Okiota series.

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These are shallow (<50 cm) residual soils with loamy to clayey textures, poor horizon development, and a high gravel and rock fragment content. Henneke soils usually support chaparral, while Montara and Okiota soils may support grassland. Around Little Blue Ridge there are also Climara clays, which are deeper (> 100 cm) colluvial soils formed from a mixture of serpentinic and sedimentary materials. Along both branches of upper Hunting Creek are deeper deposits of serpentine alluvium, known as Todos loams.

The nonserpentine soils in the reserve are loams and clay loams formed from Great Valley Sequence parent materials such as sandstone, shale, and greywacke (Franciscan Metamorphic Sandstone), mixed in some cases with volcanic material. Shallow residual soils (< 50 cm), generally found on steep slopes, include the Maymen, Millsholm and Lodo series. Moderately deep soils (50-100 cm) include the Bressa, Dibble, Hopland and Skyhigh series. Deep soils (>100 cm) include Diablo clays, which are upland residual soils, and the Yolo and Kilaga series, which are alluvial loams.

Soil series at the reserve were mapped by the D'Appolonia Company in 1982, using information from the United States Soil Conservation Service (now the Natural Resources Conservation Service). Our map, Map 3, is based on theirs, but has been simplified by combining some closely similar series. The soils of the reserve have been little studied since the D'Appolonia report was compiled.