Geology of Ring Mountain and Tiburon Peninsula, Marin County, California

By

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Table of Contents

Plate

Figures

Tables

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Abstract

Detailed Geologic mapping and petrographic analyses reveal that Ring Mountain and the adjoining northwest-trending Tiburon Peninsula are underlain by four distinct structural units separated by low-angle faults. The structurally highest unit consists of partially serpentinized peridotite (harzburgite), a possible remnant of the Coast Range Ophiolite. The underlying unit is a fault-bounded, structurally thin serpentine-matrix mélange unit herein referred to as the Ring Mountain serpentinite-matrix mélange. The mélange matrix, composed mainly of lizardite-serpentinite, with minor chrysotile and talc, has a pervasive shear-fracture fabric characterized by anastomosing shear-fracture surfaces enclosing small to relatively large, round to disk-shaped serpentinite phacoids, as well as some large blocks of antigorite-serpentinite. Entrained within, and commonly eroded from, the mélange matrix are exotic blocks of variable size and shape including blocks of low-grade greenschist facies, greenschist-like metasomatic facies, blueschist facies, amphibolite facies, and eclogite facies rock. The Ring Mountain serpentinite-matrix mélange is underlain by the Tiburon Ridge Terrane, which consists of blueschist facies, schistose metagraywacke, metachert, mafic metavolcanic rock (“greenstone”), and minor metaconglomerate units. Although individual units of the Tiburon Ridge Terrane are laterally continuous in the central and southern Tiburon Peninsula, they appear as a discontinuously exposed broken formation at Ring Mountain. The structurally lowest unit within the area, herein referred to as the Metalitharenite of Reed Station, is dominated by prehnite-pumpellyite facies metalitharenite with minor metashale. Southeast of Ring Mountain, along the Tiburon Peninsula, the stacked sequence is offset by later northeast-and northwest-trending high-angle normal faults that juxtapose sections of the four structural units.

Introduction

The Franciscan Complex of coastal California, long considered to represent a subduction accretionary prism (Hamilton, 1969), has been important to understanding accretionary belt architecture and the geologic record of paleotectonic processes (e.g., Bailey et al., 1964; Hamilton, 1969; Dickinson, 1970; Ernst, 1970, 2011; Berkland, et al., 1972; Raymond, 1973; Wakabayashi, 1992). In recent decades, one of the main interests has been that of developing an understanding of the individual tectonostratigraphic elements that comprise the Franciscan Complex (e.g., Hsu and Ohrbom, 1969; Blake et al., 1984; 1988, 2000; Dickinson and Seely, 1979; Platt, 1986; Wakabayashi, 1992; 2013; Raymond, 2014).

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Ring Mountain and the Tiburon Peninsula, located in southern Marin County, California, are well known for the number and variety of high-grade metamorphic blocks within the Franciscan Complex (e.g., Coleman and Lanphere, 1971; Dudley, 1967; 1969; Suppe and Armstrong, 1972; Wakabayashi, 1992; Tsujimori et al, 2006). Ring Mountain is also known as the "type" locality for the mineral lawsonite, a high-pressure metamorphic mineral species first described by Ransome (1895). The variety of temperature and pressure conditions recorded by distinct mineralogies of the high-grade metamorphic blocks at Ring Mountain have made this area a key laboratory for the understanding of the subduction process that is represented by the surrounding Franciscan Complex. This study is focused on the geology and structure of Ring Mountain and the adjoining Tiburon Peninsula; as such it provides background and context for numerous detailed studies.

The Franciscan Complex is mainly composed of a diverse assemblage of arc-derived detrital sedimentary rocks, mostly metasandstone and metashale, with lesser amounts of meta-basaltic volcanic rocks (greenstone), radiolarian chert and metacherts, and minor amounts of limestone, serpentinite, and high-pressure metamorphic rocks that have been subjected to post- and syn-formational structural deformation, variable degrees of metamorphism (and re-metamorphism), uplift, and erosion (e.g., Bailey, et. al., 1964; Liou and Maruyama, 1987; Jayko and Blake, 1989; Tsujimori et al., 2006). These rocks constitute mélanges, broken formations, olistostromal blocks in units with coeval or younger matrix, and laterally coherent thrust-bounded sheets comprising tectonostratigraphic terranes (e.g., Raymond, 1974; 2014; Page, 1978; Blake et al., 1984; Ernst and McLaughlin, 2012). The rocks, including associated oceanic crustal rocks, were accreted at the latitude of the study area during east-directed, west-verging subduction beneath western North America from approximately 165 Ma to about 20 Ma (Hamilton, 1969; Ernst, 1970; Page, 1981; Wahrhaftig, 1984; Blake et al., 1988; Wakabayashi, 1992, 2013; Wakabayashi and Dumitru, 2007; Dumitru, 2012). Growth of the accretionary prism was mainly accomplished by westward accretion and underplating of the trench sediments and oceanic crustal rocks that progressively become younger from east to west and structurally downward (e.g., Raymond, 1974; 2014; Wahrhaftig, 1984; Wakabayashi, 1992; Ernst, 2011).

Commonly, the Franciscan Complex is structurally overlain to the east by the Coast Range Ophiolite composed of serpentinized ultramafic rocks, gabbro, basalt, and various other volcanic, plutonic, and associated clastic rock types (Hopson et al., 1981, 2008). The Coast Range Ophiolite exhibits evidence of burial metamorphism no higher than zeolite facies and varying degrees of hydrothermal metamorphism (Evarts, 1977; Evarts and Schiffman, 1983; Hopson et al., 2008).

In this report the term "mélange" is used as defined by Raymond (1975, 1984) as a mappable body of rock consisting of exotic blocks in a finer-grained matrix (also see Cowan, 1985; Hsü, 1968). "Exotic blocks" are defined as "…variably sized masses of rock occurring in a lithologic association foreign to that in which the mass formed" (Berkland et al., 1972). "High-grade" blocks are defined here as structurally isolated, high-pressure/low- to moderate- temperature metamorphic rocks that exhibit grades of metamorphism assigned to the blueschist facies, eclogite facies, and amphibolite facies (e.g., Coleman and Lanphere, 1971; Moore, 1984; Moore and Blake, 1989; Wakabayashi, 1990). "Tectonostratigraphic terrane" is defined as a fault-bounded block of rock of regional scale that has a geologic history different from those of adjacent terranes (Irwin, 1972; Coney et al., 1980; Howell, et al., 1985). "Coherent unit" is defined as a unit of rock that may be somewhat internally deformed (i.e., folded), but in which depositional stratigraphy and/or lithologic contacts and lateral continuity are preserved. One lithologic unit described in this study qualifies provisionally as a tectonostratigraphic terrane (the Tiburon Ridge Terrane (TRT)). Raymond (2014), however, has recommended against using the term "terrane" in the absence of detailed petrographic, stratigraphic, structural, and chronostratigraphic data. The Tiburon Ridge Terrane, as well as the subjacent Metalitharenite of Reed Station, seem to correspond with Franciscan tectonostratigraphic terranes named by Blake et al. (1984; 1988; 2000).

The earliest published geologic map that includes Ring Mountain and Tiburon Peninsula was produced by Lawson (1914) and covers much of the San Francisco Bay region. A reconnaissance map that includes the geology of Ring Mountain and northern Tiburon Peninsula was later published by Taliaferro (1943). Dudley (1967) mapped the distribution of some of the larger high-grade blocks and associated serpentinite at Ring Mountain and Tiburon Peninsula during a study that focused on the mineralogy and petrology of the high-grade blocks. Serpentinization associated with a sheared serpentinite block, located in northern Tiburon Peninsula, was studied by Page (1966). In mid-1970, the U. S. Geological Survey (USGS) published a revised geologic map of the San Francisco Bay region, which includes Ring Mountain and Tiburon Peninsula (Blake et al., 1974). Rice et al. (1976) mapped Ring Mountain and the Tiburon Peninsula area as part of a larger slope stability study within central and southeastern Marin County. More recently, Wakabayashi (1992) included Ring Mountain and Tiburon Peninsula in a regional map of the central San Francisco Bay region. He also produced a sketch map of a portion of Ring Mountain showing the location and rock type of high-grade blocks (Wakabayashi, 2012; 2013). A revised geologic map of the San Francisco Bay region, including Ring Mountain and Tiburon Peninsula, at a scale of 1:75000, was published in 2000 by the USGS (Blake et al., 2000).

The geologic maps of Ring Mountain (at a scale of 1:6000), and Ring Mountain and Tiburon Peninsula (at a scale of 1:12000) included in this report (Plates 1 & 2) present new detailed information about the geologic and structural relationships of the distinct structural units that underlie the map area. A total of 375 field samples of varying lithology were collected from the map area and examined petrographically; 21 rock and soil samples were analyzed by X-ray diffraction analysis (XRD); and modal mineral contents and QFL ratios were determined for 32 samples of metaclastic rocks. It is hoped that the geologic maps and report included herein will be useful for those in the geoscience community considering, or actively involved in research in this area, as well as those teaching or leading field trips in this, one of the classic areas in the Franciscan Complex.

Geologic Setting

Tiburon Peninsula (the Peninsula), a northwest-southeast-trending ridge that projects southeastward into San Francisco Bay, is located approximately 12 km north of San Francisco (Figure 1). Ring Mountain forms the northwest portion of the Peninsula. The area mapped in this study covers approximately 23 km^2 and ranges in elevation from sea level to approximately 270 m atop Tiburon Ridge, the highest elevation on the Peninsula. The Peninsula is bordered on the northeast and east by San Francisco Bay and on the southwest by Richardson Bay. Intermittent field mapping was carried out at a scale of 1:6000 between 1996 and 2014. Although relatively good exposures of bedrock occur on the upper slopes of the study area, debris-slides, residential development, and vegetation cover most of the lower elevations.

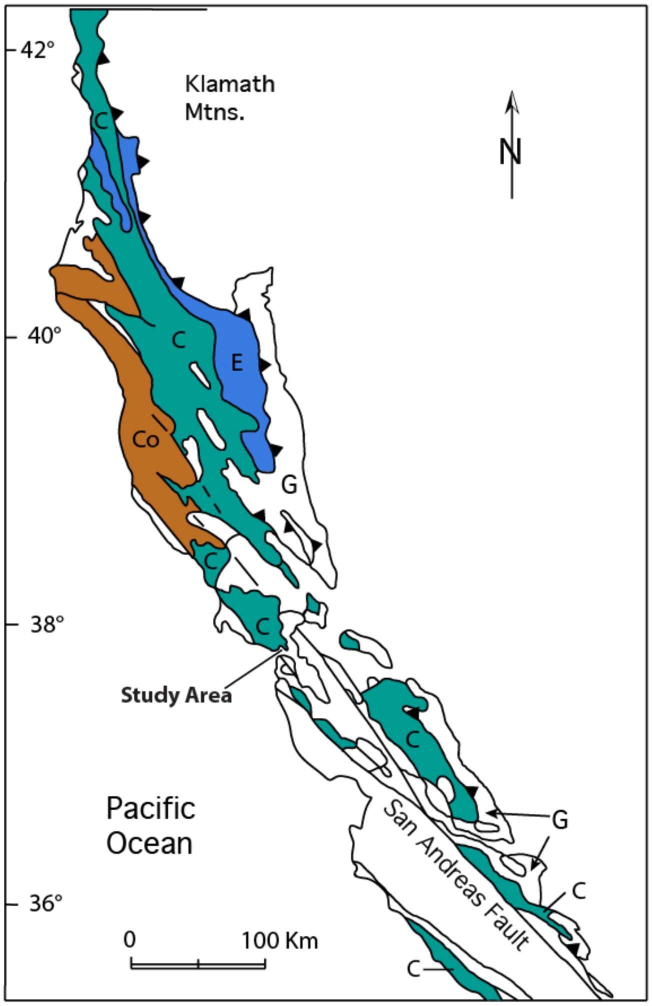

Figure 1. Generalized map of western California showing the location of the study area and areas commonly assigned to the Eastern Belt in the Northern Coast Ranges (E – dark blue); areas assigned to the Central Belt in the Northern Coast Ranges (C – dark green); and areas assigned to the Coastal Belt (Co - brown). G = Great Valley Group (uncolored). (After Raymond, 2014)

Description of the Map Units

The underlying bedrock units recognized and mapped on the Peninsula were assigned, from top to bottom, to a stack of four stratigraphic and structural units: the Coast Range Ophiolite (CRO), the Ring Mountain serpentinite-matrix mélange (RMM), the Tiburon Ridge Terrane (TRT), and the Metalitharenite of Reed Station (MRS). Each major unit is characterized by distinct and mappable lithologies. All major units, except the MRS, are juxtaposed along low-angle faults. All major units have been offset by later northeast- and northwest-trending high-angle normal faults and have been folded, faulted, and metamorphosed to varying degrees. Various Quaternary units cover much of the bedrock throughout the Peninsula. Figure 2 shows a tectonostratigraphic column with the various lithologic units of the Peninsula and their structural relationships to one another.

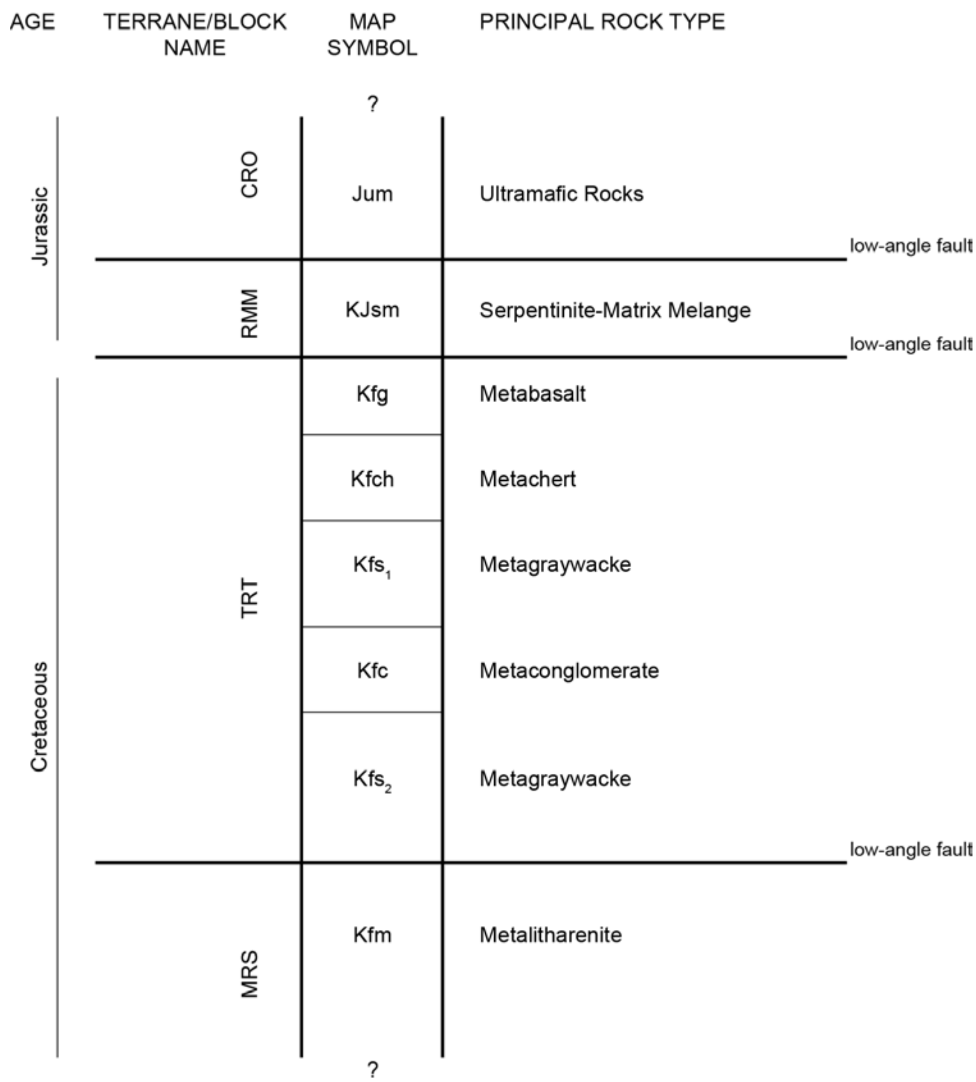

Figure 2. Tectonostratigraphic column showing the various lithologic units underlying Ring Mountain and Tiburon Peninsula. CRO = Coast Range Ophiolite; RMM = Ring Mountain Mélange; TRT = Tiburon Ridge Terrane; and MRS = Metalitharenite of Reed Station. (Not to scale)

Coast Range Ophiolite

Two relatively large, and several smaller, ridge-capping bodies of ultramafic rock occur at Ring Mountain in the NW portion of the Peninsula, and one large elongated body of ultramafic rock occurs on the southwest Peninsula (Plates 1 and 2). These ultramafic bodies represent the structurally highest terrane exposed on the Peninsula (Wakabayashi, 1990, 1992, 2013; Bero, 2003, 2004, this report). At present exposure levels, the ultramafic rocks are estimated to have a structural thickness of about 60-70 m at Ring Mountain and approximately 130 m on the southwest Peninsula.

The ultramafic rocks are composed of partially serpentinized peridotite (harzburgite) and typically appear blocky in outcrop. Thin sets of fractures and fracture-filled veins composed of fibrous serpentine (chrysotile) are common, and weathering along the fracture surfaces has given the outcrop its blocky appearance (Figure 3). The weathered surface of the peridotite is typically oxidized, yellowish-orange to orange-brown in color, and characteristically has a rough-textured surface due to partially serpentinized pyroxene ("bastite") grains that stand out in relief against the more easily weathered serpentine matrix. Petrographic and XRD analyses indicate that the blocky serpentinized harzburgite consists of relict grains of olivine + orthopyroxene ± clinopyroxene ± sphene set in a matrix of serpentine (lizardite) + iron oxides ± (minor) antigorite ± calcite.

Figure 3. Typical exposure of blocky serpentinized peridotite on Tiburon Peninsula. Hammer is about 38 cm in length.

The lack of any additional rock types typically associated with ophiolites, such as gabbro, basalt, and various other volcanic and plutonic rocks (Hopson et al., 1981, 2008), precludes definitive correlation of the blocky serpentinized harzburgite with the CRO. Because the serpentinized harzburgite is the structurally highest unit observed on the Peninsula, however, and because it is separated from the underlying rocks of the Franciscan Complex along a low-angle tectonic contact, the ultramafic rocks are tentatively assigned here to the CRO. Although the age of the serpentinized harzburgite observed on the Peninsula has not been determined, the igneous crystallization age of the CRO in the Coast Ranges is from 165-172 Ma (Hopson, et al., 1981, 1996, 2008; Shervais et al., 2005).

Ring Mountain Serpentinite-Matrix Mélange

A structurally thin lithologic unit characterized by block-in-matrix structures typical of mélanges (e.g., Raymond, 1984; Pini, 1999; Wakabayashi, 2011) occurs structurally below the blocky, partially serpentinized harzburgite described above, and is separated from it by a low-angle fault contact. The mélange unit forms a tectonic block, estimated to be up to 40 m thick, bounded above and below by low-angle tectonic contacts. This unit, here referred to as the Ring Mountain mélange (RMM), is composed of exotic blocks entrained within a fine-grained serpentinite matrix (map symbol KJsm, Plates 1 and 2). It structurally overlies blueschist-facies metamorphic rocks referred to here as the Tiburon Ridge Terrane (Figure 2).

The RMM is structurally complex and appears to vary both in lateral thickness and entrained block content. The well-foliated, shear-fracture fabric matrix of the RMM is composed of small, pale green to black, disk-shaped serpentinite phacoids bounded by numerous, sub-parallel, anastomosing shear surfaces. XRD analyses of samples collected from various locations within the serpentinite-rich mélange matrix indicate that it is primarily composed of lizardite, with minor chrysotile and tremolite. Some included blocks contain antigorite and talc.

As currently mapped, the RMM contains areas of differing character, with some areas lacking blocks, but maintaining a shear-fracture textured serpentinite matrix (Figure 4). Other areas contain blocks ranging from angular, polygonal, and lens-shaped to sub-rounded blocks and phacoids of serpentinized peridotite (Figure 5), within a matrix composed of shear-fractured scaly serpentinite, structurally similar to scaly clay (argille scagliosa), but composed entirely of serpentinite (Figure 6). Still other areas within the RMM unit are characterized by exotic high-grade blocks of various size and shape consisting of eclogite, garnet-glaucophane schist and gneiss, amphibolite, metachert, and metabasite, together with lesser numbers of blocks consisting of low-grade greenschist and greenschist-like metasomatic rock, all entrained within, or eroding from, a shear-fracture textured serpentinite matrix (Figure 7a & 7b). The petrology of the high-grade blocks has been thoroughly described in detail elsewhere (e.g., Borg, 1956; Coleman and Lee, 1963; Dudley, 1967; Moore, 1984; Oh and Liou, 1990; Wakabayashi, 1990; Tsujimori, et al., 2006). Although the RMM has been extensively folded and faulted, the variation in exotic block content of the RMM may indicate either a subtle stratification within the unit, or exotic block-bearing "zones" surrounded by block-free "lenses or slabs" of serpentinized harzburgite (Wakabayashi, 2012).

Figure 4. Serpentinite-matrix mélange (RMM) unit (lacking exotic blocks) exhibiting a shear-fracture textured serpentinite matrix. Hammer is about 38 cm in length.

Figure 5. Exposure of the serpentinite-matrix mélange (RMM) unit containing variously shaped blocks and phacoids of serpentinized peridotite entrained within a shear-fractured scaly textured serpentinite matrix. Scale card seen in lower center of photo is about 8 cm in width. Photo taken in the SE portion of Ring Mountain.

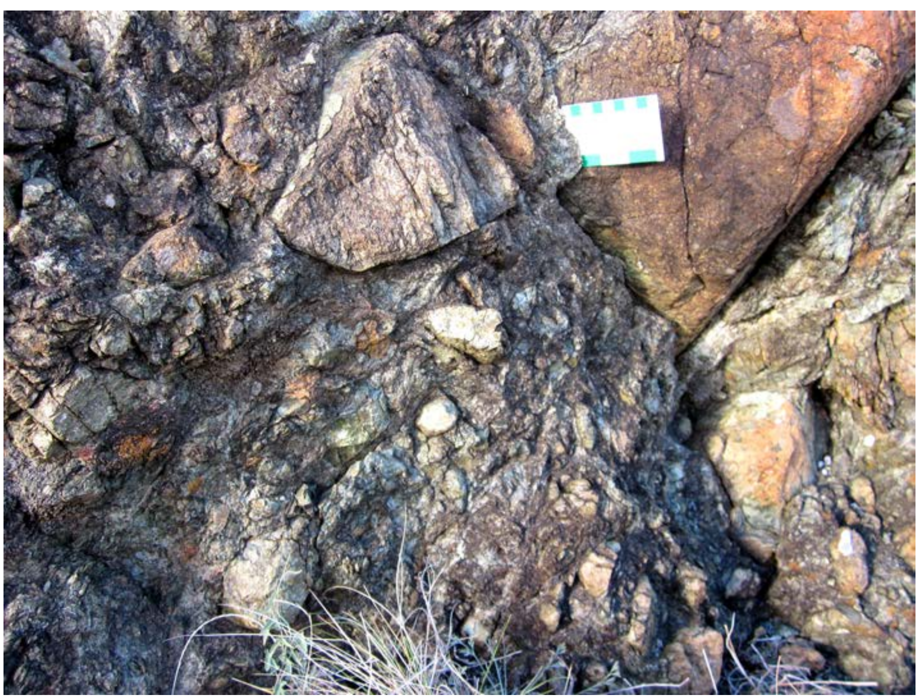

Figure 6. Close-up of outcrop shown in Figure 5. Note elongation and rotation of entrained blocks. Scale card about 8 cm. in length.

Figure 7a. Sub-rounded and foliated high-grade metamorphic block of coarse-grained blueschist (center of photo) entrained within shear-fracture textured serpentinite matrix of the RMM unit. Note large sub-rounded and elongated block of serpentinite entrained within the matrix at left-center of photo. Scale card is about 15 cm in length.

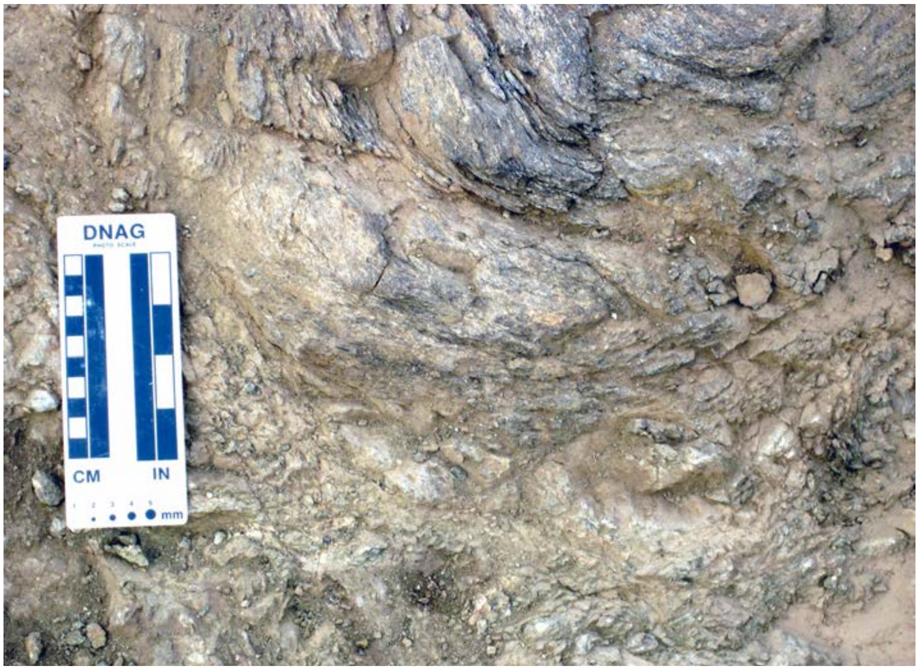

Figure 7b. Close-up of Figure 5a showing the sub-parallel foliation of the blueschist block and the surrounding sheared serpentinite matrix.

Exotic blocks of distinctive low-grade greenschist character occur in the north and south-central areas of Ring Mountain within the upper portion of the RMM unit and adjacent to one of the large Jum bodies (map symbol $elgb_1$, Plates 1 & 2). These blocks are composed of elongate and sub-rounded clasts of serpentinite, up to 50 cm in diameter, that are entrained within an intensely sheared and foliated, but relatively coherent serpentinite matrix (Figure 8a & 8b). The largest of these blocks, of rectangular shape and about 100 m in length, is located on the north-central slope of Ring Mountain. The clast-rich portion of the block grades from east to west into a fine-grained, bright turquoise-colored, well-foliated subunit that lacks both blocks and smaller clasts. This subunit is intensely folded into tight antiforms and synforms (some possibly overturned) with sub-parallel fold axes trending about N50°W. Petrographic and XRD analysis indicate that this fine-grained turquoise-colored subunit is composed of antigorite-serpentinite ± minor talc. It remains unclear if these low-grade exotic blocks ($elgb_1$) are entrained within the upper portions of the RMM, or if they represent structurally deformed fragments of the base of the overlying Jum.

A few low-grade chlorite-rich blocks of aphanitic to aphanitic-porphyritic greenschist facies metavolcanic rock (map symbol $elgb_2$, Plates 1 & 2) are found widely scattered within the serpentinite-matrix mélange of the RMM at Ring Mountain. Although most occur as isolated blocks of various size and shape, two of the blocks are found adjacent to, and closely associated with, the rectangular-shaped $elgb_1$ block described above.

The eclogites, glaucophane schists and gneisses, and amphibolite blocks are commonly wrapped in a “rind” composed of successive layers of retrograde lithologies, such as talc schist and talc-actinolite schist (Figure 9a & 9b). Eclogite blocks commonly have an intervening layer of glaucophane schist. Similar rinds associated with high- and low-grade exotic blocks reported from other locations within the Franciscan Complex are thought to have formed by metasomatic reaction of the blocks with surrounding ultramafic and other matrix material at elevated temperatures (Coleman and Lanphere, 1971; Moore, 1984; Cloos, 1986; Ukar and Cloos, 2013). Scattered blocks consisting of talc schist and talc-actinolite schist (map symbol $elgb_3$, Plates 1 & 2) that are similar to the overprint rinds described above also occur within the serpentinite-matrix mélange at Ring Mountain. These exposed masses of greenschist facies-like metasomatic rock may possibly represent either *in situ* “rinds” of buried high-grade blocks, or detached, partially buried fragments of these “rinds”.

Many of the coarse-grained, garnet-bearing blueschist blocks contain thin bands of pale green foliation-parallel omphacite-rich rock suggesting partial retrograde overprinting of eclogite by blueschist-facies assemblages, leaving relict eclogite bands (L.A. Raymond, personal communication, 2013; Wakabayashi, 1990; 1992, 2011). Metachert is typically white to pale pink in color. The rock is composed of coarse-grained, recrystallized quartz ± microscopic, euhedral garnet porphyroblasts that commonly occur as concentrated strands within the white, quartz-rich matrix, giving some of the metachert blocks the pale pink color. Small, thin, dark blue to black blades of Na-rich amphibole scattered along foliation planes or layers within some metachert blocks give them a thin-banded appearance. Similar high-grade metamorphic blocks, associated with both intra-Franciscan serpentinite masses (Wakabayashi, 2004) and at the base of the CRO (Raymond, 1973), have long been interpreted as having a tectonic origin associated with subduction (Ernst, 1970, 1971, 2013; Moore, 1984).

Figure 8a. Blocks of elongate and sub-rounded clasts composed of massive serpentinite ± minor talc entrained within an intensely sheared and foliated serpentinite matrix. Lens cap for scale.

Figure 8b. Close-up of Figure 8a showing elongate serpentinite clasts entrained within a shear-fractured serpentinite matrix.

Figure 9a. Partial exposure of large, sub-rounded blueschist block (foreground) wrapped in a rind (behind hammer) composed of successive layers of talc schist. Hammer is about 38 cm in length.

Figure 9b. Close-up of the thinly foliated rind composed of talc schist shown in Figure 9a. Scale card is about 8 cm in length.

Although the high-grade blocks appear to be more concentrated in the NW portion of the Peninsula (at Ring Mountain), they also occur sporadically throughout the rest of the Peninsula in association with the RMM. Completely exposed blocks range up to about 140 m in maximum diameter, and up to about 25 m thick. Because they appear to be less susceptible to local weathering processes than the surrounding shear-fractured serpentinite matrix, they commonly occur as isolated blocks on the surrounding landscape (Figure 10). Owing to their typical sub-rounded shape, the blocks commonly become unstable once eroded from their serpentinite matrix and move gravitationally down-slope breaking into angular fragments scattered on the lower slopes.

Figure 10. Exotic blocks of various composition, size, and shape commonly occur as isolated blocks on the surrounding landscape. Photo taken looking south in the SE portion of Ring Mountain.

Local exposures of lawsonite- and jadeitic-pyroxene-bearing metagraywacke, thin-bedded, white-colored metachert, and associated thick-bedded, red-brown colored metashale — similar in character and composition to those lithologies observed with the subjacent TRT— were observed in an outcrop located near what appears to be the structural base of the RMM located in north-central Ring Mountain. These rocks likely represent either an erosional window in the structural base of the overlying RMM, or tectonic slices of the subjacent TRT that were entrained as fault slices into the lower RMM (Wakabayashi, 2012; this report). Field observations also indicate that the shear fabric of the serpentinite-rich mélange matrix becomes more pervasive near the structural base of the unit and locally contains small, phacoid-shaped to rounded clasts of high-grade schist (Figure 11). The foliated and rounded nature of these clasts is compatible with an origin by tectonic rounding within the plane of the basal fault separating the RMM from the subjacent TRT, during emplacement.

Sub-rounded to rounded clasts of tremolite schist, tremolite-antigorite schist, and metavolcanic rock enclosed by the mélange matrix have also been reported from various locations within the RMM at Ring Mountain (Wakabayashi, 2012). These clasts have been described as granular and sedimentary in

Figure 11. Exposure of a small, well-rounded phacoid-shaped clast of amphibolite schist entrained with the pervasively sheared serpentinite-matrix mélange located at the structural base of the RMM unit. Coin for scale.

nature and have been cited as evidence of a sedimentary origin for the RMM, so that the serpentinite-rich body would be an olistostromal unit containing high-grade rocks, a body that was later subjected to deformation and recrystallization during emplacement into the Franciscan accretionary prism (Wakabayashi, 2012).

Metamorphic ages have been reported for some of the high-grade metamorphic blocks at Ring Mountain. Dates include K/Ar dates of 149 ± 8 and 171 ± 2 Ma for white mica and pyroxene, respectively, collected from an eclogite block (Coleman and Lanphere, 1971), and a K/Ar date of 147 ± 3 Ma for white mica collected from a blueschist block (Suppe and Armstrong, 1972). Recently, a Lu-Hf age of 145.5 ± 2.4 Ma was obtained for lawsonite-blueschist facies metamorphism from a lawsonite-bearing high-grade block at Ring Mountain (Mulcahy, et al., 2009) and a date of >170 Ma on inclusions in pyroxene grains suggests a date for pyroxene crystallization (S. Mulcahy, pers. comm., 2014). High-grade blocks from other localities within the Franciscan complex have yielded Ar/Ar ages of 157-168 Ma (Wakabayashi and Dumitru, 2007), indicating that these blocks are the oldest metamorphic rocks within the Franciscan Complex. Their age is only slightly younger than, or essentially equivalent to, the igneous crystallization age of the CRO, which ranges from 165-172 Ma (Hopson, et al., 1981, 1996, 2008; Shervais et al., 2005).

Based on block ages (e.g., Wakabayashi and Dumitru, 2007; Mulcahy et al., 2009), lithology (Wakabayashi, 1990; this report), metamorphic evolution (Wakabayashi, 1990), and comparative age to the CRO (Hopson, et al., 1981, 1996, 2008; Shervais et al., 2005), the high-grade metamorphic blocks observed on the Peninsula may have formed from igneous rocks (basites) and related protoliths composing the upper portion of a down-going oceanic crustal slab. As the slab was subducted and accreted beneath the hot, sub-oceanic crustal upper mantle (of the CRO) during initial stages of east-directed subduction, metamorphism at various sites converted the rocks to the high-grade lithologies we see today. These high-grade blocks, entrained within a hydrated upper mantle serpentinite matrix, were later exhumed to the near surface by a mechanism(s) not yet fully understood (Wakabayashi, 2013), and were later exposed by erosion accompanying uplift. The talc and actinolite-rich “rinds” that partially enclose many of the high-grade blocks on the Peninsula, likely formed by metasomatic reaction with the surrounding serpentinite matrix as temperature decreased during exhumation (e.g., Moore, 1984, Cloos, 1986).

Serpentinite matrix mélange units, similar in nature to the RMM observed on the Peninsula, have been described from diverse localities within the Franciscan Complex and have been interpreted to have formed either by tectonic or sedimentary processes (e.g., Moiseyev, 1966; Saleeby, 1984; Suzuki, 1986; Shervais et al., 2011; Wakabayashi, 2012; 2013). Based on the mapping and field observations made during this study, it is concluded that the serpentinite-matrix mélange (RMM) unit observed on the Peninsula is of tectonic origin (see Wakabayashi, 2012, for an alternative interpretation). This finding is based on the following: (1) the RMM occurs structurally below and adjacent to a serpentinized peridotite body that, on a larger scale, is either genetically related to, or is the likely source for, the serpentinized mélange matrix; (2) the mélange matrix has a pervasive tectonic (shear-fracture) fabric and includes boudinaged layers that would likely not survive sedimentary transport; (3) the mélange contains clasts, but in every case observed, the clasts are bounded by sheared serpentinite surfaces; (4) while some clasts appear rounded toward the faulted base of the RMM, fragment rounding is known to occur during tectonic deformation (Moore and Rymer, 2012; Bial and Trepmann, , 2013); and (5) sedimentary structures, such as bedding and fossils, were not observed within the RMM during the current study. Furthermore, some blocks in the mélange have a thickness approximating the maximum thickness of the RMM as a whole, and could only be mélange-thickness olistoliths or clasts in an olistostromal megabreccia, in the unlikely circumstance that the unit is of sedimentary origin. Taken together, the data support a tectonic origin rather than a sedimentary origin for the RMM observed on the Peninsula.

Because of its thickness, distinct composition, pervasive shear-fracture fabric, and entrained high-grade metamorphic blocks, the RMM is presented here as a mappable unit (Plates 1 & 2). Due to its sheared, tectonized fabric, the RMM is herein considered to have a younger age than the blocky ultramafic rocks of the overlying the CRO, from which it is considered here to be, in part, derived.

Franciscan Complex

The rocks of the Franciscan Complex exposed on the Peninsula are composed of two separate and distinct (probable) tectonostratigraphic terranes of differing age and lithologic character. A structurally higher, stratigraphically diverse, fault-bounded, blueschist facies terrane seems lithologically equivalent to units described within the Yolla Bolly Terrane of Blake et al. (1984; 1999; 2000). A structurally lower, prehnite-pumpellyite grade unit, the MRS, bounded above by a low-angle fault, but with an unexposed base, is seemingly lithologically equivalent in age and composition to the Alcatraz Terrane of Blake et al (1984; 2000). These two possible tectonostratifigraphic terranes are separated by a low-angle fault located at the base of the TRT. As noted, the base of the subjacent MRS (cf. Alcatraz Terrane) has not been recognized on the Peninsula.

Tiburon Ridge Terrane

The structurally high RMM is structurally underlain by blueschist facies rocks of the Tiburon Ridge Terrane (TRT) consisting of schistose metagreywacke, metachert, metabasalt, and minor metaconglomerate. Because their structural position, similar composition, and metamorphic facies are like those of rocks found on Angel Island, located just south of the Peninsula, these units have also been correlated with, and assigned to, the Angel Island Nappe by Wakabayashi (1992). Individual units of the TRT are laterally coherent in the central and southern Peninsula, but are somewhat discontinuous and form a broken formation (or formations) at Ring Mountain (Figure 2). On the southern Peninsula, exposures reveal the stratigraphic and structural relationships of the different lithologic units of the TRT.

The structurally highest unit exposed within the TRT is composed of metabasalt (greenstone) (map symbol Kfg, Plates 1 & 2), bounded above by a low-angle fault separating it from the overlying RMM (Figure 2). Outcrops of metabasalt consist of fine-grained, dark gray-green rock that commonly exhibits a red-brown to orange-yellow oxidation discoloration on weathered surfaces. Most outcrops are composed of small, brittle, fragmented pieces of rock that create rounded, reddish-brown weathered slopes, although a few outcrops are locally massive. Petrographic and XRD analyses indicate that the metabasalt is partially serpentinized and composed of serpentine (lizardite) + magnetite ± plagioclase ± Ca-clinopyroxene ± quartz ± pumpellyite ± lawsonite ± jadeitic-pyroxene ± glaucophane, indicating that the unit has been incompletely, but perhaps multiply metamorphosed. Relatively small, angular blocks of dark, blue-gray riebeckite-bearing metachert (described below) are locally associated with the upper part of this unit at various locations throughout the Peninsula.

Thin-bedded metachert is common throughout the Peninsula and forms the second highest unit of the TRT (map symbol Kfmc, Plates 1 & 2). Although a few metachert outcrops exhibit the common red-brown color of bedded cherts widely observed within the Franciscan Complex, other outcrops appear pale green in color, owing to the presence of tiny pumpellyite needles in the groundmass, and tan in color, due to the presence of stilpnomelane (Figure 12 a & 12b). Thin-bedded, tightly folded, and microbrecciated, white-colored to very pale green metachert is also common throughout the Peninsula, and is typically associated with, or occurs adjacent to fault contacts (Bero, 2003) (Figure 13a & 13b). Petrographically, these white to very pale green metacherts exhibit multiple generations of crosscutting, quartz-filled fractures, some containing tiny pumpellyite needles growing into the quartz veinlets from the fracture walls. XRD analyses of samples of this pale colored chert detected quartz with very low background levels indicating that any original amorphous component has likely been completely crystallized to quartz ± pumpellyite.

Scattered outcrops of very dense, dark blue-gray metachert, often associated with metabasalt in the very upper portions of the metabasalt unit (map symbol Kfmcr, Plates 1 & 2), occur locally on the Peninsula (Figure 14a & 14b). Petrographic and XRD analysis indicates that these relatively small and localized metachert bodies are composed of quartz + riebeckite ± stilpnomelane ± chlorite ± white mica. Recrystallized quartz forms the coarse-grained groundmass of these rocks and the multiple crosscutting quartz-filled fractures. Dark blue acicular riebeckite neoblasts up to ~2 mm in length appear as thin, semi-parallel crystals within the groundmass. Chlorite also occurs both as thin contorted bands and as small isolated patches throughout the groundmass of these rocks.

Figure 12a. Outcrop of brown-colored metachert from the upper Tiburon Ridge Terrane located in south Tiburon Peninsula. Hammer is about 38 cm in length.

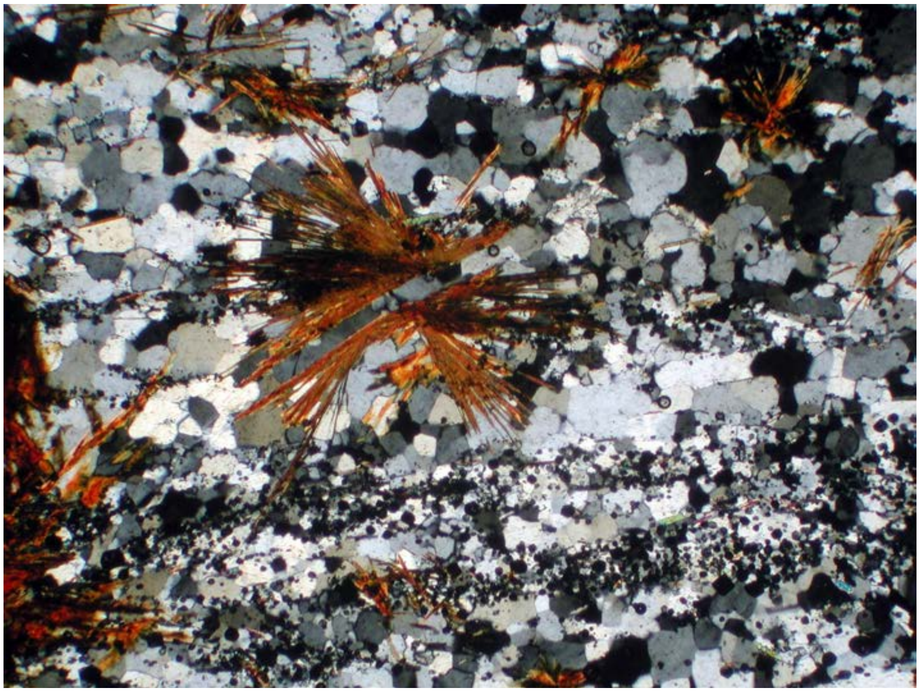

Figure 12b. Photomicrograph of brown-colored metachert shown in Figure 12a. The matrix is composed of recrystallized quartz + acicular stilpnomelane + "streams" of small euhedral (isotropic) garnet. (Magnification: x40, XPL.)

Figure 13a. Outcrop of thin-bedded and tightly folded white colored metachert (Kfmc) from the Tiburon Ridge Terrane located adjacent to a high-angle fault in west-central Tiburon Peninsula. Hammer in central area of photo is about 38 cm in length.

Figure 13b. Close-up of Figure 13a showing tight folds commonly seen in thin-bedded white to pale green chert. Hammer is about 38 cm in length.

Figure 14a. Localized outcrop of dense, dark blue-gray metachert (Kfmcr), from the upper Tiburon Ridge Terrane located in south Tiburon Peninsula. Hammer is about 38 cm in length.

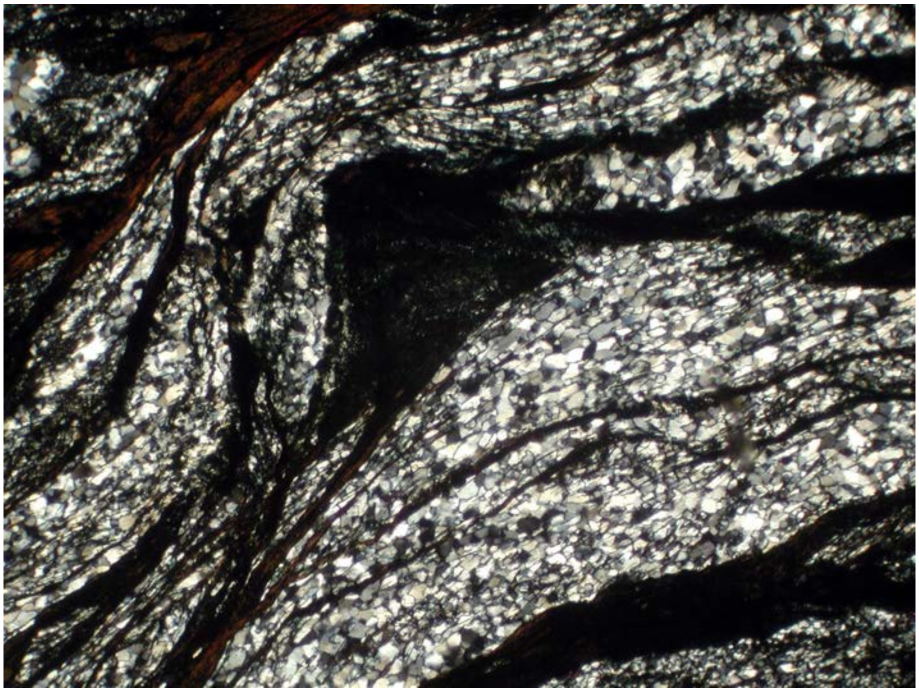

Figure 14b. Photomicrograph of dark blue-gray metachert unit shown in Figure 14a composed of re-crystallized quartz + blue-black needles of Na-amphibole (riebeckite) + stilpnomelane + chlorite. (Magnification: x40, XPL)

Two somewhat similar looking metagraywacke units, designated Kfs_1 and Kfs_2 on Plate 1, together form the bulk of the rock within the TRT. The two blueschist facies metagraywacke units are separated by a relatively narrow, but laterally continuous metaconglomerate unit of the TRT in the south Peninsula. Although widespread in the southeast portion of the Peninsula, the Kfs_2 metagraywacke unit is not present in the north-central or northern parts of the Peninsula. Although the two metagraywacke units are similar, the structurally high Kfs_1metagraywacke unit is fine- to medium-grained with a semi-planar foliation (Figure 15a) typical of Textural Zone 2 (TZ-2) of Blake et al. (1967), and commonly contains foliation-normal (secondary) quartz veins. The structurally lower Kfs_2 metagraywacke unit is typically finer-grained than the Kfs_1 unit and although it exhibits a semi-planar foliation locally, it is generally less strongly foliated than the Kfs_1 metagraywacke. Where present, cleavage in these units is defined by anastomosing chlorite + white mica ± stilpnomelane within the matrix. The phyllosilicates enclose porphyroclasts of relict quartz grains elongated by deformation and fabric-parallel overgrowths, together with neoblasts of the blueschist facies assemblage lawsonite ± albite ± aragonite ± jadeitic-pyroxene ± glaucophane (Figure 15b). Although this blueschist facies assemblage occurs in both metagraywacke units, the Kfs_1 unit generally has coarser lawsonite and jadeitic-pyroxene grains, where present, whereas the Kfs_2 unit commonly contains finer-grained lawsonite and lesser amounts of modal jadeitic-pyroxene, where the latter is present. Structural position, finer grain size, the less-well developed foliation, and the generally lower abundances of lawsonite and jadeitic-pyroxene distinguish this unit from Kfs_1 metagraywacke.

Metaconglomerate occurs in scattered outcrops at Ring Mountain, where the TRT is relatively dismembered, but forms a laterally continuous unit in the south Peninsula (Plate 1). It is composed of well-rounded cobbles of chert, diorite, and porphyry ranging in size up to about 25 cm in diameter, entrained within a well-foliated sandstone matrix (Figure 16). Although commonly well rounded, the clasts are locally stretched, flattened, and entrained within the foliated matrix. Petrographic analysis of the metaconglomerate matrix indicates it is composed of quartz + albite + chlorite + white mica + lawsonite ± glaucophane ± jadeitic-pyroxene.

Recent detrital zircon U-Pb geochronological age determinations indicate that clastic sedimentation within the type area of the Yolla Bolly Terrane of Blake et al. (1984; 1988; 2000) occurred during the Cretaceous Period between 120 to 95 Ma (Dumitru, 2012; Ernst et al., 2012). Wakabayashi (2012) suggests that the metagraywacke units of the Angel Island Nappe on the Peninsula (herein designated TRT) may correlate with a similar blueschist-grade "nappe" to the south in the El Cerrrito, CA area. The latter are reported to have a detrital zircon U-Pb depositional age of 102 Ma (Snow et al., 2010). If this correlation is correct, then the date may support a Yolla Bolly Terrane assignment for the Tiburon Ridge Terrane rocks (although Ernst et al., 2009 and Raymond, 2014 report similar ages for generally younger terranes of the central and northwestern Diablo Range, respectively).

Metalitharenite of Reed Station

The blueschist facies rocks of the TRT are structurally underlain by a thick sequence of gently to tightly folded coherent metaclastic rocks similar to those of the Alcatraz Terrane described by Jakyo and Blake (1984) and here designated as the Metalitharenite of Reed Station (MRS). The MRS is the structurally lowest unit exposed on the Peninsula. Limited outcrops indicate that the unit is composed

Figure 15a. Outcrop of fine- to medium-grained metagraywacke (Kfs_1) from the Tiburon Ridge Terrane exhibiting Textural Zone-2 semi-planar foliation. Outcrop located in southern Tiburon Peninsula. Coin for scale.

Figure 15b. Photomicrograph of TZ-2 metagraywacke (Kfs_1) showing relic clastic quartz grains and re-crystallized quartz (Q) in the matrix with foliation defined by fabric-parallel chlorite (C), white mica (M), and stilpnomelane (S) enclosing strands of lawsonite (L). (Magnification: x40, XPL)

Figure 16. Outcrop of metaconglomerate composed of well-rounded cobbles of chert, diorite, and porphyry entrained within a well-foliated sandstone matrix composed of quartz + albite + chlorite + white mica + lawsonite ± glaucophane ± jadeitic-pyroxene. Outcrop located in south Tiburon Peninsula. Hammer is about 38 cm in length.

chiefly of metalitharenite with minor interbedded metashale that typically appears unmetamorphosed in outcrop. The Kfm underlies most of the northern and central portions of the Peninsula, is deeply weathered, and typically forms rounded hills and smooth weathered slopes with few outcrops. Limited exposures of the metalitharenite and metashale indicate that the terrane generally strikes northwest-southeast with most dip angles ranging between 30º and 60º to the southwest in the east portion of the Peninsula, and between 30º and 60º to the northeast in the west portion of the Peninsula, suggesting a synformal structure.

In outcrop, the metalitharenite appears locally with thin interbedded metashale (Figure 17a), but more commonly the rock is massive. The rock is fine- to medium-grained and commonly contains small fragments of dark gray shale, chert grains, and oxidized biotite flakes. Thin sections of the metalitharenite show that these rocks are composed of angular to sub-rounded grains of detrital quartz + albite + biotite ± epidote ± (rare) potassium feldspar ± lithic fragments in a matrix composed of silt- and clay-sized particles (Figure 17b). Metamorphic minerals include pumpellyite, chlorite, and calcite. Pumpellyite occurs as small radiating patches of fine needles that grow into both feldspar and quartz along grain boundaries. Calcite occurs both in secondary fracture-filled veins and as secondary minerals within the matrix. Prehnite was not recognized in these rocks.

Texturally the rock has the appearance of typical Textural Zone 1 (TZ-1) rocks of Blake et al. (1967). Structurally, the bedding and interbedding reveal submarine fan facies representing those ranging from proximal to distal parts of a fan. Where interbedded metashale is absent, bedding attitudes are difficult to determine, although the alignment of flat shale fragments may reflect a bedding attitude.

Modal mineral contents and ratios were determined for 32 samples of metalitharenite from the MRS located within the north and central Peninsula for comparison with established modal data for similar rocks from the Alcatraz Terrane described by Jakyo and Blake (1984) exposed adjacent to the

Figure 17a. Outcrop of tightly folded beds of TZ-1 metalitharenite with interbedded metashale from the Metalitharenite of Reed Station unit located on the north side of Ring Mountain. The hammer is about 38 cm in length.

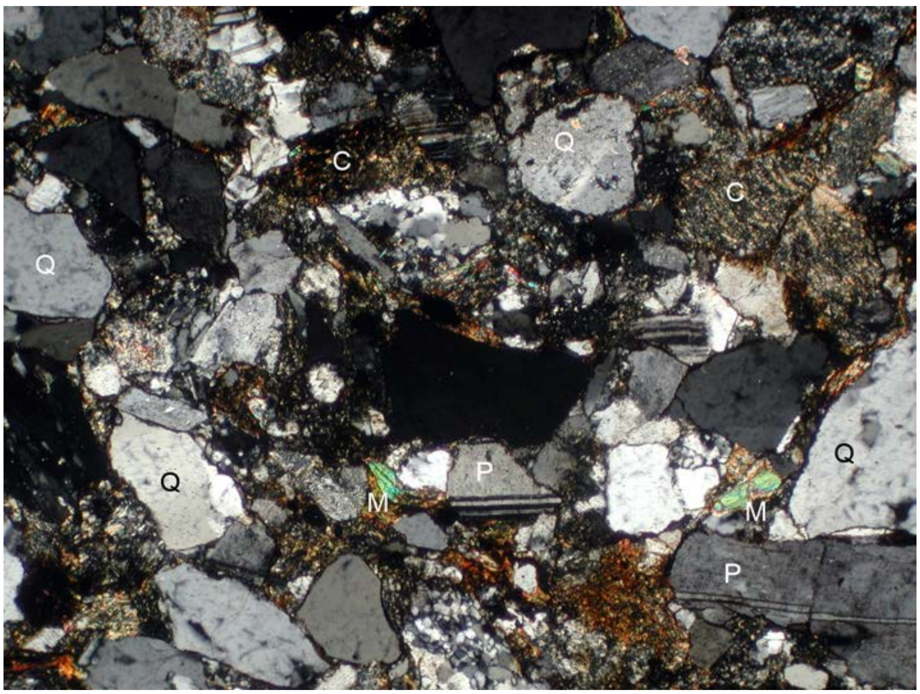

Figure 17b. Photomicrograph of TZ-1 metalitharenite composed of detrital quartz (Q) + albite (P) + white mica (M) ± epidote ± potassium feldspar ± lithic fragments with secondary minerals including pumpellyite, chlorite (C), and calcite. (Magnification: x100, XPL)

Peninsula. The methods used to point-count the samples closely follow those described by Jayko and Blake (1984). QFL modal ratios were determined for each sample and plotted on a QFL diagram (Figure 18). Table 1 lists the complete modal data for each sample. The results indicate that the metalitharenite samples collected from the Peninsula exhibit a mean QFL modal ratio (35-45-20), similar to “graywacke” samples reported from the Alcatraz Terrane (Jayko and Blake, 1984). These data support a possible correlation of the lowest structural unit underlying both the northwest (Ring Mountain) and central portions of the Peninsula, with the Alcatraz Terrane of Jayko and Blake (1984).

The age of the Metalitharenite of Reed Station has not been thoroughly established. A single sample collected from the Kfm along Paradise Drive on the north side of Ring Mountain, revealed a maximum depositional age of 94 Ma (Dumitru, 2012, Wakabayashi, 2013).

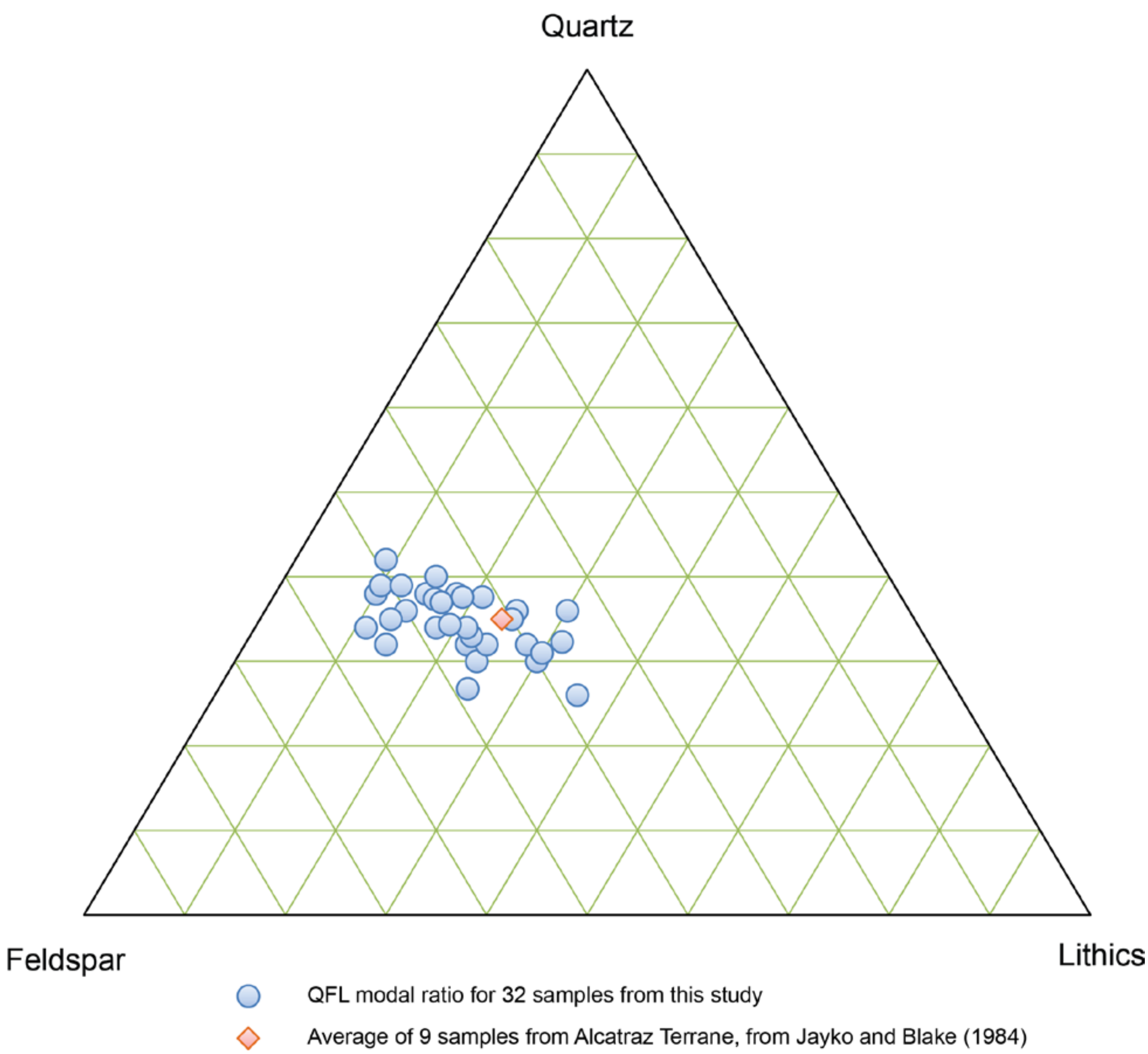

Figure 18. Quartz-feldspar-lithic (QFL) modal ratios.

Structural Geology

The structural geology of Tiburon Peninsula is complex and not completely understood. The study area forms an elongate, northwest-southeast-trending peninsula (Plate 1) that generally parallels the structural trend of the Franciscan Complex in the northern California Coast Ranges. The lithologic units recognized and mapped on the Peninsula - the Coast Range Ophiolite, the Ring Mountain serpentinite-matrix mélange, the Tiburon Ridge Terrane, and the Metalitharenite of Reed Station - form a stack of fault-bounded, nappe-like structures that become younger from top to bottom. In the north, the units appear to be folded into a gentle synform with an axial trace that generally parallels the strike of the Peninsula. Overall, four sets of faults, including thrust faults, normal faults, and strike-slip faults, together with at least two sets of folds, delineate and deform each of the major units.

Ring Mountain Thrust Fault System

The Ring Mountain Thrust Fault system consists of three thrust faults that mark the base of the CRO, RMM, and TRT. In the northern and central portions of the Peninsula, these thrust faults occur high on the ridge, above the subjacent Metalitharenite of Reed Station (Kfm). Cross sections and attitudes reveal that some thrust faults are folded at least twice. The thrust faults are inferred to be west-verging, low-angle faults that initially emplaced the Coast Range Ophiolite (172-165 Ma; Hopson, et al., 1981, 1996, 2008; Shervais et al., 2011) over the Ring Mountain serpentinite-matrix mélange rocks (of unknown age) and the Tiburon Ridge Terrane rocks (±102 Ma; Snow et al., 2010), and juxtaposed these structurally higher units over the Alcatraz Terrane-like rocks (MRS; 94 Ma, Wakabayashi, 2013). Because of folding, the initial dip of the thrust faults cannot be determined.

Unnamed Northwest-Southeast-Trending Normal Faults

Three northwest-southeast-trending high-angle normal faults (down to the southwest) cut both the rock units and the earlier formed structures on the northern portion of the Peninsula at Ring Mountain, as well as on the south Peninsula. Evidence for these faults include small scarps and juxtaposition of structurally lower against structurally higher rock units. On Ring Mountain, the easternmost normal fault is nearly vertical, whereas the westernmost normal fault appears to dip steeply westward.

In the southern Peninsula, a northwest-southeast-trending normal fault of highly variable orientation juxtaposes the northeast margin of a large CRO block (oriented down to the southwest) against units of the subjacent TRT, creating a half-graben-like structure within this portion of the CRO. The low- to high-angle dip of this fault ranges in orientation from northeast to southwest. In part, this may result from subsequent folding along northeast-southwest-trending fold axes (see below).

Trestle Glen Fault, Seafirth Fault, and Hacienda End Fault

Northeast-southwest-trending high-angle normal faults produced offsets of the earlier northwest-southeast-trending normal faults on the Peninsula. The two most prominent of these faults, here referred to as the Trestle Glen Fault and Hacienda End Fault, divide the Peninsula into three high-angle, fault-bounded blocks (from northwest to southeast): the Ring Mountain Block, the Central Tiburon Block, and Southern Tiburon Block (Figure 19). Although evidence of uplift and erosion is seen throughout the

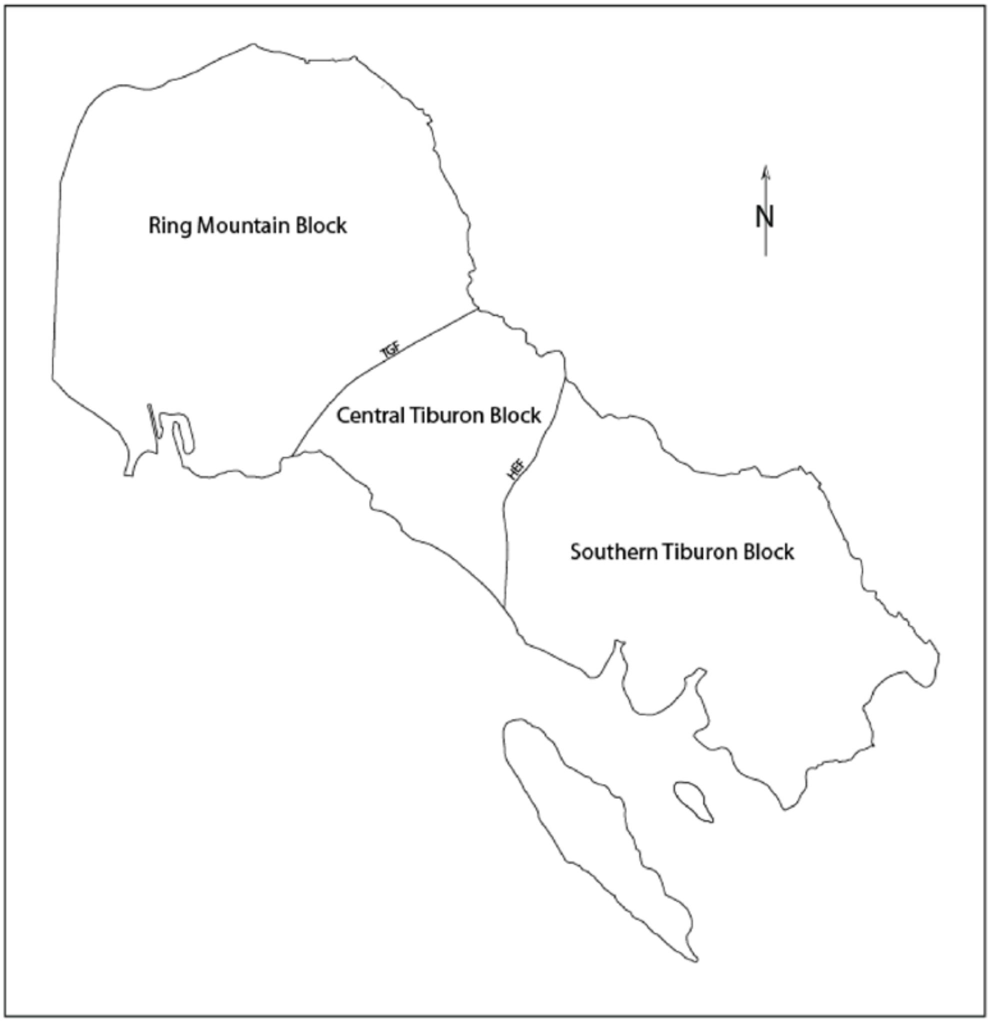

Figure 19. The three high-angle fault-bounded blocks composing Tiburon Peninsula, the Ring Mountain Block, the Central Tiburon Block, and the Southern Tiburon Block are separated by the Trestle Glen Fault (TGF), the Hacienda End Fault (HEF).

Peninsula, the most extensive erosion appears to have occurred in the Central Tiburon Block, where the structurally high CRO is absent and only two small klippe of the RMM remain.

The Trestle Glen Fault is named for the road of that name that crosses the southern Ring Mountain Block. Although the fault is entirely concealed beneath Quaternary deposits, it is likely present due to contrasts in rock units across the valleys in which it lies. A branch of the Trestle Glen Fault, here referred to as the Seafirth Fault, extends east to the area of Seafirth Place on the east-central side of the Peninsula. Both the Trestle Glen and Seafirth Faults are northeast-southwest-trending normal faults. While the Trestle Glen Fault dips southeast (oriented down to the southeast), the Seafirth Fault is slightly arcuate (concave northward) and dips northward to northwestward (oriented down to the north and northwest) making the northern portion of the Central Tiburon Block a graben. The Hacienda End Fault takes its name from its location at the end of Hacienda Drive, where the fault crosses the south-central portion of the Peninsula. The fault has a variable dip along its strike, but notably on the central portion it appears to dip southeast, making the southern portion of the Central Tiburon Block a horst.

Richardson Bay Fault

A shear zone exposed on a narrow portion of beach adjacent to the Richardson Bay Audubon Center and Wildlife Sanctuary, located in the southwest portion of the Ring Mountain Block, appears to be the best exposure of a steeply dipping right-lateral, strike-slip fault that extends southeast across Richardson Bay and passes through the depression occupied by Belvedere Lagoon. Rocks exposed in this shear zone include elongate and brecciated blocks of chert, greenstone, and sandstone entrained within sheared shale exhibiting a shear-fracture fabric trending about N50°W. Wave action has eroded the fault zone lithologies to nearly beach level, and sand has covered much of the exposure, making it hard to judge its width; however, several exposures of the fault zone lithologies can seen along the beach during low tide (Figure 20a & 20b) Another zone of local fault zone brecciation is exposed along the east side of Tiburon Boulevard northeast of the beach exposure (Plates 1 & 2) and may either represent a branch of the Richardson Bay Fault, or the northeast extent of its width in this area of the Peninsula. If so, the zone could locally be over 400 m wide.

Tiburon Ridge Synform and Related Folds

The most prominent fold on the Peninsula is a synform (the Tiburon Ridge Synform), the axis of which is occupied by Jum units of the CRO. In general, the northwest-southeast-trending fold is an open synform, the axis of which has been re-folded within the Ring Mountain Block by an overprinting northeast-southwest-trending fold set (Plate 2). The folding makes the two main Jum units appear as though they are “draped” over the underlying topography. Parallel to the Tiburon Ridge Synform are a series of smaller localized antiforms and synforms best displayed on both the Ring Mountain and Southern Tiburon blocks. The sub-parallel folds observed in the RMM, underlying the more openly folded Jum unit, appear to be tighter, a feature clearly displayed in the RMM and subjacent TRT rocks on the Southern Tiburon Block. In the RMM located northwest of the crest of Ring Mountain (Plate 2), a series of mesoscopic to megascopic antiforms and synforms reveal some asymmetry and tighter folding than that suggested by the contact with the overlying Jum unit.

Unnamed Northeast-Southwest-Trending Folds

Both the northwest-southeast-trending Tiburon Ridge Synform, and the tighter folds observed within the subjacent RMM and TRT units, are refolded along northeast-southwest-trending fold axes. These folds resulted in fold interference patterns most evident on the Southern Tiburon Block. The uplifted block on the northeast side of the Jum unit on the Southern Tiburon Block exhibits a narrow klippe of RMM with a northwest-southeast-trending fold axis that is a part of the Tiburon Ridge Synform (prior to uplift and erosion). This RMM remnant is located above the most complete section of TRT lithologies observed on the Peninsula. Initial folding yielding a synform with a northwest-southeast-trending fold axis, appears to have similarly affected both the RMM and the subjacent TRT lithologies in the Southern Tiburon Block. The synform was later re-folded during a northwest-southeast-directed compressional event that produced northeast-southwest-trending cross-folds. Subsequent uplift of the northeast block along the northwest-southeast-trending high-angle normal fault on the northeast margin of the Jum unit, raised underlying RMM and TRT lithologies to positions now adjacent to the Jum. Both sets of folds, along with the adjacent Jum unit, were then cut by northeast-southwest-trending high-angle normal faults.

Figure 20a. Beach exposure of the fault zone lithologies at low tide (looking SE) exhibiting brecciation and shear-fracture fabric trending about N50°W. Belvedere Island and Angel Island are in background.

Figure 20b. Elongate block of sandstone exhibiting cross fractures and entrained within sheared shale exhibiting a shear-fracture fabric. Note elongate red chert clast within, and oriented parallel to, the shear fabric on lower right side of the hammer. Hammer is about 38 cm in length.

Structural History

A dated chronology of the folding and faulting events on Tiburon Peninsula is not available, although some constraints are known. Clearly, the San Andreas related strike-slip faulting is post-20 Ma. The age of thrusting on the Ring Mountain Thrust Fault System is related to underthrusting of the Franciscan Complex beneath the CRO, which had to have occurred after both emplacement of the CRO onto western North America (165 to 172 Ma.; Hopson, et al., 1981, 1996, 2008; Shervais et al., 2005) and initiation of Franciscan trench sedimentation (post- 125 m.y (?), e.g., Ernst, 2011). Either this faulting occurred post-Yolla Bolly Terrane plus Alcatraz Terrane deposition (<98 Ma, Ernst et al., 2012; <94 Ma, Wakabayashi, 2013), since the Yolla Bolly Terrane-like rocks and Alcatraz Terrane-like rocks on the Peninsula are cut by the thrust faults, or progressive thrusting events occurred, first on the sub-CRO thrust and later on the subjacent thrusts. After thrusting, folds developed in the Jum peridotite of the CRO (inasmuch as the sub-CRO fault is folded). On Ring Mountain, it appears that similar folding is present in the underlying RMM and TRT. On the southern Tiburon Block, tight and overturned, NE-vergent folds on the TRT clearly developed after deposition of TRT rocks, but the relationship of those folds to other structures on the Peninsula, and their different character, render their history enigmatic at the present time.

In general on the Peninsula, the more open folds and thrust faults trend northwest-southeast, reflecting northeast-southwest compression, generally like that which produced the thrust faults. Subsequent to the compressional event(s), tension along a line generally northeast-southwest resulted in high angle faulting parallel to the trend of the Peninsula. Later Peninsula-parallel tension produced a second set of high-angle normal faults (e.g., the Trestle Glen Fault) that cut both earlier-formed structures and all of the pre-Cenozoic units of the Peninsula. Finally, the northwest-southeast-trending, San Andreas- related, Richardson Bay Fault cut across the southwest side of the Peninsula, transporting the block containing the Peninsula toward the southeast relative to rocks of western Marin County (e.g., Marin Headlands Terrane).

Acknowledgements

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Table 1. Modal data from samples from the Metalitharenite of Reed Station collected from Ring Mountain and Tiburon Peninsula.

				Total Rock Fragments												Modal Ratio		
Map No.	Sample No.	Total feldspar	Quartz	Chert	Volcanic and hypabyssal rock fragments	Sedimentary rock fragments	Metamorphic rock fragments	Mica[1]	Chlorite	Opaque	Single mineral[2]	Matrix[3]	Calcite	Other	Total points counted	Q	F	L[4]
27	083103-2	142	132	8	10	61	13	69	22	14	6e, 2p	45	1	2	527	36	39	25
28	090103-1	102	108	6	14	45	25	53	37	19	8e, 2p	84	14	0	517	36	34	30
36	040804-1	179	143	4	4	43	8	55	35	7	3e, 3p, px	39	0	0	525	38	47	15
44	040904-2	109	97	9	3	65	16	78	8	23	4e	102	0	0	514	32	36	31
55	041304-4	133	94	4	2	56	3	98	30	14	5e	62	6	0	507	32	46	22
57	070604-2	134	103	7	5	74	16	110	6	24	10e	41	0	1	526	30	40	30
61	070604-6	153	138	1	4	41	6	70	10	14	2e, 3p	70	0	0	504	40	45	15
63	070804-2	158	137	4	3	54	2	79	13	16	4e, 5p	29	0	0	504	38	44	18
71	071404-2	127	116	4	14	39	6	99	27	17	8e, 4z, 1p	56	0	1	518	38	42	21
76	111304-1	116	92	8	13	47	11	92	49	26	1e, 1z, 2p	60	0	0	518	32	40	28
134	041805-1	149	81	6	6	50	13	126	21	18	3e,1p	48	0	0	522	27	49	25
135	041805-2	127	84	4	8	51	4	116	39	26	2e	65	0	0	526	30	46	24
136	041805-3	116	78	5	17	75	13	78	48	15	7e	52	6	0	510	26	38	36
137	041805-4	117	101	5	9	53	4	112	49	11	3e,1p	47	4	0	516	35	40	25
138	041805-5	113	91	10	7	62	8	91	39	17	2e	67	0	0	507	31	39	30
141	042205-2	137	101	2	15	45	12	55	42	9	16e, 6z, 1cz	66	0	0	506	32	44	24
536	032008-7	131	113	9	7	27	13	97	15	21	6e	74	3	0	516	38	44	19
546	032708-8	166	120	3	8	34	2	61	6	22	11e, 2p	68	0	0	503	36	50	14
152	062605-5	147	127	4	4	18	1	95	18	19	12e, 3z	55	0	0	503	42	49	9
155	032909-1	147	117	7	14	28	6	89	49	19	6e, 1z	22	0	0	505	37	46	17
339	101902-1	162	118	0	17	13	1	85	31	17	11e	50	0	0	505	38	52	10
458	062605-2	149	114	3	10	15	2	117	34	20	9e	29	0	1	503	39	51	10
496	121607-1	160	119	0	44	30	3	56	15	15	9e	52	0	1	504	33	45	22
499	121607-4	126	101	3	27	11	3	64	74	17	8e, 1z	62	7	2	506	37	46	16
500	121607-5	158	126	2	27	9	1	39	59	7	7e	68	0	0	503	39	49	12
501	121607-6	159	100	1	16	14	1	82	53	22	3e	52	0	0	503	34	55	11
502	121607-7	154	109	3	25	22	7	59	32	21	7e	64	0	2	505	34	48	18
528	031508-1	137	103	7	13	33	12	103	28	26	6e	40	0	0	508	34	45	21
529	031508-2	136	100	8	31	14	4	83	84	21	5e	21	0	0	507	34	46	19
538	032008-9	150	119	0	29	16	9	96	24	26	5e	28	0	1	503	37	46	17
549	041808-1	171	116	1	9	32	0	55	4	28	6e	79	0	1	501	35	52	13
609	111008-1	155	92	2	28	8	1	71	87	24	0	32	5	0	505	32	54	14
															Ave	35	45	20

[1] Includes muscovite, biotite, and/or sericite

[2] Single mineral: e = epidote, px = pyroxene, cz = clinozoisite, p = pumpellyite

[3] Mainly includes medium to dark brow n clay-sized particles

[4] Includes chert

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