NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

NCGS FIELD TRIP

The Geology of Sonoma Mountain
Sonoma County, California

Saturday, May 16, 2009

Field Trip Leaders:

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Road Log:

SSU to
Stop 1:

0.0 Miles	Depart parking lot F, Sonoma State University. Make a left onto South Redwood Drive as you depart Parking Lot F. Make a left onto Sequoia Way (campus main entrance).
0.2 Miles	Make a left onto East Cotati Avenue.
0.6 Miles	Make a right onto Petaluma Hill Road and head south for 1.5 miles. Get comfy and prep for an amazing ride on Sonoma County infrastructure at its best!
2.8 Miles	Make a left onto Adobe Road and travel about 5 miles to Old Adobe Road/Frates Road.
8 Miles	Make a right onto Frates Road, travel southwest and make a left onto
9.25 Miles	Hwy. 116 Lakeville Hwy. Travel southeast.
	Keep going straight down Lakeville Highway. Do not turn left where Highway 116 peals away from Lakeville Highway around 11.85 miles. On the right side (about 1:00) is Mt Burdell across the Petaluma River Valley. This prominent mountain is composed of 11 Ma volcanics overlying an unnamed Miocene marine sandstone, which overlies Franciscan Complex. This assemblage is nearly identical to an assemblage to the 11Ma Quien Sabe Volcanics/Mid Miocene Lone Tree Formation/Franciscan Complex east of Hollister and has provided strong evidence for about 190 km of combined offset along faults in the East Bay such as the Hayward and Calaveras Faults.
12.95 Miles	Make a right onto Cannon Lane.
13.35 Miles	**Stop 1: Cannon Lane.**
	Leaving Cannon Lane, make a right back onto Lakeville Highway and head North.
14.45 Miles	Make a right onto 116/Stage Gulch Road. Half way along this route the Lower Petaluma is exposed in gullies and the base of the Middle Petaluma is exposed in the road cuts.
16.45 Miles	Turn **right** onto Adobe/116-Stage Gulch Road at stop sign. Head east. There a great exposures of middle Petaluma Formation friable sandstone and Franciscan-derived gravels in the road cut on your right, near the stop sign.
17.35 Miles	Around this mile mark you are driving through the Rodgers Creek fault zone, so 1. be careful, 2. wear your seat belt and 3. don't text while driving. From this point eastward, you will begin to drop into the Sonoma Valley.
19.5 Miles	Turn Left onto Arnold Drive and head North.
22.4 Miles	Make a left from Arnold Drive onto Grove Street. Here you are looking at the backside of Sonoma Mountain. Follow Grove Street in all it's twists and turns.

Road Map

N
Sonoma State
Parking Lot F
Petaluma Hill Road
Roberts Rd.
Curtis Dr
Lichau Rd.
STOP 3
STOP 4
Willow Brook
Penngrove
Old Redwood Hwy
Oak St
Adobe Rd
Corona Rd
Adobe Road
Petaluma Municipal Airport
Adobe Creek Golf Club
Rainier Ave
N McDowell Blvd
E Washington St
Ely Blvd S
Caulfield Ln
Crinella Dr
S McDowell Blvd
472B
Lakeville St
Petaluma
Petaluma Blvd S
101
Frates Rd
Frates Road
Lakeville Hwy
Lakeville Hwy/116
Adobe Road
Stage Gulch Rd
Stage Gulch Road/116
Lakeville Hwy.
Lakeville
STOP 1
Cannon Lane
MAPQUEST.
STOP 2
Grove Street
Lark Ave
W Verano Ave
El Verano
Sonoma Hwy
Petaluma Ave
W Napa St
Sonoma
Broadway
Arnold Dr
Leveroni Rd
Arnold Drive
W Watmaugh Rd
Stage Gulch Rd
E Bonness Rd
0
800 m
2400 ft

24.2 Miles	**Stop 2: Grove Street.** Here we will look at diatomite and tuff. Note: If there were just a tunnel here, we could be at Stop 3 in no time, however, eat a snack and we'll have a massive lunch wine tasting ordeal at Stop 3 upon circumnavigating the mountain.
26 Miles	Turn right (south) onto Arnold Drive.
27.7 Miles	Turn right Highway 116 (Stage Gulch Road). We will cross Sonoma Mountain along this portion of the drive.
30.3 Miles	Continue straight on what has become Adobe Road. Highway 116 turns off to the left onto Stage Gulch Road. Do not go that way. Stay on Adobe Road heading northwest. We are now back on the west side of Sonoma Mountain with the Petaluma River Valley and the City of Petaluma off to our left.
31 Miles	Big road cut on right side of road exposes Middle Petaluma Formation conglomerate. The clasts are predominantly Franciscan Complex derived. However there is a minor component of fossiliferous sandstone clasts derived from the Briones Formation in the East Bay.
33.2 Miles	Stop sign. Turn right. Do not go straight. The right turn keeps us on Adobe Road.
33.6 Miles	Petaluma Adobe State Historic Park. To the right is the adobe structure that was built in the 1830's and 1840's by General Vallejo.
38.5 Miles	Turn right at the signal onto Petaluma Hill Road.
40.3 Miles	Turn right at the signal onto Roberts Road.
41.7 Miles	Turn right onto Lichau Road
42.9 Miles	Turn right onto paved Road
43 Miles	Turn right into the driveway with the 5001 sign, continue to house and park on grass field next to garden. This is a private residence and the owners have been kind to allow us access to their property. Please be respectful (**STOP 3- Copeland Creek**). Leave Stop 3 the same way we came in, back towards Lichau Road.
43.1 Miles	Turn right onto Lichau Road. Note the hummocky landscape on this part of Sonoma Mountain. We are on a landslide and within the Rodgers Creek Fault Zone.
44.2 Miles	"Gravity Hill" as you cross the crest in the road it appears as if you're going downhill. This is an illusion. Often you will encounter people who will park their cars in neutral and experience what appears to be rolling up hill. Continue Straight on Lichau Road.
44.8 Miles	Stop sign. Go straight.
50 Miles	**Fairfield Osborn Preserve (Stop 4)**

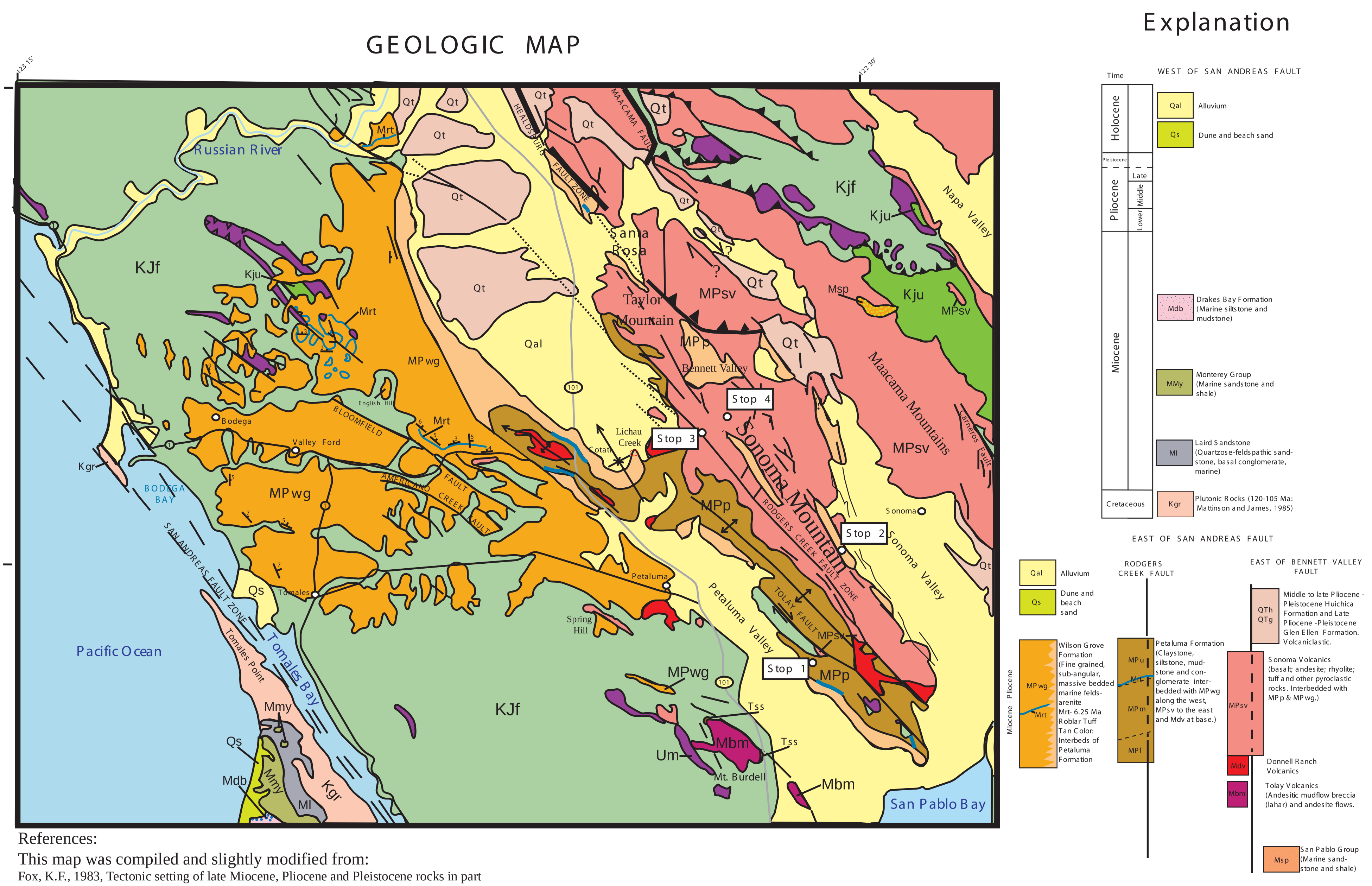
Field Trip Introduction

The Sonoma Mountains (often referred to as ‘Sonoma Mountain’) is bordered on the west by the Petaluma River Valley and the Cotati/Santa Rosa Plain, on the East by the Sonoma Valley and on the south by the San Pablo Bay (Figure 1). The range is about 25 miles long in the north/south direction and at most only 9 miles wide in an east-west direction. Sonoma Mountain reaches an elevation of a little over 2,200 feet above sea level and when viewed from places along the south margin of San Pablo Bay such as Pinole or Richmond appears as a steep-sided plateau. The range is bounded on the East by unnamed faults and the Bennett Valley fault. The Rodgers Creek fault is sub-parallel to the axis of the range however it obliquely crosses the axis of the range from southeast to northwest in the southern portion of the Range. The Tolay fault occurs along the western side of the Range.

Sonoma Mountain contains a relatively thick accumulation of Neogene sedimentary and volcanic rocks in the northern San Francisco Bay Area which typically is characterized by vast exposures of the Jurassic-Cretaceous Franciscan Complex. Between the Tolay fault on the west flank of Sonoma Mountain and the Maacama Mountains, which is the next range to the east, there are no rocks exposed that are older than Late Miocene.

Previous geologic maps indicate that Sonoma Mountain is predominantly composed of volcanic rocks from the Sonoma Volcanics with a subordinate amount of sedimentary rocks of the Petaluma Formation (Wagner and Bortugno, 1982). Recent mapping by Wagner et al. (2002 and 2003) shows in more detail the sedimentary units present on the mountain. Continuing mapping by the authors along remote creek canyons and exposures within landslide headscarps reveals that much of the geology that is obscured by vegetation is actually composed of thick and abundant interbedded fluvial and lacustrine sedimentary units which probably represent about half of the rocks within the mountain. Mesozoic basement doesn't crop out on Sonoma Mountain east of Tolay fault and the depth to basement is unknown within the mountain. Therefore, correlation between known stratigraphic sections in other areas compared with the units mapped at the surface of the mountain is a way at deciphering stratigraphic thickness within the mountain. Since deposition of the non-marine Petaluma formation ceased about 3.5ma, the mountain has undergone uplift and incision. The resulting over-steepened flanks coupled with weak interbedded sedimentary units has resulted in numerous deep seated landslide complexes. Many of these landslides may have been triggered by local large magnitude earthquakes on the Tolay, Rodgers Creek, Bennett Valley and unnamed faults along western Sonoma Valley.

In an effort to build upon the recent maps by Wagner et al. (2002 and 2003), this fieldtrip will focus on describing the ongoing work of mapping the mountain. This includes mapping sedimentary units and additional landslides in more detail. We will also discuss the Neogene tectonic setting of the North Bay with emphasis on palinspastic reconstruction along the Tolay, Rodgers Creek, Bennett Valley and other associated faults.



References:

This map was compiled and slightly modified from:

Fox, K.F., 1983, Tectonic setting of late Miocene, Pliocene and Pleistocene rocks in part of the Coast Ranges north of San Francisco, California: U.S.G.S. Professional Paper, p. 1239, 33.

Dickerson, R.E., 1922, Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles: California Academy of Sciences Proceedings, ser. 5, v. 11, no. 19, p. 527-601.

Wagner, D.L. and Bortugno, D.L., 1982, Geologic Map of the Santa Rosa Quadrangle, California, 1:250,000, Regional Geologic Map Series, Santa Rosa Quadrangle-Map No. 2A.

Figure 1: Geologic map from Wagner and Bortugno (1982). Petaluma Formation modified to show aerial extent of Upper Petaluma Formation. Faults shown in red bounding Sonoma Valley are inferred herein.

Overview of Geologic Units on Sonoma Mountain

Upper Cenozoic units analyzed in Sonoma Mountain and the Sonoma County area are the Wilson Grove Formation, Petaluma Formation, Tolay and Sonoma Volcanics. This field trip builds on studies which modify the stratigraphic nomenclature of these units chiefly on the basis of variations in the composition of conglomerate clasts (Allen, 2003). New data from Wagner et al. (*in press*) on formation descriptions, such as Tolay and Sonoma Volcanics, are implemented here.

The upper Miocene-upper Pliocene Wilson Grove Formation consists chiefly of marine sandstone. Thus far, the Wilson Grove has only been found in Bennett Valley, which is at the northern end of Sonoma Mountain. Conglomerate is interbedded with the sandstone along the eastern margin of the formation near the towns of: Trenton, Molino, Hessel and Cotati (Powell and Allen, 2001; Powell, Allen and Holland, 2004). This interbedded zone was called the Fresh Water Merced by Johnson (1934), the “sand and gravel of Cotati” by Fox (1983), and the “Cotati Member” of the Wilson Grove Formation by Davies (1986). Fox (1983) reported that this interbedded sequence unconformably overlies the Wilson Grove and Petaluma formations, whereas Davies (1986) correlated this sequence with the uppermost Petaluma Formation. Due to new age data, detailed mapping producing reliable stratigraphic sections, the so-called "Cotati Member" is herein late Miocene to Pliocene in age and simply is an interfingering between the Petaluma and Wilson Grove formations. Plainly, the unit name came from describing the area the Wilson Grove and Petaluma formation are interbedded.

The upper Miocene-Pliocene Petaluma Formation (Dickerson, 1922; Youngman, 1989) was divided by Morse and Bailey (1935) into the Lower Petaluma Formation, consisting predominantly of mudstone, and the Upper Petaluma Formation, consisting of sandstone and conglomerate. Morse and Bailey (1935) did not further subdivide the Upper Petaluma Formation, but they did note that the main source of the clasts in the lower portion of the section was the Franciscan Complex, and the main source of the clasts in the upper part of the section was the Monterey.

In this study, the stratigraphic nomenclature of Morse and Bailey (1935) is modified as follows: we follow the usage of later workers (e.g., Weaver, 1949; Travis, 1952; Youngman, 1989) in grouping Morse and Bailey’s Lower and Upper Petaluma formations into the Petaluma Formation. We consider Morse and Bailey’s “Lower Petaluma Formation” to be an informal lower member of the Petaluma Formation. We assign rocks of Morse and Bailey’s “Upper Petaluma Formation” to informal middle and upper members of the Petaluma Formation based on the differences in composition of conglomerate clasts that Morse and Bailey noted and that we quantified in this study. Throughout this guidebook, we refer to these new informal subdivisions as the lower Petaluma, middle Petaluma, and upper Petaluma.

In this study, we assign the interbedded marine sandstone of the eastern Wilson Grove Formation and conglomerate of the western Petaluma Formation to an informal map unit referred to as the “Interbedded Wilson Grove and Petaluma formations”. The western limit of this zone is placed where conglomerate disappears. The eastern limit of this unit was placed where marine sandstone disappears.

In this study, the stratigraphic position of conglomerate clasts of different composition was used to informally subdivide the late Cenozoic units, as described in detail in later sections. The most diagnostic clast types are Franciscan Complex graywacke; white and gray, laminated, foraminiferal, Monterey-derived chert; and Tertiary volcanic rocks.

Description of Upper Cenozoic Units

Late Cenozoic units on which this study focuses are the Wilson Grove Formation, the Petaluma Formation, an informal map unit called “Interbedded Wilson Grove and Petaluma formations,” and the Tolay and Sonoma volcanics.

Wilson Grove Formation

The Wilson Grove Formation consists predominantly of fine- to medium-grained marine sandstone, but exhibits significant lateral (west to east) differences. The east-dipping formation includes a basal conglomerate in the west that is overlain by sandstone. Along its eastern margin, the Wilson Grove sandstone is interbedded with Petaluma conglomerate from its base to its top; this interbedded zone will be discussed in a section following the Petaluma Formation.

The Wilson Grove Formation generally overlies rocks of the Franciscan Complex along an angular unconformity, but it disconformably overlies Tertiary volcanic rocks at Spring Hill and adjacent to the Dunham fault (Travis, 1950). Fox et al. (1985) reported a K-Ar age of 11.76 ± 0.44 Ma for the volcanic rocks at Spring Hill. Because clasts of the volcanic rock are present in the Wilson Grove Formation at Spring Hill, an erosional disconformable contact is indicated.

Thickness varies throughout the Wilson Grove Formation due to the irregular basin it filled (Johnson, 1934). The restored minimum thickness of the Wilson Grove Formation is approximately 2,110 m in the deepest parts of the basin to the west and 610 m to 1,219 m in shallower parts of the basin to the east (Powell et al., 2003).

The lithology of the Wilson Grove changes from the base of the section, in the west near Tomales, to the top of the section, in the east near Steinbeck Ranch.

The base of the Wilson Grove Formation is especially well-exposed at Estero San Antonio. A 5-m-thick, clast-supported basal conglomerate consists of poorly sorted, angular clasts of graywacke, shale, and greenstone that are 5 to 50 cm in diameter encased in a carbonate-cemented, coarse-grained sandstone matrix that contains marine foraminifera, bryozoans, and cetacean bones. The basal conglomerate fines upward into a 3-m-thick bed of matrix-supported, pebbly sandstone followed by a 3-m-thick bed of thick-bedded, low-angle-stratified, fine- to medium-grained sandstone. A 5-m-thick, thick-bedded, bioturbated, fine-grained sandstone unit overlies the low-angle-stratified sediment. The top of this unit is locally channelized.

A resistant, 15- to 17-m-thick, carbonate-cemented, coarse-grained sandstone unit overlies the bioturbated unit at Estero San Antonio and unconformably overlies the Franciscan Complex elsewhere. Burrows in the underlying sandstone are in-filled by overlying coarse-grained sandstone. The coarse-grained sandstone is locally thick-bedded to vaguely planar-cross-stratified and contains minor plane-parallel sets of cross strata. This unit is a litharenite (Folk, 1970). The sand grains are about 2 mm in diameter and are composed of Franciscan Complex metamorphic lithic fragments and minor Tertiary volcanic (red cinder) lithic fragments. The sandstone contains uncommon 20- to 30-cm-thick pebble layers. Imbricated pebbles show transport to the northwest.

The remainder of the section (2,080 m) above this basal sequence consists of thick-bedded to hummocky cross-stratified, marine subfeldsarenite and lithic arkose (Folk, 1970).

The central outcrops of the Wilson Grove Formation between the towns of Bloomfield, Bodega, and Sebastopol and west of the Santa Rosa Valley consist of thick-bedded to hummocky cross-stratified (Harms et al., 1975), fine- to medium-grained, subangular feldsarenite (Holland and Allen, 1998), feldspathic litharenite, and lithic arkose. The thick-bedded sandstone contains numerous burrows.

At Steinbeck Ranch, the ~ 6-Ma Roblar Tuff (Sarna-Wojcicki, 1992) crops out approximately 105 m above the basal contact with the Franciscan Complex (Holland and Allen, 1998). The Roblar is absent from the section south of the Bloomfield fault, apparently due to uplift and erosion (Holland and Allen, 1998; Powell et al., 2003). The tuff contains dish structures. The Roblar is overlain by fine- to medium- grained sandstone that contains fossiliferous lenses that are approximately 15 m long and 25 cm thick. Invertebrate fossils in these lenses consist of disarticulated, broken pelecypods and gastropods that are typically packed tightly.

The Wilson Grove ranges in age from late Miocene to late Pliocene (Powell and Allen, 2001). Newly collected fossils are late Miocene at the base of the formation and late Pliocene at the top (Powell et al., 2003). The ~6-Ma Roblar Tuff has been identified in this formation (Sarna-Wojcicki, 1992).

Sand dollars (*Scutellaster oregonensis*) from the base of the Wilson Grove Formation at Spring Hill are late Miocene (Richard Mooi, California Academy of Sciences, personal communication, 2003; Charles Powell, II, U.S. Geological Survey, personal communication, 2003).

A bird humerus was collected from a fossiliferous bed west of the Meacham Hill fault that has abundant marine pelecypods and gastropods. This humerus may be middle Pliocene in age (Thomas Stidman, University of California Museum of Paleontology, personal communication, 2002). Other fossils from this locality indicate a Pliocene age for the Wilson Grove (Bedrossian, 1971).

Late Pliocene marine fossils occur at the top of the Wilson Grove near Trenton (Powell and Allen, 2001; Powell et al., 2003).

Petaluma Formation

See Stop 1: Cannon Lane

Interbedded Wilson Grove and Petaluma Formations

Rocks in the easternmost outcrop area of the Wilson Grove Formation are interbedded with the westernmost outcrops of the Petaluma Formation. This distinctive interbedded sequence, herein called "Interbedded Wilson Grove and Petaluma formations," is used as an informal map unit and locally unconformably overlies the Franciscan Complex and late Miocene volcanic rocks of Fox et al. (1985).

The most complete sequence of these rocks crops out near the Stony Point Rock Quarry. At the base of the Stony Point section, about 91 m of lower Petaluma Formation shale rests on a volcanic flow (Travis, 1952; Phil Frame, personal communication, 2002).

The shale is overlain by up to 30 m of Franciscan-derived Petaluma conglomerate that contains some Tertiary volcanic clasts. A thin olivine basalt overlies the conglomerate and is overlain by about 1,100 m of interbedded Wilson Grove sandstone and Petaluma conglomerate. The sandstone contains invertebrate marine fossils. Conglomerate clasts lower in the section were derived chiefly from the Franciscan Complex, whereas those higher in the section were derived chiefly from the Monterey. This change in conglomerate clast lithology, plus the presence of the Roblar Tuff in mid-section, correspond to the stratigraphy of the main body of the Petaluma Formation.

Sandstone beds in the interbedded zone are 1 to 3 m thick and locally show high-angle to planar stratification and herringbone cross-stratification. Burrows and disarticulated marine invertebrate fossils occur in structureless sandstone. Three-dimensional views of cross strata and cosets have not been observed due to poor outcrop, so current-direction indicators have not been obtained.

Conglomerate beds in the interbedded zone range in thickness from 25 cm to at least 5 m, and thin and pinch out to the west, as indicated by the absence of conglomerate in outcrops of thick to hummocky cross-stratified sandstone west of this area. The conglomerate is well-sorted, and clasts are very well-rounded. Clast size is approximately 2 cm to 10 cm. Some beds contain clasts that are uniformly 1 to 2 cm in diameter, whereas other conglomeratic beds contain clasts that are uniformly 10 cm in diameter. Conglomerate is typically thick-bedded, although it locally exhibits trough cross-stratification.

Volcanic rocks below the interbedded unit have been dated at ~9 Ma (Graymer et al., 2002). The late Miocene *Scutelaster oregonensis* was collected at the base of this unit at Spring Hill (Richard Mooi, California Academy of Sciences, personal communication, 2003; Charles Powell, II, U.S. Geological Survey, personal communication, 2003). The ~6-Ma Roblar Tuff crops out mid-way through the interbedded zone. Invertebrate marine fossils collected at the top of the interbedded zone at Stony Point and Pepper roads are Pliocene (Bedrossian, 1971).

Tolay Volcanics

The Miocene Tolay Volcanics consist of mafic flows, rhyolite, tuff and breccias that occur in the southern portion of the Sonoma Mountains (Weaver, 1949; Chesterman, Rose and Rice, 1955; Wagner et al., 2002 and 2007; Randolph, 2002 and Allen, 2003). These volcanic rocks range in age between about ~10 and 8 Ma. Many previous geologic maps have referred to these volcanic rocks as “Donnell Ranch Volcanics” but identical ages and lithologies between the Donnell Ranch Volcanics and Tolay Volcanics have lead us to disregard the name “Donnell Ranch Volcanics” for the more widely used and previously established Tolay Volcanics name. It is important to note that the Tolay Volcanics are virtually indistinguishable in hand sample between the slightly older Burdell Mountain Volcanics in Marin County and the slightly younger Sonoma Volcanics which will be discussed below. Besides for outcrops of the Tolay Volcanics in the southern Sonoma Mountains there are also small isolated occurrences west of Sonoma Mountain that underlie the Wilson Grove Formation.

Sonoma Volcanics

At this time the basal contact of the Sonoma Volcanics is concealed on Sonoma Mountain. The southern Maacama Mountains east of Sonoma Mountain, between Sonoma and Napa valleys, yield a more complete stratigraphic sequence of Mesozoic basement, members of the San Pablo and Monterey groups, "Sonoma Volcanics", Glen Ellen and Huichica formations. This stratigraphy is far different to that of Sonoma Mountain. Exposures west of the Rodgers Creek fault indicate the basal contact is within the middle member of the Petaluma Formation. Volcanics mapped as far east as Fairfield, Ca. and east of Napa, Ca. are all lumped as "Sonoma Volcanics". In reviewing maps you will notice the volcanics occupy fault bounded, NW-trending mountain belts that all curve curiously more westerly in concert at their northern terminus. These volcanics rest on different basement rocks, are interbedded with differing formations and range in age. Beginning with Sonoma Mountain, these belts from west to east warrant more study and perhaps may indicate they are of differing origins and may be juxtaposed next to each other today via strike-slip faulting. The Sonoma Volcanics may be viewed as a continuation of the Tolay volcanism being that the arbitrary line drawn between the units is based loosely on time. The Sonoma Volcanics at Sonoma Mountain are recently reported to be about ~8 to 5 Ma in age and the Tolay are reported to be about ~10 to ~8 Ma, therefore close in age and room for overlap. Faulting, folding, uplift and erosion does not permit a continuous stratigraphic sequence, so we're left to mapping bits and pieces and correlating these across the area.

According to Wagner et al. (*in press*), the thickness of the Sonoma Volcanics in the Sonoma Mountain area is about 700m, although the unit is variable. The preliminary geologic map of the Sears Point 7.5' quadrangle by Wagner et al. (2002) shows the Sonoma Volcanics in the southern Sonoma Mountain area consist of a basal rhyolitic unit, overlain by more mafic rocks and tuffs ranging in age from 8.17 to 5.2 Ma from west to east (Youngman, 1989; Van Landingham and Allen, 2007). This Stratigraphy may occupy Sonoma Mountain in its entirety, however, only the younger mafic flows and tuffs conceal the underlying rhyolite unit and basement rocks.

Depositional Environments

Wilson Grove Formation

In the Estero San Antonio area, the ~16-m-thick, coarse-grained unit at the base of the section is thick-bedded, has a concave-up morphology, and contains grains of uniform size. It is interpreted as a channel deposit at the shelf-slope break (Allen and Holland, 1998), but here I interpret it as a sediment-gravity-flow deposit that accumulated in a channel near the head of a submarine canyon. Sandy channel-fill deposits at canyon heads along the outer shelf are commonly thick-bedded (up to 350 m thick), have a concave-up outcrop pattern, and show uniform grain sizes (Stanley and Urug, 1972; Stanley et al., 1978). Foraminifera from this unit include *Buccella frigida* group (transitional and inner shelf), *Neoconorbina* sp. (inner shelf), *Cibicides* sp. (shelf-bathyal; 0-2,000 m), *Cibicidina* sp. (shelf, bathyal?), and *Cibicidoides* sp. (shelf-bathyal). The mixture of shallow-water and deeper-water benthic foraminifera in the same outcrop probably indicates down slope transport of the shallow-water fauna. Rapid deposition of this unit is suggested by the burrows in the fine-grained sandstone below this unit that are in-filled with coarse-grained sediment. Hummocky cross-stratified, fine-grained sandstone in this area is a key indicator of deposition on the continental shelf (Boggs, 1992; Miall, 1995; Powell and Allen, 2001; Powell et al., 2003). Invertebrate fossils from these outcrops suggest water depths of at least 100 m, which is similar to the modern water depths on the outer continental shelf.

In the Steinbeck Ranch area, the Wilson Grove is dominantly thick-bedded and hummocky cross-stratified. Marine fossils from this area suggest water depths of 50 m, which is typical of water depths on modern continental shelves. Immediately prior to deposition, the Tolay Volcanics began erupting in this area. A flow of basalt beneath the Wilson Grove is present along the Dunham Fault near Steinbeck Ranch. Later in time, volcanism of the Sonoma Volcanics is recorded in the Wilson Grove by deposition of the 6.25 Ma Roblar Tuff, now sandwiched between sandstone layers at Steinbeck Ranch, near English Hill, Sebastopol and the Cotati area where the tuff is found in gravelly deposits associated with the interfingered Wilson Grove and Petaluma formations.

The eastern part of the formation ("Interbedded Wilson Grove and Petaluma formations") was deposited in coastal environments, as indicated by interbedding of marine sandstone and fluvial conglomerate. This interpretation is supported by marine invertebrate fossils that were deposited in very shallow-water deltaic environments (Powell and Allen, 2001; Powell et al., 2003).

Petaluma Formation

The Petaluma Formation coarsens upward from mudstone of the lower Petaluma to the sandstone and conglomerate of the middle and upper Petaluma. The lower Petaluma Formation contains transitional marine and lacustrine ostracodes, a barnacle plate (marine), marine foraminifera, and marine diatoms. Some of the ostracodes required fresh-water environments (Dawn Peterson, personal communication, 2002), so the lower Petaluma Formation represents interfingering of fresh-water environments with a marine system. The lower Petaluma Formation has been described as a fine-grained unit that was deposited in a low-energy lacustrine and estuarine environment (Morse and Bailey, 1935). The results of this study support that interpretation. The environment of deposition of the lower Petaluma Formation must have been low-energy and near sea level . The lower Petaluma is interpreted to have been deposited as a distal, fine-grained unit in a delta (Davies, 1986). Distal facies of deltas typically consist of thinner and finer-grained sediment that are coeval with thicker, coarser proximal units (Coleman and Wright, 1975; Heward, 1978; Miall, 1995).

The middle and upper Petaluma contain terrestrial vertebrates and sparse marine invertebrates. The sandstone beds that contain marine fossils exhibit herringbone cross-stratification, which is evidence of a tidal-flat environment (Miall, 1995).

Within the middle and upper Petaluma, abundant normal-graded conglomerate to plane-stratified sandstone are interpreted as gravels and sand deposited within a braided stream environment (Miall, 1977; Boggs, 1992; Reading, 1996).

From about 7 Ma to at least 4.65 Ma, the lower Petaluma Formation was covered by a westward-advancing fluvial system of the middle and upper Petaluma Formation.

Because marine interbeds of the Wilson Grove Formation are present in all three members of the Petaluma Formation, one or both of the following must have occurred: the Petaluma basin was continuously subsiding during deposition of the Petaluma Formation, and/or sea level was continuously rising during deposition of the Petaluma Formation.

Paleocurrents

Paleocurrent measurements from imbricated clasts in the Petaluma Formation and Garrity Member show that paleoflow was to the west-northwest. Thus, interbedding of the fluvial-deltaic Petaluma and marine Wilson Grove indicates a generally west-flowing continental drainage that emptied into a marine basin (open ocean) to the west. This corroborates the paleogeography suggested by Sarna-Wojcicki (1992).

Provenance

The compositions of sandstones and conglomerate clasts in the "interbedded Wilson Grove and Petaluma Formations," and Petaluma Formation provide clues about their provenance.

Sandstone in all units was derived chiefly from the Franciscan Complex, as had been deduced by previous studies (Johnson, 1934; Travis, 1952). However, the middle Petaluma Formation also contains abundant Tertiary volcanic sediment that could have been derived locally from the upper Miocene Donnell Ranch Volcanics and upper Miocene-Pliocene Sonoma Volcanics or from reworking of more distal sources.

Conglomerate in all units was derived chiefly from the Franciscan Complex, the Great Valley Group, the Monterey Group, Tertiary volcanic rocks, and Tertiary quartz-veined sandstone. Strata dominated by Franciscan clasts contain ~7-Ma volcanic rocks and late Miocene (Hemphillian) fossils. Strata dominated by Monterey and Tertiary sandstone clasts contain the 6.25 Ma Roblar Tuff, early Pliocene (early Blancan) vertebrate fossils, and the 4.65-Ma Healdsburg Tuff.

Paleocurrent data from this study indicate that the source rocks for the Wilson Grove and Petaluma formations must have lain to the east, but modern outcrops probably were not sources. Tertiary strata east of the study area consist of friable clastic rocks that lack sources of the clasts of laminated Monterey chert and well-indurated, quartz-veined Tertiary sandstone that are abundant in the study area. Thus, appropriate source rocks either have been eroded away or exist elsewhere. I concur with previous studies (Sarna-Wojcicki, 1992; Dickerman, 1999) that favor the latter option. Furthermore, the Franciscan, Great Valley, and Monterey rocks along the Hayward fault lay beneath the Contra Costa Group in the late Miocene to Pliocene and were not exhumed until after deposition of late Tertiary rocks of the northern Bay Area (Wakabayashi, 1999; Graymer et al., 2002). Thus, Franciscan, Great Valley, and Monterey clasts probably were derived from an indeterminate part of the northern Diablo Range, as was suggested by Dickerman (1999).

Tertiary volcanic clasts in the middle Petaluma probably were derived from the interbeds of Donnell Ranch Volcanics and Sonoma Volcanics.

Tertiary sandstone clasts with quartz veins provide the strongest tie to a specific source area to the east. These distinctive clasts contain veins of microcrystalline to polycrystalline quartz, are cemented by silica or clay, and contain accessory biotite and glauconite.

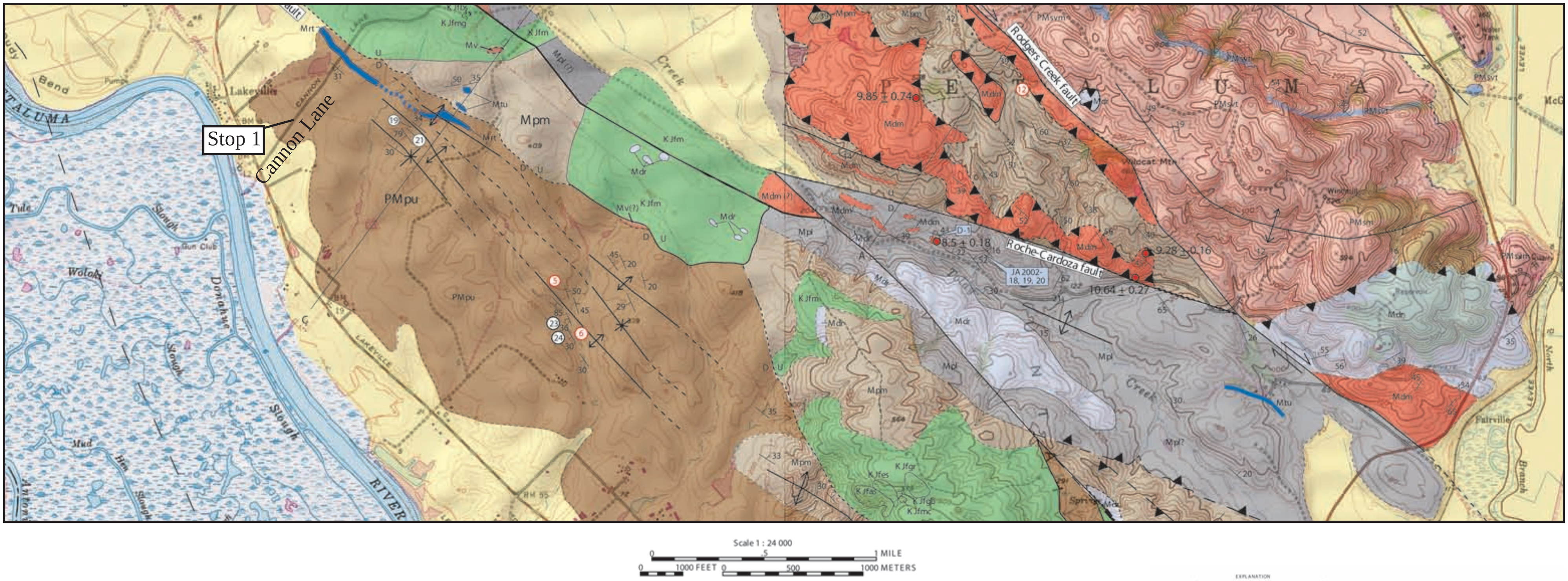
My field checks corroborate dozens of field studies that find widespread veins in sandstones of the Franciscan Complex and Briones Formation, but few to no veins in sandstones of the Great Valley Group and Monterey Group. The clasts of veined sandstone were not derived from the Franciscan because they lack high-pressure minerals typical of the Franciscan and contain accessory biotite and glauconite that do not persist at Franciscan metamorphic conditions. Thus, I conclude that the sandstones with veined quartz probably were derived from the Briones Formation.

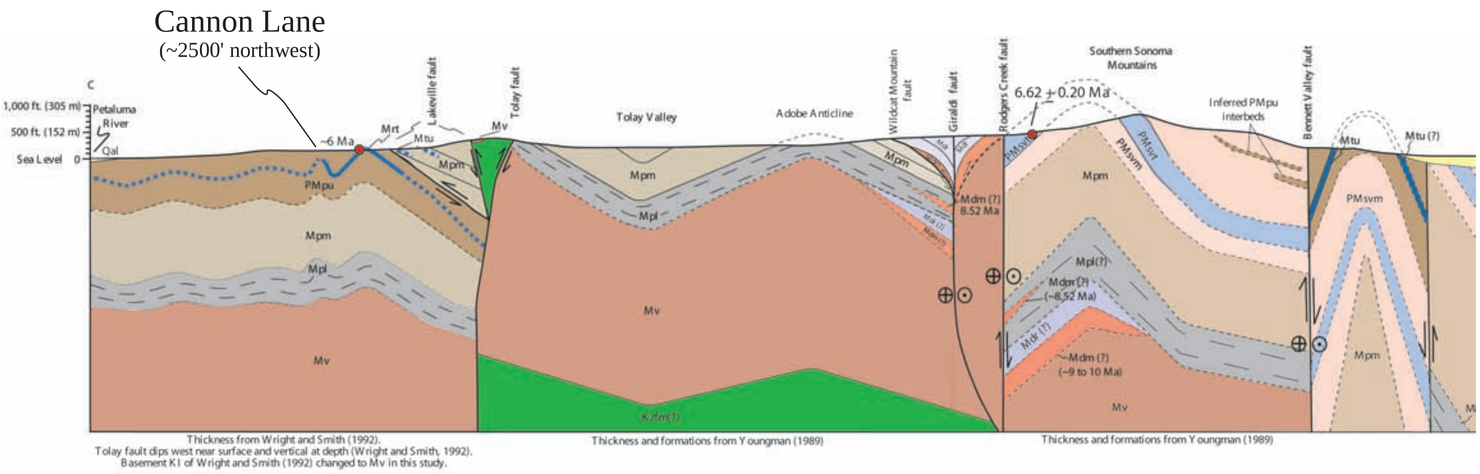
Field examination of the Briones in the eastern Bay Area shows that quartz veins are present near Clayton Road east of San José, but not farther to the north. Veined Briones sandstone crops out within the higher-temperature zeolite zone (peak temperatures 85 °C to at least 100 °C) identified by Murata and Whiteley (1973). The Briones in the higher-temperature zone is cemented by silica and clay, whereas the Briones in the lower-temperature (40–59 °C) zeolite zone north of Niles is cemented by carbonate. Veined Briones clasts in the Petaluma are cemented by silica and clay, further supporting derivation from the Clayton Road region. Conglomerates of the Contra Costa Group that overlie the Briones near Clayton Road also contain Briones sandstone clasts riddled with quartz veins. The combination of quartz veins and high-temperature zeolites is extraordinarily uncommon in rocks younger than about 12 Ma in the Bay Area (Murata and Whiteley, 1973). I consider the Briones near Clayton Road to be the source of the quartz-veined clasts in the “interbedded Wilson Grove and Petaluma Formations,” Petaluma Formation, and Garrity Member in the northern Bay Area.

In light of this evidence, I conclude that the late Miocene – Pliocene Wilson Grove-Petaluma-Garrity Member basin lay much further south than it is today. After deposition of these formations, the basin was extremely fragmented.

Stop 1: Cannon Lane

Here will see the Upper Petaluma Formation (Figure 2). We saw similar exposures of this unit on the field trips last year in the Cotati and Bennett Valley areas (Allen, 2003; Allen et al., 2008). The Roblar Tuff crops out further east along Cannon Lane. The 6.25 Ma Roblar Tuff and overlying Pliocene Upper Petaluma Formation dip west based on mapping in the area between Lakeville Highway and the Tolay Fault by Allen (2003) and Wagner et al. (2002). The stratigraphy of the Petaluma Formation at the surface here is this relationship of Roblar tuff overlain by Monterey-derived gravels/friable conglomerate and tuffaceous sandstone interbeds. Stratigaphically below the Roblar Tuff is the Lower and Middle Petaluma Formation from the base-up section. The Upper Petaluma is well exposed in the Cotati area, but in Cotati the Petaluma interfingers with the marine Wilson Grove Formation. This has caused complexity in various reports of this unit, often giving it a name and unique formation designation of "Cotati gravels" or "Sand and Gravel of Cotati" Fox (1984) and Davies (1986). I came to understand the unit as the Upper Petaluma Formation as a lateral facies encroaching westward and into a marine environment during deposition. Based on marine invertebrate





Photograph of Monterey-derived gravels in Upper Petaluma Formation along Cannon Lane, up-section from Roblar Tuff located further east down Cannon Lane.

Figure 2: Portion of Plate 2 from Allen (2003) showing geology of southern Sonoma Mountains.

paleontology data gathered during Allen (2003), the lower and middle members of the Petaluma contain rare, but exceedingly important marine fossil indicators.

The Petaluma Formation coarsens upward from claystone and siltstone at its base to sandstone and conglomerate higher in the section. The formation crops out between Petaluma Valley and western Sonoma Valley (east of the Rodgers Creek and Bennett Valley faults), through Sonoma Mountain and west of Glen Ellen, within Bennett Valley, and north of Santa Rosa. The formation is covered by Quaternary alluvium in the Santa Rosa-Cotati plain and is exposed from the Cotati area south to Sears Point (Cardwell, 1958). The Petaluma is highly folded and faulted on either side of the Rodgers Creek fault, especially in the Sears Point area.

I split the Upper Petaluma of Morse and Bailey (1935) into informal “middle” and “upper” parts (Allen, 2003; Figure 3). The basis of this revision is the composition of conglomerate clasts, with Franciscan-derived clasts predominant in the middle Petaluma Formation and Monterey-derived clasts predominant in the upper Petaluma Formation. These compositional differences were noted by Morse and Bailey (1935) and were confirmed in my thesis (Allen, 2003).

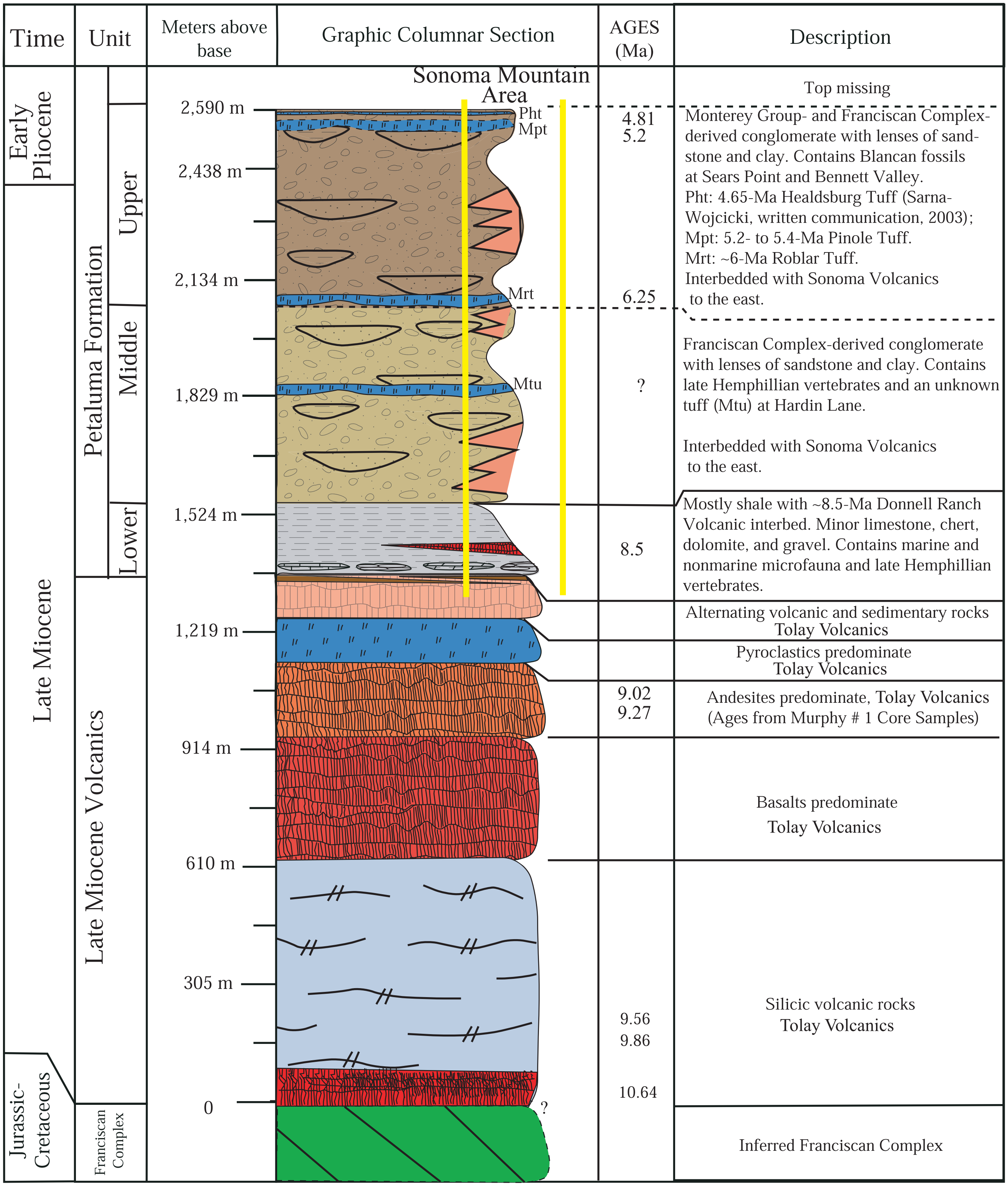
The lower shale, middle and upper conglomerates of the Petaluma Formation interfinger with sandstone of the Wilson Grove Formation to the west (Johnson, 1934); this interbedded zone is described in the next section. This is evidenced by rare marine fossils found in all members of the largely lacustrine and fluvial Petaluma Formation. The Petaluma is interbedded with several mafic flows and tuffs of the Sonoma Volcanics to the east, as indicated by preliminary mapping in the Taylor Mountain and southern Sonoma Mountains areas.

The Petaluma Formation locally overlies 8-10 Ma Tolay Volcanics rocks (Wagner et al., 2007) and the Jurassic-Cretaceous Franciscan Complex along an angular unconformity (Allen, 2003; Youngman, 1989). Borehole data show that the Petaluma Formation overlies Tertiary volcanic rocks in the Petaluma Oil Field area and at the Stony Point Rock Quarry (Morse and Bailey, 1935; Youngman, 1989). The Petaluma Formation unconformably overlies the Franciscan Complex west of the Tolay fault in the Sears Point-Lakeville area and east of the Dunham fault.

At the Petaluma Oil Field general area, the Petaluma Formation is at least 1,220 m thick, including 183 m of basal mudstone (lower Petaluma) and at least 1,037 m of conglomerate and sandstone of the middle and upper Petaluma. The lower Petaluma Formation thins to 91 m at the Stony Point Rock Quarry.

Complete sections of the lower, middle, and upper Petaluma are exposed in the Stony Point Rock Quarry area and in an unnamed creek between Lynch and Adobe creeks. Total stratigraphic thickness at each location is about 1,220 m, which is similar to the total thickness for the formation at the Petaluma Oil Field. The following section describes the stratigraphy and lithology of the Petaluma Formation based chiefly on the outcrops in these two key areas.

The lower Petaluma Formation consists of blue-gray, thick- and thin-bedded, structureless to thinly laminated mudstone and very fine-grained sandstone. The unit is buried in Sonoma Mountain where younger rocks at the surface conceal it. The predominant rock type is thin-bedded to thinly laminated, planar-cross-stratified clayey siltstone. Laminae are 0.5 to 1.0 mm thick and have fissile parting. Cross strata, if present, must exceed 120 cm in thickness (McKee and Weir, 1953). The thick-bedded,



Top missing

Monterey Group- and Franciscan Complex-derived conglomerate with lenses of sandstone and clay. Contains Blancan fossils at Sears Point and Bennett Valley.
Pht: 4.65-Ma Healdsburg Tuff (Sarna-Wojcicki, written communication, 2003);
Mpt: 5.2- to 5.4-Ma Pinole Tuff.
Mrt: ~6-Ma Roblar Tuff.
Interbedded with Sonoma Volcanics to the east.

Franciscan Complex-derived conglomerate with lenses of sandstone and clay. Contains late Hemphillian vertebrates and an unknown tuff (Mtu) at Hardin Lane.

Interbedded with Sonoma Volcanics to the east.

Mostly shale with ~8.5-Ma Donnell Ranch Volcanic interbed. Minor limestone, chert, dolomite, and gravel. Contains marine and nonmarine microfauna and late Hemphillian vertebrates.

Alternating volcanic and sedimentary rocks
Tolay Volcanics

Pyroclastics predominate
Tolay Volcanics

Andesites predominate, Tolay Volcanics
(Ages from Murphy # 1 Core Samples)

Basalts predominate
Tolay Volcanics

Silicic volcanic rocks
Tolay Volcanics

Inferred Franciscan Complex

Figure 3. Stratigraphic section of Petaluma Formation and underlying Miocene volcanic rocks at the Petaluma Oil Field Area in the foothills of Sonoma Mountain. Geology of Sonoma Mountain delineated by yellow lines. Thickness of Petaluma Formation from Morse and Bailey(1935) with lithology data from Allen (2003). Volcanic rocks below Petaluma Formation from Morse and Bailey (1935); ages from Youngman (1989). Lithologic symbols from Compton (1985).

structureless lower Petaluma Formation contains microfossils and has flaggy to slabby parting (McKee and Weir, 1953).

In the southern Tolay Valley area, the lower Petaluma Formation includes chert, dolomite, and limestone. The chert is brown and orange-brown with abundant siliceous cement. Petrographic analysis shows that the chert contains 20-30% diatoms. Creamy-white dolomite crops out locally. Petrographic analysis shows this rock contains mostly fine-grained dolomite and a few large dolomite rhombs, with clusters of closely packed ostracode shells. Limestone is grayish-white.

The lower Petaluma also contains minor clastic interbeds of sandstone and conglomerate. Clasts are about 2 cm across and angular, and consist chiefly of metagraywacke and chips of black, angular shale. Sandstone is poorly sorted, medium- to coarse-grained, and planar- to trough-cross-stratified, and forms beds about 5 cm thick.

The contact between the lower and middle Petaluma is placed at the top of the highest laminated shale that is overlain by thick beds of either coarse-grained, planar- to trough-cross-stratified sandstone or coarse conglomerate. Conglomerate is channelized into the uppermost portion of the lower Petaluma Formation. Rip-up clasts of the lower Petaluma up to 10 cm long are present within the lowest 30 cm of the middle Petaluma. These rip-up clasts comprise up to 15% of the clast population.

Most conglomerate beds in the middle and upper Petaluma are lenticular, with a maximum length of 5 m and maximum thickness of 2 m. Conglomerate beds up to 7 m thick have been observed in the field, but their lateral extents are not well-constrained due to poor exposure. Thin, lenticular pebble conglomerate forms interbeds 20 to 25 cm long and 10 cm thick in thick-bedded sandstone outcrops. Conglomerate beds are planar- and trough-cross-stratified and clast-supported, and fine upwards into planar-stratified sandstone. Clasts are subangular and poorly to moderately sorted.

Conglomerate clasts in the middle Petaluma Formation are dominated by Franciscan Complex material; those in the upper Petaluma Formation are dominated by Monterey sources. Average clast size is about 5 cm, with some clasts up to 25 cm by 15 cm. Outcrops in Bennett Valley and north of Santa Rosa contain clasts 4 to 6 cm across. These outcrops are rare and poorly exposed, so larger clasts may be present. Six paleocurrent measurements show westward flow.

Sandstone is thin- to thick-bedded (a few centimeters to about 20 m thick), planar- and trough-cross-stratified, low-angle cross-bedded, and plane-parallel-bedded. Sand grains are well-sorted, medium- to coarse-grained, angular to subangular, and lithic-rich. According to petrologic data, sandstone in both the middle and upper Petaluma is litharenite derived from metamorphic rocks (Franciscan Complex), as recognized by Johnson (1934). Sandstone in the middle Petaluma contains a higher percentage of volcanic lithic fragments than sandstone in the upper Petaluma.

The Petaluma Formation is late Miocene to Pliocene according to radiometric and paleontological data. Vertebrate, invertebrate, and plant fossils from the Petaluma Formation were identified by Osmont (1905), Dickerson (1922), Morse and Bailey (1935), Stirton (1952), and Davies (1986). New microfossils and vertebrate and invertebrate fossils were collected during this study. All fossil descriptions, ages, and localities, as well as descriptions of their host rocks, are presented in.

The lower Petaluma contains an interbedded mafic flow dated at about 8.5 Ma (Youngman, 1989), and overlies ~9.3-Ma volcanic rocks of Graymer et al. (2002). A late

Miocene (Hemphillian) horse tooth was collected at the top of this unit at the Stony Point Rock Quarry (Charles Repenning, written communication, 2002).

The middle Petaluma contains interbeds of the Sonoma Volcanics that have yielded K-Ar and Ar-Ar dates of about 7.37 to 6 Ma (Fox et al., 1985; Youngman, 1989). Fossils collected in this unit are Hemphillian in age.

The ~6-Ma Roblar Tuff crops out near the base of the upper Petaluma. The upper Petaluma contains early Pliocene fossils and the 4.65-Ma Healdsburg Tuff in Bennett Valley.

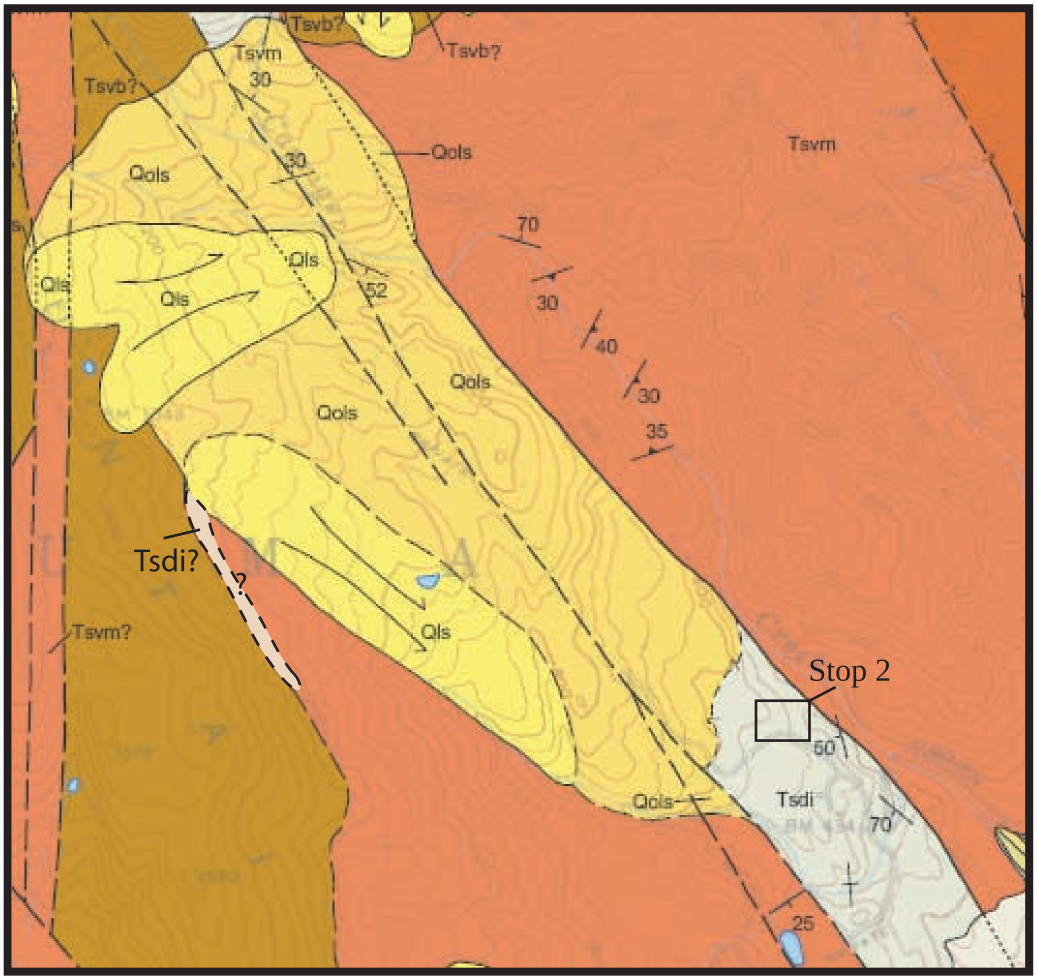
Stop 2: Grove Road

Here we will see diatomite and interbedded tuff of the Petaluma Formation (Figure 4). Further up-section, the diatomite grades into sandstone and gravelly sandstone. Diatomite and associated sediments of claystone and sandstone are exposed as interbeds in the volcanic sequences of Sonoma Mountain (Figure 5). East of the Rodgers Creek fault, this unit outcrops several miles to the south of the field trip stop and several miles to north to Jack London State Park and Bennett Valley. The Late Miocene-Pliocene ages of the unit fit well with the Late Miocene-Pliocene ages from the Petaluma Formation.

Diatomite is light in color, low density, very finely porous, soft and chalky, very friable, very fine-grained, siliceous sedimentary rock. It also has low thermal conductivity and a rather high fusion point. Diatomite is used as a filter; an absorbent for industrial spills, pet litter, a filler in a variety of products from paints to dry chemicals, an insulation material as sawn and molded shapes as well as loose granular, a mild abrasive in polishes, and a silica additive in cement and various other compounds.

New diatom and tephra data indicate the age of this unit is Late Miocene-Pliocene (Figure 5). A 4.88 Ma tuff is exposed in this section of diatomite. The tuff was kindly dated by Ar/Ar method by Dr. Alan Deino at Berkeley Geochronology Center, Berkeley, CA. Further south at Donnell Ranch, Dr. Deino and I collected a pumice lapilli tuff interbedded with diatomite. The age of this tuff is about 5.2 Ma, indicating this diatomite/tuff unit would be stratigraphically below us at Grove Road.

Diatomite units are often mapped near major landslides exposures (Figure 6). New maps by the CGS (Wagner et al., 2002 and 2003) depict more accurately the amount of sedimentary units exposed through Sonoma Mountain as opposed to older maps of the area (Weaver, 1949; Wagner and Bortugno, 1992).



Map Source: Wagner. D.L., Randolph-Loar, C.E., Witter, R.C., and Huffman, M.E., 2003, California Geological Survey Preliminary geologic map of the Glen Ellen 7.5' Quadrangle: Available at: http://www.consrv.ca.gov/cgs/information/geologic_mapping/index.htm

Explanation

Qls Landslides. Includes debris flow and block slump landslides. Arrows show the direction of movement.

Tsv (**Tsvb**, **Tsvm**, **Tsvt**, **Tsvr**) Sonoma Volcanics- Mafic lava flows, breccias, agglomerate tuff, tuff breccia with interbedded tuffaceous sediments; also includes dacitic to rhyolitic lava flows, debris flows, tuff, and tuffaceous sediment. The age range for the Sonoma Volcanics on this quadrangle is 8.65 to 3.80 Ma (Fox and others, 1985). There is a diatomite-rich sequence within the Sonoma Volcanics (Tsvdi). The Sonoma Volcanics are divided into the following subunits:

Tsvb- Basalt flows. The basalt flows near Carriger Creek yielded an Ar/Ar date of 4.1 Ma (Robert Fleck, Personal communication, 2004).

Tsvm- Mafic flows and breccias. Andesite and basaltic andesite.

Tsvt- Silicic tuff and interbedded tuffaceous sediments. Interbedded sand and gravel is similar to the Petaluma Formation.

Tsvr- Rhyolitic to dacitic flows, breccias, and sediments. Pink, white, gray, brown flow banded rhyolite in flows, debris flows and breccia. Interbeds of sand, gravel, and tuff. Dacite near Carriger Creek is dated at 5.79 +/- 0.3 Ma; Robert Fleck (Personal communication, 2004).

Ts (Tsdi) Sand and gravel, tuff and diatomite. Rich in both Franciscan and Sonoma Volcanic detritus. Contains tuff dated at 4.8 +/- 0.03 Ma (J. Allen, Written communication).

Tp (**Tpu**, **Tpm**, Tpd) Petaluma (?)Formation. A predominantly fluvial deposit with lacustrine diatomite, lignite, and tuff. Maybe correlative with the upper part of the Petaluma Formation on the Sears Point and Petaluma River quadrangles.

Tpu - A predominantly fluvial siltstone, that contains diatomite, tuff, and gravel. The gravel contains siliceous shale chips from the Monterey Formation. Tpu may be correlative with the upper part of the Petaluma Formation west of the Rodgers Creek Fault. Tpd - A diatomite-rich facies of the Upper Petalume Fm. Also contains tuff interbeds.

Tpm - Middle part of the Petaluma Formation west of the Rodgers Creek Fault. Characterized by gravel rich in Franciscan detritus.

Figure 4: Geologic map and photo of diatomite and tuff sequence at Grove street; Stop 2.

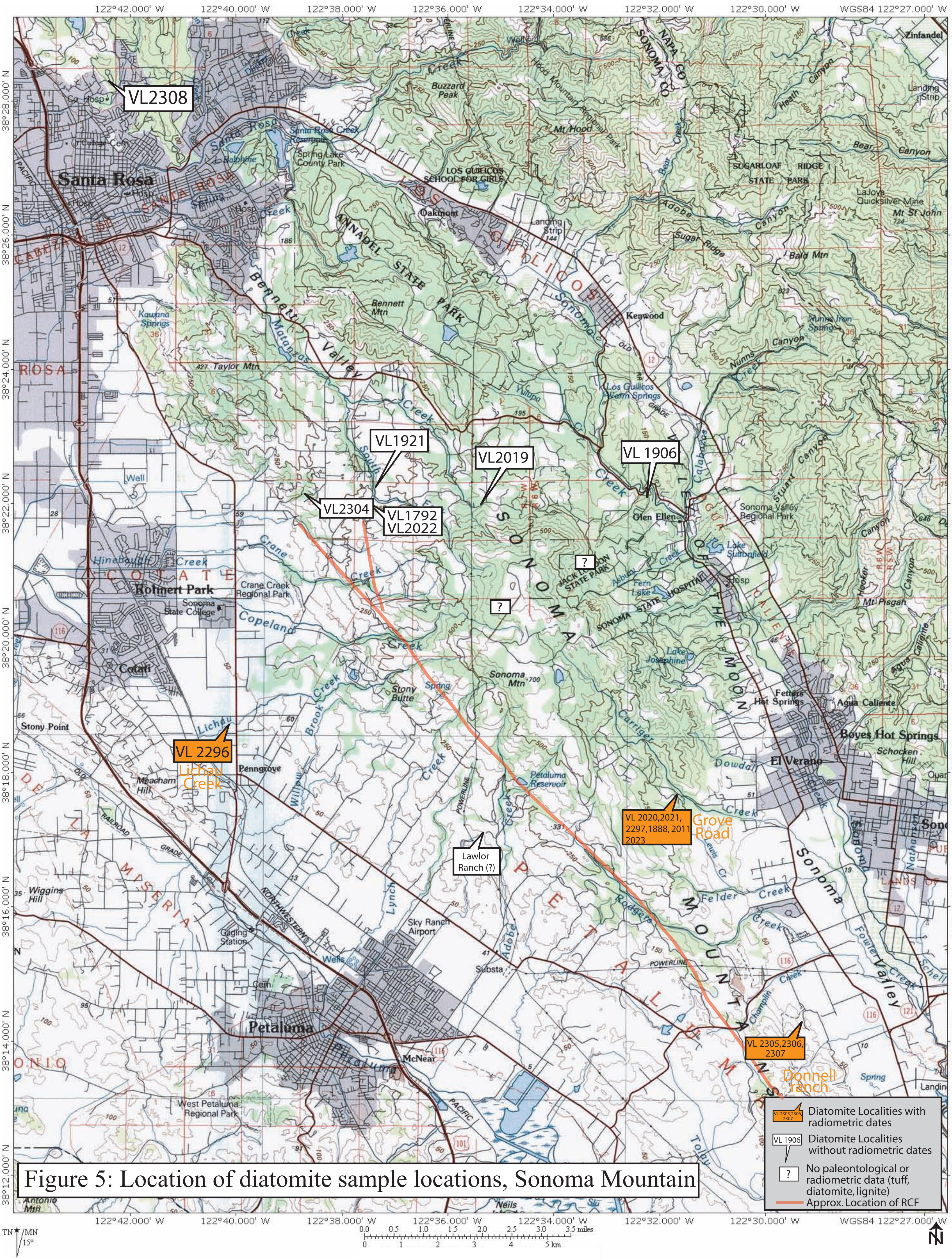
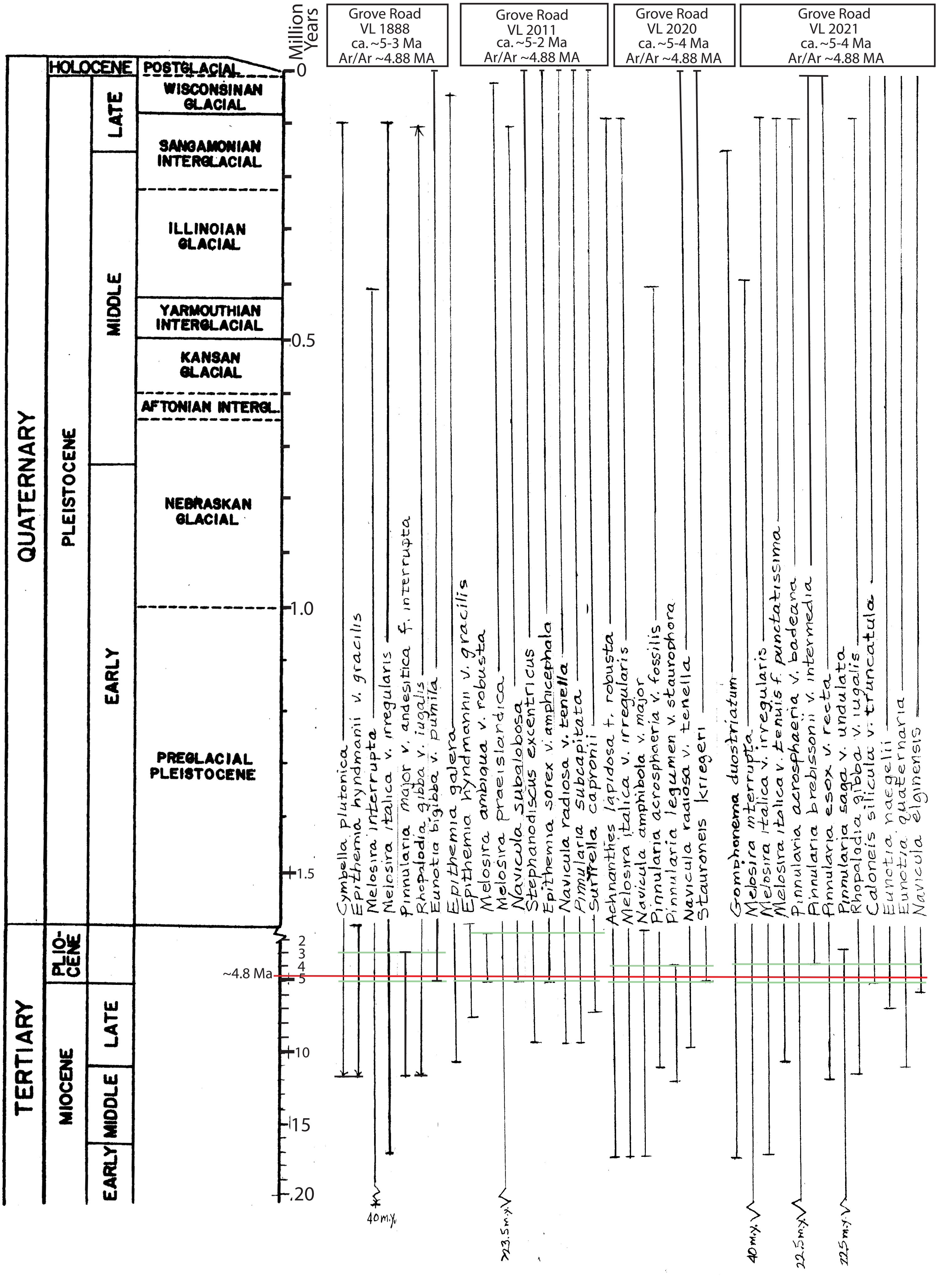
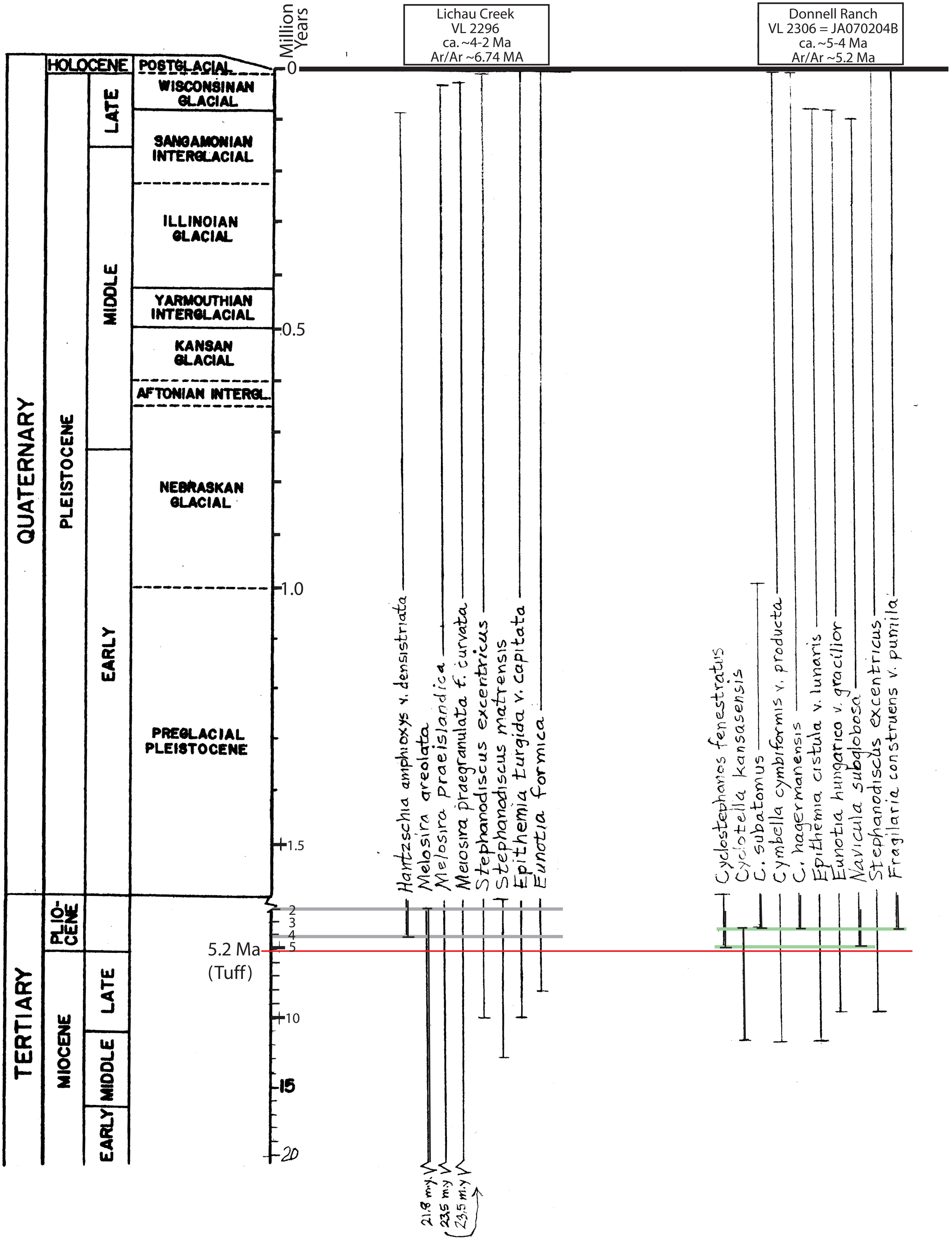
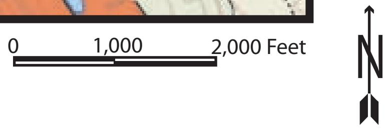


Figure 5: Location of diatomite sample locations, Sonoma Mountain


Grove Road
VL 1888
ca. ~5-3 Ma
Ar/Ar ~4.88 MA
Grove Road
VL 2011
ca. ~5-2 Ma
Ar/Ar ~4.88 MA
Grove Road
VL 2020
ca. ~5-4 Ma
Ar/Ar ~4.88 MA
Grove Road
VL 2021
ca. ~5-4 Ma
Ar/Ar ~4.88 MA
Million Years
0
0.5
1.0
1.5
2
3
4
5
10
15
20
~4.8 Ma
QUATERNARY
PLEISTOCENE
HOLOCENE
POSTGLACIAL
LATE
MIDDLE
EARLY
WISCONSINAN GLACIAL
SANGAMONIAN INTERGLACIAL
ILLINOIAN GLACIAL
YARMOUTHIAN INTERGLACIAL
KANSAN GLACIAL
AFTONIAN INTERGL.
NEBRASKAN GLACIAL
PREGLACIAL PLEISTOCENE
TERTIARY
PLIO-CENE
MIOCENE
LATE
MIDDLE
EARLY
Cymbella plutonica
Epithemia hyndmanii v. gracilis
Melosira interrupta
Melosira italica v. irregularis
Pinnularia major v. andesitica f. interrupta
Rhopalodia gibba v. iugalis
Eunotia bigibba v. pumila
Epithemia galera
Epithemia hyndmanii v. gracilis
Melosira ambigua v. robusta
Melosira praeislandica
Navicula subalobosa
Stephanodiscus excentricus
Epithemia sorex v. amphicephala
Navicula radiosa v. tenella
Pinnularia subcapitata
Surirella capronii
Achnanthes lapidosa f. robusta
Melosira italica v. irregularis
Navicula amphibola v. major
Pinnularia acrosphaeria v. fossilis
Pinnularia legumen v. staurophora
Navicula radiosa v. tenella
Stauroneis kriegeri
Gomphonema duostriatum
Melosira interrupta
Melosira italica v. irregularis
Melosira italica v. tenuis f. punctatissima
Pinnularia acrosphaeria v. badeana
Pinnularia brebissonii v. intermedia
Pinnularia esox v. recta
Pinnularia saga v. undulata
Rhopalodia gibba v. iugalis
Caloneis silicula v. truncatula
Eunotia naegelii
Eunotia quaternaria
Navicula elginensis
40m.y.
>23.5m.y.
40m.y.
22.5m.y.
22.5m.y.

Lichau Creek
VL 2296
ca. ~4-2 Ma
Ar/Ar ~6.74 MA
Donnell Ranch
VL 2306 = JA070204B
ca. ~5-4 Ma
Ar/Ar ~5.2 Ma
Million Years
0
0.5
1.0
1.5
2
3
4
5
10
15
20
5.2 Ma
(Tuff)
QUATERNARY
TERTIARY
HOLOCENE
PLEISTOCENE
PLIO-CENE
MIOCENE
LATE
MIDDLE
EARLY
LATE
MIDDLE
EARLY
POSTGLACIAL
WISCONSINAN GLACIAL
SANGAMONIAN INTERGLACIAL
ILLINOIAN GLACIAL
YARMOUTHIAN INTERGLACIAL
KANSAN GLACIAL
AFTONIAN INTERGL.
NEBRASKAN GLACIAL
PREGLACIAL PLEISTOCENE
Hantzschia amphioxys v. densistriata
Melosira areolata
Melosira praeislandica
Melosira praegranulata f. curvata
Stephanodiscus excentricus
Stephanodiscus matrensis
Epithemia turgida v. capitata
Eunotia formica
Cyclostephanos fenestratus
Cyclotella kansasensis
C. subatomus
Cymbella cymbiformis v. producta
C. hagermanensis
Epithemia cistula v. lunaris
Eunotia hungarica v. gracilior
Navicula subglobosa
Stephanodiscus excentricus
Fragilaria construens v. pumila
21.8 m.y.
23.5 m.y
23.5 m.y

Map Source: Wagner. D.L., Randolph-Loar, C.E., Witter, R.C., and Huffman, M.E., 2003, California Geological Survey Preliminary geologic map of the Glen Ellen 7.5' Quadrangle: Available at: http://www.consrv.ca.gov/cgs/information/geologic_mapping/index.htm



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Ts (**Tsdi**) Sand and gravel, tuff and diatomite. Rich in both Franciscan and Sonoma Volcanic detritus. Contains tuff dated at 4.8 +/- 0.03 Ma (J. Allen, Written communication).

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Tp (**Tpd**, **Tpu**, **Tpm**) Tpu - A predominantly fluvial siltstone, that contains diatomite, tuff, and gravel. The gravel contains siliceous shale chips from the Monterey Formation. Tpu may be correlative with the upper part of the Petaluma Formation west of the Rodgers Creek Fault. Tpd - A diatomite-rich facies of the Upper Petalume Fm. Also contains tuff interbeds.

Tpm - Middle part of the Petaluma Formation west of the Rodgers Creek Fault. Characterized by gravel rich in Franciscan detritus.

Figure 6: Geology of Sonoma Mountain at the Grove Road area.

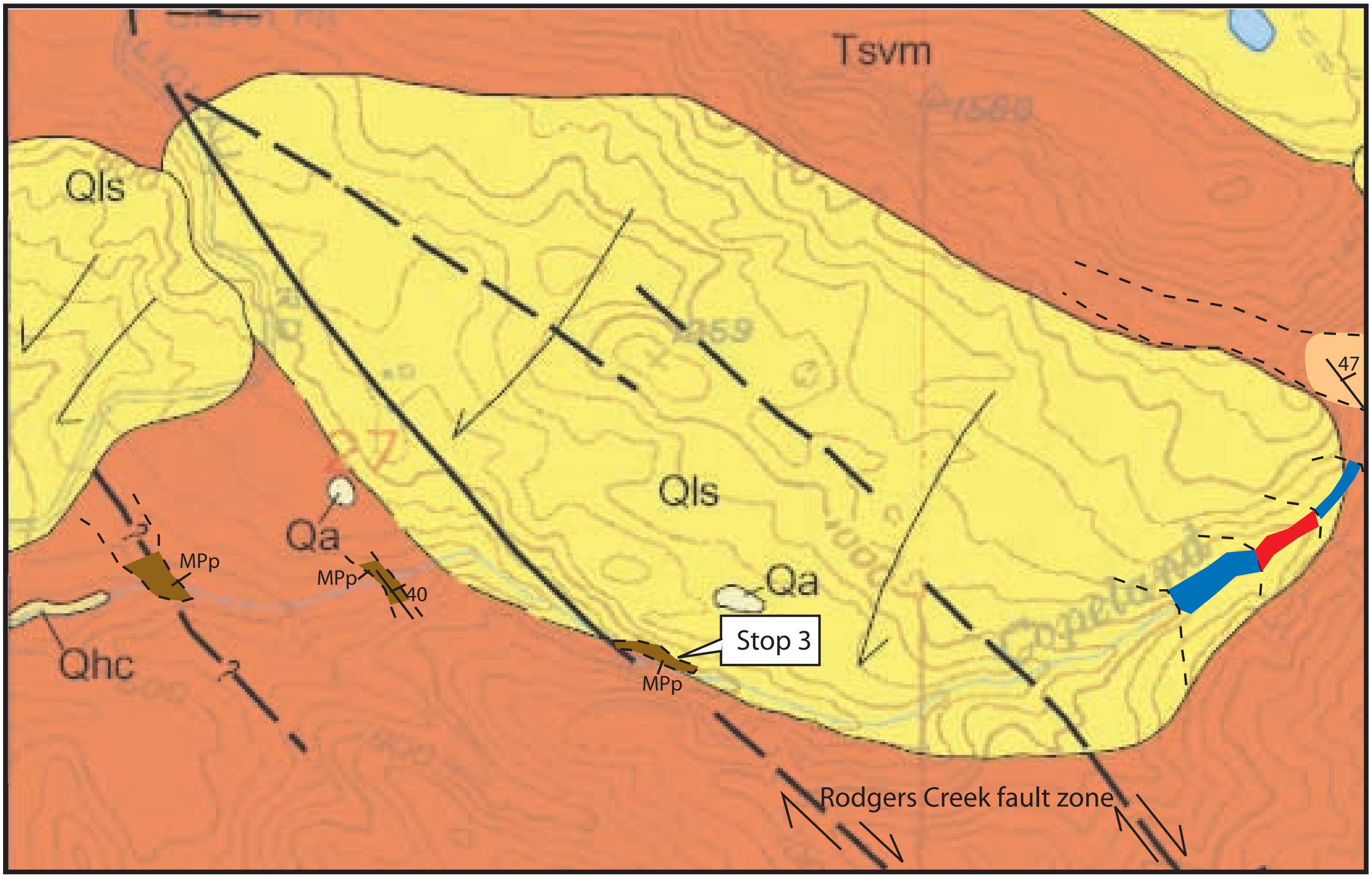
Stop 3: Copeland Creek

Middle Petaluma Formation consisting of lacustrine claystone, fluvial sandstone and Franciscan-derived conglomerate are exposed in the Copeland Creek as interbeds within the Sonoma Volcanics. Some of the units display some shearing both by Rodgers Creek fault splays and landslide movement (Figure 7). Similar Petaluma formation is exposed east of the RCF at Lafferty Ranch, giving an offset of 4km using this data point alone. Taken with other data such as offset mafic flows and rhyolite flows, and diatomite units, these combined argue with some confidence ~ 4-7 km max displacement along the Rodgers Creek fault. This conclusion still needs to be tested. Wagner et al. (2007) brings to the table another long-term displacement study that is very detailed and suggests about 25 km of total offset along the RCF since late Miocene time. Although both studies provide reasonable data, there is future work to be done in order to get closer to perfecting the models.

A piercing point using rhyolitic flows, agglomerates and tuffs has been suggested by Wagner et al. (2007; Figures 8 & 9). The piercing point/area according to them is a rhyolite sequence east of the RCF near Sears Point and a similar sequence at Taylor Mountain west of the fault. This is probably the case for determining about 25 km long-term displacement along the RCF, if it can be shown that basal Sonoma Volcanic rhyolite units do not underlie the rest of Sonoma Mountain north of Sears Point and east of the RCF, where younger units, presently at the surface, may conceal the rhyolite at depth. Also, straddling along the RCF on either side of the fault are several rhyolite units between Sears Point and Taylor Mountain. Some of these units are mappable at 1:24,000 scale and some are small windows of rhyolite and rhyolitic tuffs near the base of the mafic sections which dip east and into the mountain. To study the similarity of these rhyolite units, three areas of rhyolite were sampled, taken to CSU Fresno by the author and analyzed by kindly using their XRF. Similar flow-banded rhyolite samples both in hand sample and petrographically were selected.

What we found was the three sampled locations (Sears Point, Manor Lane and Taylor Mountain) were indeed rhyolite! However, exact chemical fingerprint matching cannot be concluded between all three samples as the major and trace element geochemistry is quite different for each, suggesting they are all different flows represented by different chemistries of possible slightly different magma chambers, all coincidentally erupting flows at around the same time, as the basal Sonoma rhyolites sequences are about 7-8 Ma at Sonoma Mountain. In terms of comparing and correlating samples based on closest matches, the Manor Lane and Sears Point samples are more similar in their trace and major element geochemistry. This would suggest ~5km offset since around 7 Ma if these two rhyolite units are correlative (Table 1).

On the other hand, these units on either side of the fault may look the same, but are different in age and therefore may be shown to be offset 25-30 km along the RCF. Actively recorded seismicity along the fault is occurring in western Bennett Valley. From this point south to San Pablo Bay, the fault is considered locked and has a high probability of producing a M7 or greater quake within the next 30 years or less (WGCEP, 2003).



Map Source: Wagner. D.L., Randolph-Loar, C.E., Witter, R.C., and Huffman, M.E., 2003, California Geological Survey Preliminary geologic map of the Glen Ellen 7.5' Quadrangle: Available at: http://www.consrv.ca.gov/cgs/information/geologic_mapping/index.htm

Explanation

Qls Landslides. Includes debris flow and block slump landslides. Arrows show the direction of movement.

Tsv **Tsvb** **Tsvm** **Tsvt** **Tsvr** Sonoma Volcanics- Mafic lava flows, breccias, agglomerate tuff, tuff breccia with interbedded tuffaceous sediments; also includes dacitic to rhyolitic lava flows, debris flows, tuff, and tuffaceous sediment. The age range for the Sonoma Volcanics on this quadrangle is 8.65 to 3.80 Ma (Fox and others, 1985). There is a diatomite-rich sequence within the Sonoma Volcanics (Tsvdi). The Sonoma Volcanics are divided into the following subunits:

Tsvb- Basalt flows. The basalt flows near Carriger Creek yielded an Ar/Ar date of 4.1 Ma (Robert Fleck, Personal communication, 2004).

Tsvm- Mafic flows and breccias. Andesite and basaltic andesite.

Tsvt- Silicic tuff and interbedded tuffaceous sediments. Interbedded sand and gravel is similar to the Petaluma Formation.

Tsvr- Rhyolitic to dacitic flows, breccias, and sediments. Pink, white, gray, brown flow banded rhyolite in flows, debris flows and breccia. Interbeds of sand, gravel, and tuff. Dacite near Carriger Creek is dated at 5.79 +/- 0.3 Ma; Robert Fleck (Personal communication, 2004).

🟧 Thick diatomite, claystone and sandstone

🟦 Massive agglomerates, fine-grained ash and coarse pumice-lappilli tuff.

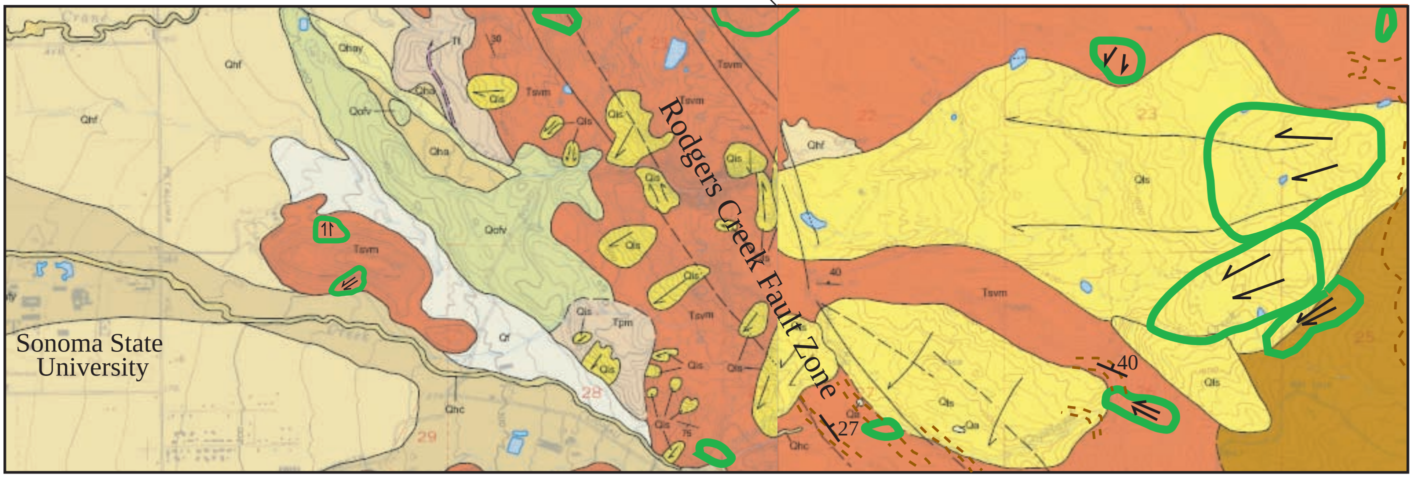
Figure 7: Geology of Sonoma Mountain at Copeland Creek.

A

Reference: Huffman, M.E. and Armstrong C.F., 1980, Geology for Planning in Sonoma County, California, SR 120.

Area where quadrangles do not overlap properly

B



Reference: Wagner. D.L., Randolph-Loar, C.E., Witter, R.C., and Huffman, M.E., 2003, California Geological Survey Preliminary geologic map of the Glen Ellen 7.5' Quadrangle: Available at: http://www.consrv.ca.gov/cgs/information/geologic_mapping/index.htm and Clahan, K.B., Bezore, S.P., Wagner, D.L., Koehler, R.D., and Witter, R.C. ,2003,Geologic map of the Cotati 7.5' Quadrangle, Sonoma County, California: A digital database: California Geological Survey. Available at:http://www.consrv.ca.gov/cgs/information/geologic_mapping/index.htm

Figure 8:
A & B.: Commonly used landslide hazard map in industry. Scale is 1: 62:500 for A.
B. Recent geologic maps by the California Geological Survey at 1:24,000 scale, reduced here for convenience. Areas outlined in green are approximate limits landslides mapped for this project using aerial photo, LiDar & DEM datasets and verified in the field. Yellow areas are landslides, red areas are volcanic rocks and lighter colored areas are Miocene to Holocene sedimentary rocks and deposits mapped by the CGS. Brown outlined areas are unmapped Miocene to Pliocene diatomite, claystone, sandstone and conglomerate units all prone to sliding during preliminary mapping for this project.

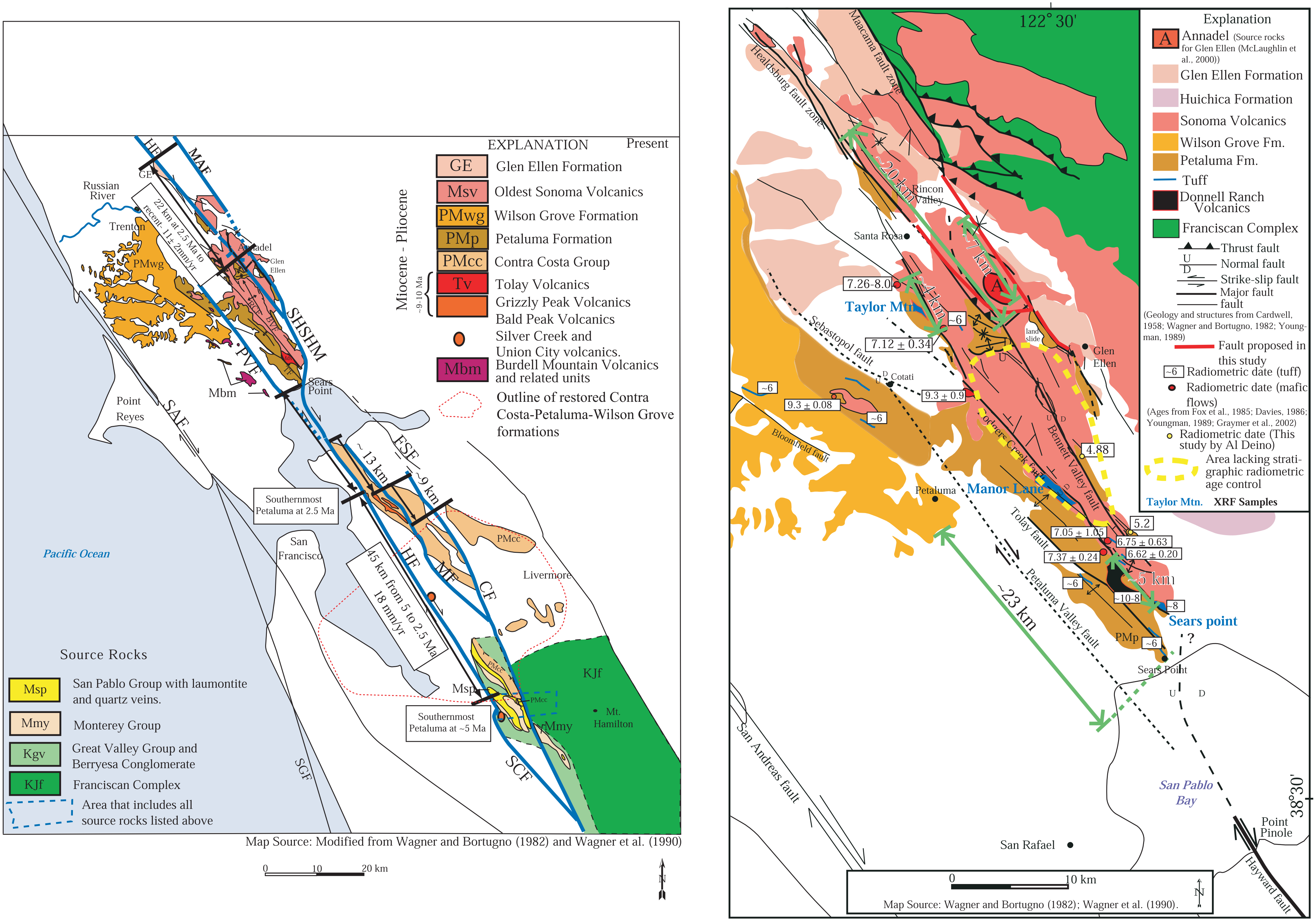
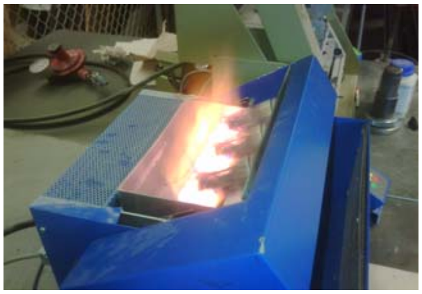


Figure 9 . Map of late Cenozoic Tertiary strata and volcanic rocks in the northern Bay Area, faults discussed in text, and possible offset features. Radiometric dates from Davies (1986), Youngman (1989), Fox et al. (1985), Sarna-Wojcicki (written communication, 2003), and D. Wagner (personal communication, 2003). Petaluma Formation mapped from this study. Sonoma Volcanics, Glen Ellen Formation, Franciscan Complex, and faults and structures from Wagner and Bortugno (1982).

XRF Geochemical Data: Basal Sonoma Volcanics flow-banded rhyolite

Sample ID	TM-1	TM-2	SP-1	SP-2	ML-1	ML-2
Locality	Taylor Mtn. Warrington Rd.	Taylor Mtn. Warringtonl Rd.	Sears Point Infineon Raceway	Sears Point Infineon Raceway	Manor Lane Sonoma Mtn	Manor Lane Sonoma Mtn
Major Element						
	99.4984	99.3614	100.0445	100.1485	100.0004	100.0046
SiO_2	76.88	76.85	75.77	75.72	78.29	79.03
TiO_2	0.14	0.13	0.33	0.33	0.09	0.12
Al_2O_3	14.26	14.22	15.38	15.38	13.33	13.34
Fe_2O_3	0.26	0.29	1.41	1.42	0.55	0.59
MnO	0	0	0	0	0	0
MgO	0	0.01	0.02	0.02	0	0
CaO	0.71	0.72	1.21	1.2	0.37	0.33
Na_2O	3.87	3.75	2.76	2.89	3.37	2.79
K_2O	3.39	3.41	3.16	3.18	4.01	3.83
Cr	0	0	0.2	0.5	0	0
P_2O_5	0.016	0.016	0.014	0.016	0.017	0.017
Trace Element						
Sc	11.3			17.5	11.9	12.3
V	24.9	Sample erupted :(		44	18.7	18.1
Cr	105.5			106.3	106.3	106.3
Co	238.9			341	144.7	148.1
Ni	595.1			600.2	598.5	599.3
Zn	38.8			35.6	41.1	34.8
Ga	36.8			19.8	36.5	19.9
Rb	120			17.8	135.3	18.1
Sr	124.8			79.1	97.3	86
Y	34			18.9	37.9	21.7
Zr	235.6			66.2	161.4	53.4
Nb	19.4			18.3	23.4	19.1
Ba	352.3			424.4	248.3	257.7
La	30.5			29.8	27.7	28.2
Ce	60.4			75.7	28.1	32.6
Nd	35.5			35.7	36.4	36.6
Sm	6.9			7.2	7.2	7.3
Eu	2			2	2	2
Tb	0.9			0.9	0.9	0.9
Yb	3.1			3.1	3.1	3.1
Hf	6.4			7.3	6.4	6.3
Ta	3.8			3.8	3.8	3.8
Th	50.4			0	51.8	0

🟨	Close match
🟧	Data quality



Molten again! Melting samples into pellets (Hot)

XRF

TABLE 1

Stop 4: Fairfield Osborne Preserve

Here at Fairfield Osborne Preserve, we can observe many generations of nested landslides and hazards to existing development (Rubin and Allen, 2008). Based on recent field observations, bedrock underlying the Preserve is siltstone and sandstone of the middle and upper Petaluma Formation, with interbedded volcanics. Quaternary alluvial and various mass wasting deposits materials have been deposited along creeks, and within swales and other topographic depressions. However, the entire area is within a large ancient landslide complex extending west from near the top of a local peak, to the base of the mountain near where Copeland Creek crosses Lichau Road near Stop 3 (Figure 10). Copeland Creek to the south locally marks the lateral boundary the landslide complex. Fairfield Osborne Preserve occupies a relatively small area within the large landslide complex north of Copeland Creek, yet a majority of the Preserve is within a smaller landslide complex that appears to have altered the course of the Creek. Ages of the landslides are uncertain, however it is commonly assumed that the largest landslides are Quaternary in age, and we will see that portions of this complex are active today.

As we approach Stop 3 along Lichau Road around Address #6540, begin to notice distress to the road surface. The road has been repaired at several locations, and in other areas cracks are visible where it has been displaced by active landslide creep and incipient scarp development. It is as if we are driving up a staircase, and the areas of distress can be thought of as steps that grow as the landslide slowly advances toward Copeland Creek. This analogy of a staircase can be applied at many scales.

From the area where we park the vans, follow along with the air photo map (Figure 11) as we traverse down another ‘staircase’ of sorts, however in places we can see that younger landslide and debris flow deposits actually overlie older scarps and deposits. We will then cross a large, generally level surface or ‘bench’ that marks the upper portion of a large landslide deposit. An incised channel can be observed along the right side of the ‘bench’ at one location. Note that what is exposed appears to be a coarse-grained debris flow-type deposit, which was likely sourced within the headscarp area and flowed out into the void behind the landslide deposit below. Boulders in a younger debris flow deposit on the left reflect the various bedrock material upslope of the Preserve. Walking along the large bench at the bottom of the slope it is interesting to contemplate such large masses of materials mobilized at various times, and even more impressive to observe that this particular slide complex comprises only a small corner of the larger complex that spans this portion of Sonoma Mountain.

At the end of the traverse near the Preserve utility buildings we come to the upslope edge of the landslide ‘toe’ area. Note that bedrock, rather than younger deposits, forms the landslide mass along the face of the toe area. West of the buildings, it becomes obvious that the landslide mass itself is failing in several locations, as evidenced by the progression of ‘steps’ along its leading edge that represent headscarps of smaller landslides. Some of these features are coincident with those that we drove across on Lichau Road.

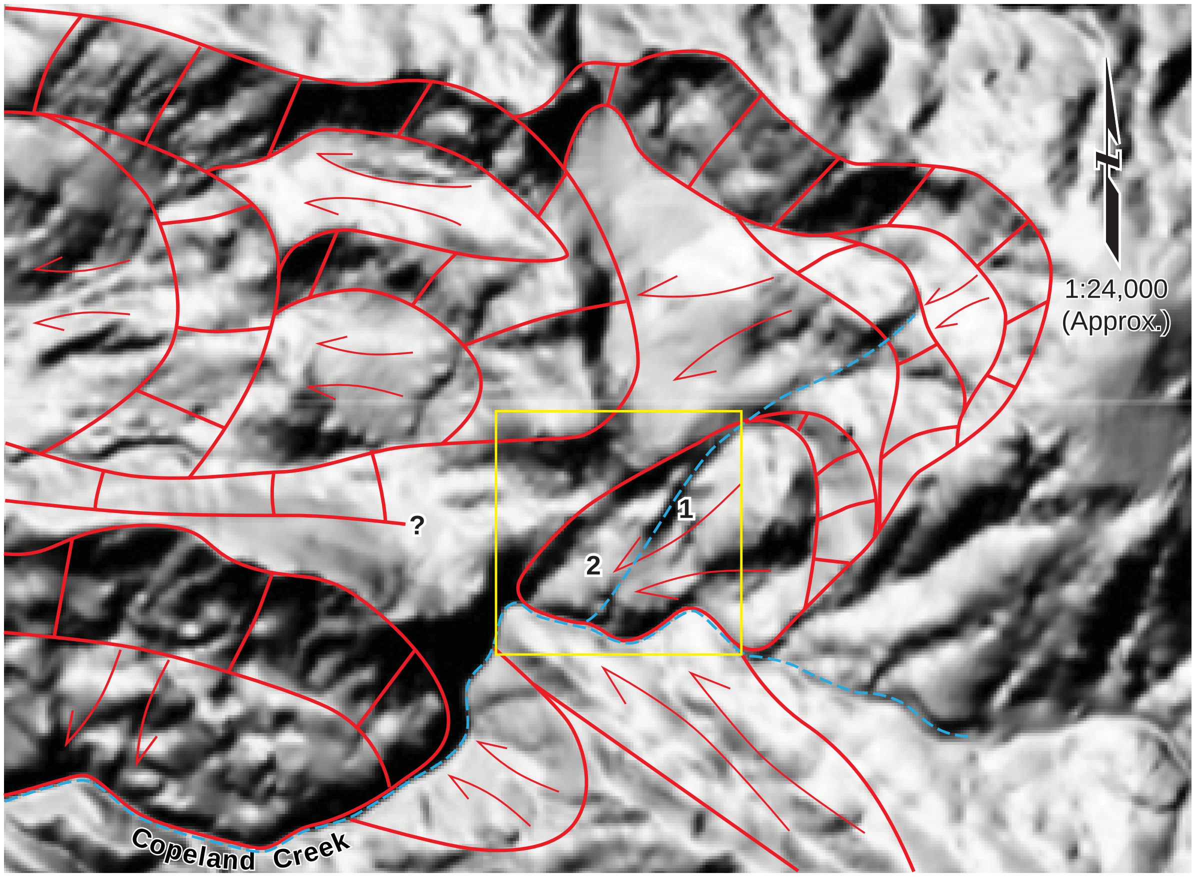


Figure 10. Generalized landslide map of the Fairfield Osborne Preserve region. Mapped landslides are based on stereo air photo interpretation. Yellow box indicates area of detailed mapping on Figure 11. Base map is shaded relief derived from a USGS 10m DEM.

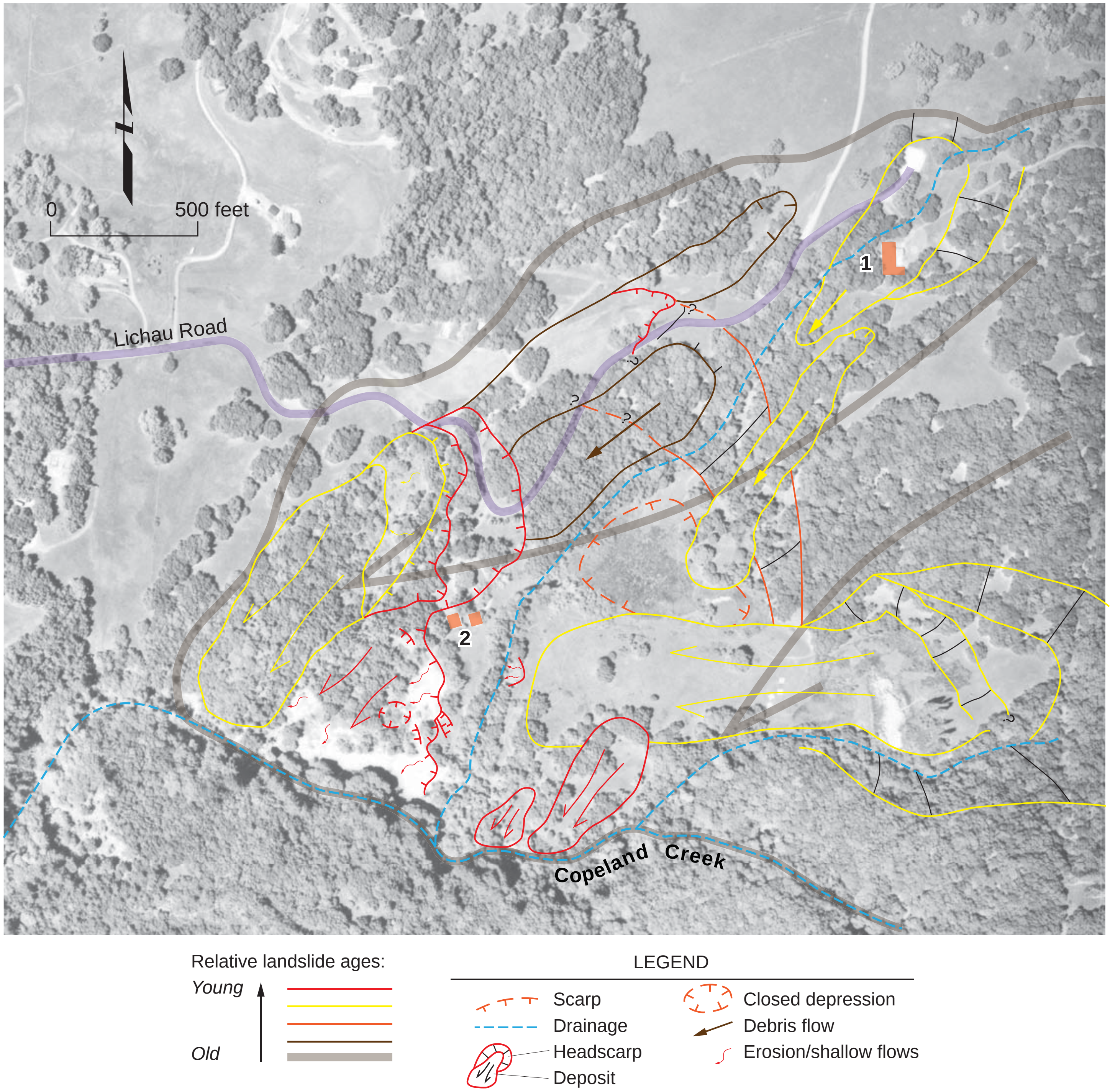


Figure 11. Aerial photograph map showing landslides at Stop 4. Mapped landslides are based on stereo air photo interpretation and field reconnaissance. Points 1 and 2 indicate beginning and end of field traverse.

The existing buildings are clearly in jeopardy of being damaged by progressive failures along the toe (Figure 12), which will likely continue to progress beyond the limits of this small area over time. This portion of the landslide will continue to move as lateral support is removed by undermining from erosion along Copeland Creek and by 'smaller' failures such as the ones observed at this site. Though these buildings are small and not representative of what might be constructed today, this could easily be a site that one might consider 'perfect' for residential development today because it is easily accessible from the road, it is flat, and has spectacular views. Consequently, it is a great example of how recognition of geologic hazards is critical for planning prior to design and construction.

The mechanism of failure of the overall landslide at the Preserve is uncertain. Based on regional relations and the complexity of the various landslides. They may not be structurally controlled. Rather, this landslide and other large landslides in the area likely reflect the overall weakness of the bedrock materials involved in the slide. It is also easy to imagine landslide activity triggered by large earthquakes on the nearby Rodgers Creek fault.

Goals of Landslide Mapping and Sonoma Mountain mapping:

Earthquake-induced landslides and the Holocene-active Rodgers Creek fault (RCF), a fault capable of generating a **M** 7.1 earthquake according to the Working Group on California Earthquake Probabilities (2003), are two top geologic hazards we are investigating further for the on-going task of trying to reduce losses in expanding urban areas presently encroaching Sonoma Mountain. As a high-priority effort to minimize landslide and earthquake-related damage for the Sonoma Mountain area, we are trying to create landslide hazards maps and more detailed strip-maps of the RCF, focusing on recently-active traces, as well as the bedrock geology and surficial (Quaternary) deposits associated with the fault.

Earthquake-induced landslides were documented in the Bay Area as recently as 1989, caused by the Loma Prieta Earthquake. Above-average amounts of rainfall can also trigger landslides of all sizes, and many such landslides were documented in Sonoma County during the 1997-1998 El Nino storm events, when some existing slides were reactivated. The current state of mapping of the RCF and the landslide hazards adjacent rely upon generalized mapping or dated compilations. They do not depict accurately the: number of landslides present, the main trace and splays of the RCF, accurate mapping of the bedrock and Quaternary deposits. A detailed and accurate inventory of landslides, their bedrock relationships, coupled with precise mapping of the RCF is fundamental to understanding the hazards associated with the continued evolution of the RCF.

To map the landslides hazards and RCF in precise detail, the approach and objectives are manifold, beginning with the difficult business of gaining additional property access to augment that which we have secured to date, reviewing aerial photographs at 1:12,000 scale, reviewing LiDAR imagery along the RCF zone and DEM data covering the entire area. Field mapping includes both bedrock and surficial (Quaternary) deposits. While landslide mapping in the field, the bedrock and surficial deposits along the RCF will be mapped to aid in future locations of paleoseismic

Figure 12. Photograph of barn at Fairfield Osborne Preserve. Red hachured lines delineate approximate locations of active landslide scarps. View to South.

investigations.We intend to collect volcanic rocks in a stratigraphic order, rather than spot-sampling, for radiometric dating to aid in our understanding of long-term displacement along the RCF.

Implications of the project results are improved landslide and seismic hazards map products to be used in risk assessments conducted by city and other government agencies, planners, developers and the general public to reduce losses by aiding in assessing potential ground shaking and geologic hazards. The hazards map products from this project are essential for development of cost effective mitigation measures and practices in geotechnical structural design, construction, and planning.

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