2006

Geologic investigation of erosional surfaces east of Napa Valley, California

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Recommended Citation

Jones, Christopher A., "Geologic investigation of erosional surfaces east of Napa Valley, California" (2006). *Master's Theses*. 2891.
DOI: https://doi.org/10.31979/etd.nga3-e7b8
https://scholarworks.sjsu.edu/etd_theses/2891

GEOLOGIC INVESTIGATION OF EROSIONAL SURFACES EAST OF NAPA VALLEY, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements of the Degree

Master of Science

by

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May 2006

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ABSTRACT

GEOLOGIC INVESTIGATION OF EROSIONAL SURFACES EAST OF NAPA VALLEY, CALIFORNIA

By Christopher A. Jones

Remnants of at least two once-continuous erosional surfaces are preserved on six structural blocks in the study area. Similar volcanic sequences found on the structural blocks are separated by west-dipping normal faults related to the Soda Creek fault southeast of the study area. The single trace of the Soda Creek Fault splays into a more diffuse fault zone north of Rector Canyon.

Core stones found at the ground surface and in the soil are the spheroidally weathered remnants of the jointed bedrock. By using the thickness of the weathering rinds that form around the edges of core stones, it is possible to correlate the relative ages of the weathered surfaces. There is a distinguishable difference in rind thickness and, presumably, age between the erosional surfaces. When viewed graphically, gaps in the measured thickness of the weathering rinds may indicate periods of erosion corresponding to the uplift of the Vaca Mountains.

ACKNOWLEDGMENTS

I wish to thank Dr. David Howell of the U.S. Geological Survey for his help and for suggesting the topic for this study. I also wish to thank Dr. John Williams and Dr. Richard Sedlock of San Jose State University for their help, encouragement, and critical review of this thesis. Special thanks are also due my wife, Mhairi Jones, who accompanied me in the field. Thanks also goes to the landowners and individuals who allowed access to the study area including Jan Krupp of Stage Coach Vineyards, Dana Johnson, Gary Brookman and David Miner of Oakville Ranch Vineyards, Eugene and Valentina Zavarin, David Ramey of Rudd Vineyards, Mia Klein of Dalla Valle Vineyards, Charles Thomas, and Steve Klein.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Plate

LIST OF TABLES

INTRODUCTION

Research Problem

The purpose of this study is to investigate the lithology, structure, and geomorphology of the step and bench topography in the Vaca Mountains, east of Napa Valley California (Fig. 1). This study was prompted by discussions with David Howell (USGS), who first suggested these surfaces as features evincing a mega-landslide (Swinchatt and Howell, 2004). Subsequent reconnaissance trips to the study area indicated that the benched surfaces occupy six potential structural blocks (Fig. 2). From lowest to highest, the blocks are the Rudd, Dalla Valle, Oakville Ranch, Lower Stage Coach, Dana Johnson, and Upper Stage Coach (named for the vineyards that provided access to each area). Twenty-five remnants comprising 14 potential benched surfaces were identified on the structural blocks during this study (Fig. 3).

Two possible mechanisms for the offset of the blocks are faulting and mega-landsliding. Swinchatt and Howell (2004), support the idea of offset through a mega-landslide, and after viewing oblique-angle shaded relief maps with DOQ overlay (Swinchatt and Howell, 2004; Figures 27 and 29), their hypothesis is very plausible; however, at the scale of this investigation it is impossible to differentiate between faults and slip surfaces of a ten-mile long mega-landslide. Determining whether the displacement surfaces are the result of a landslide or normal faulting is beyond the scope of this study and would require the investigation of the orientation and location of the

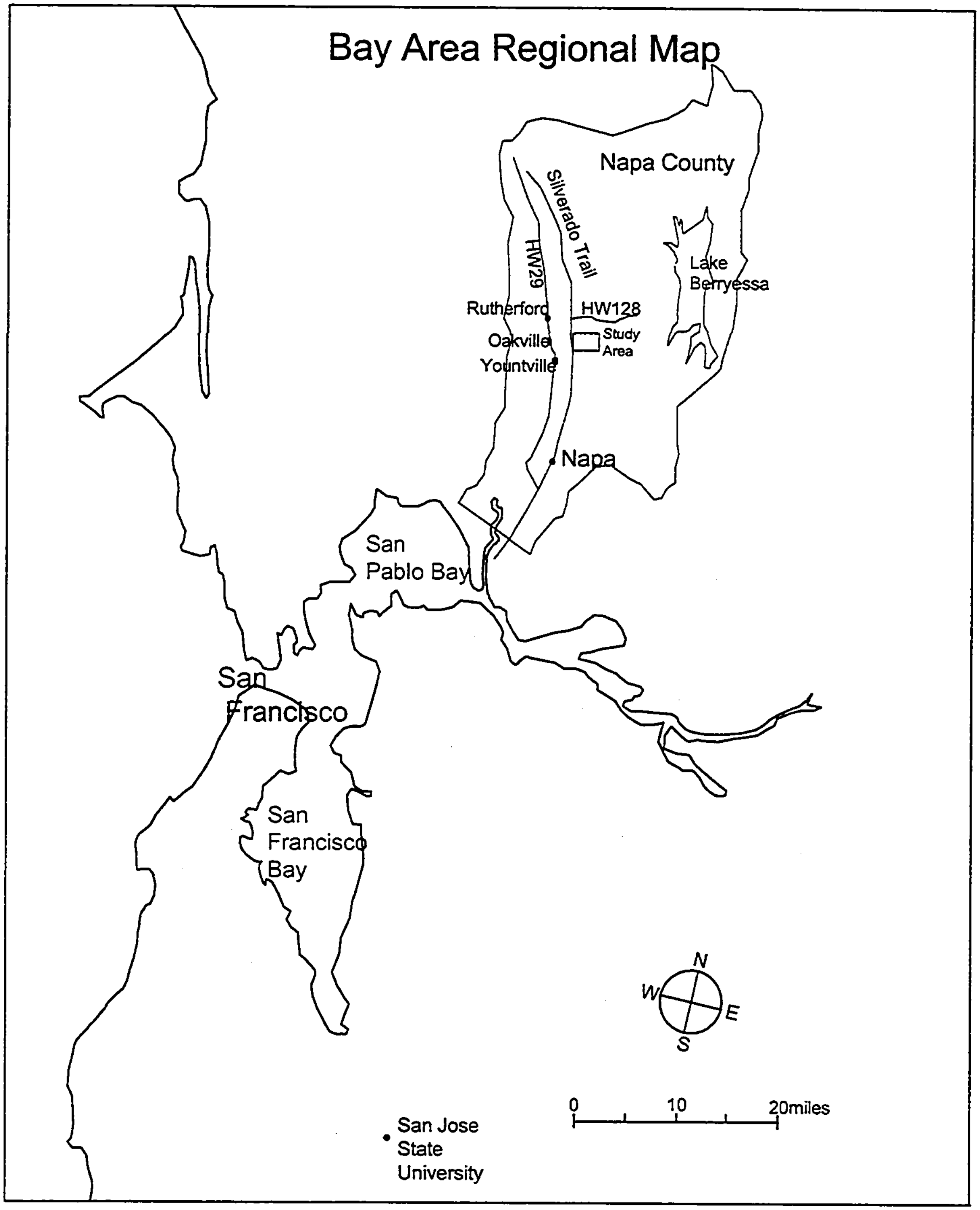


Figure 1. Bay area regional map with Napa County and study area shown.

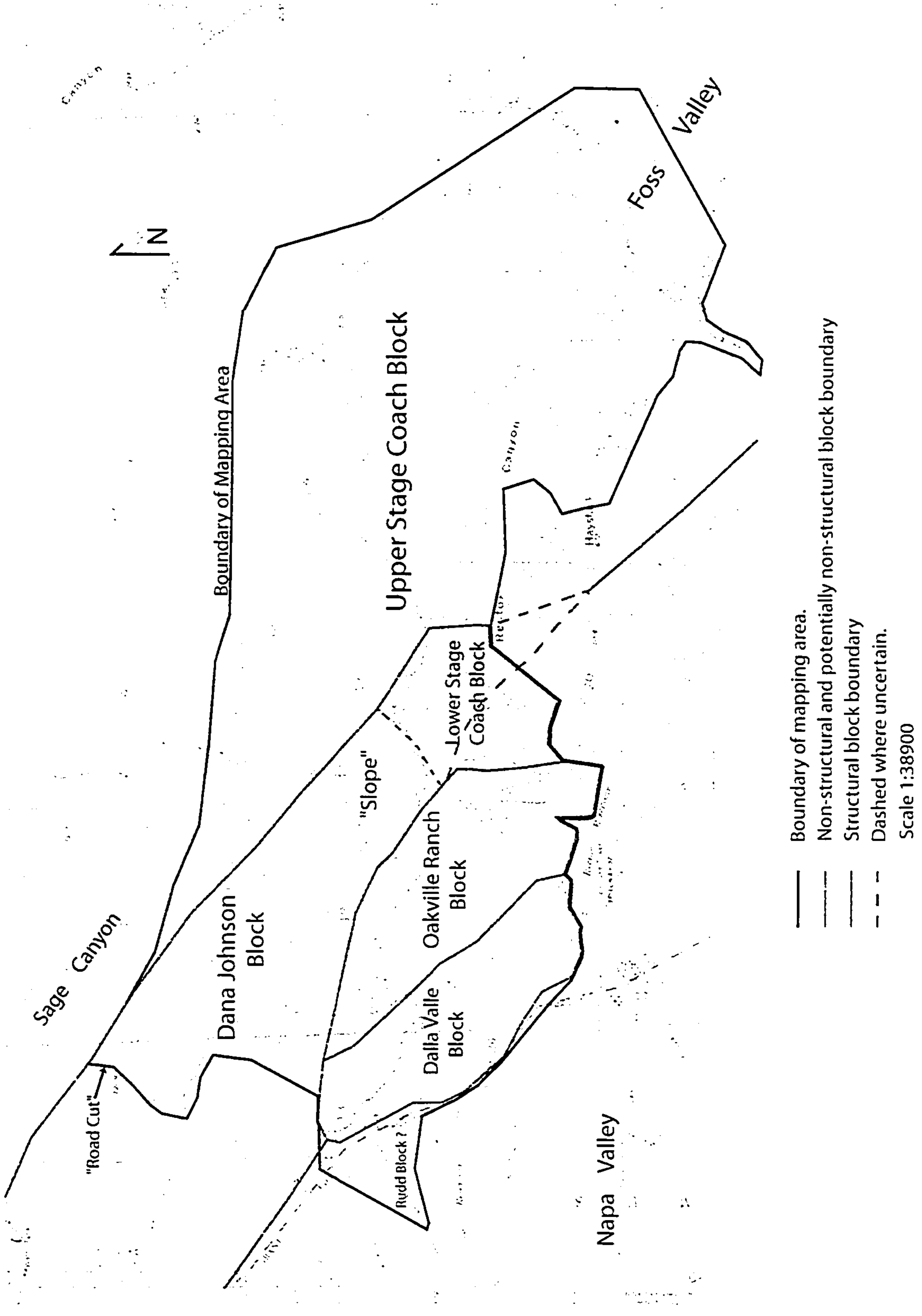


Figure 2. Map of study area and the six identified blocks.

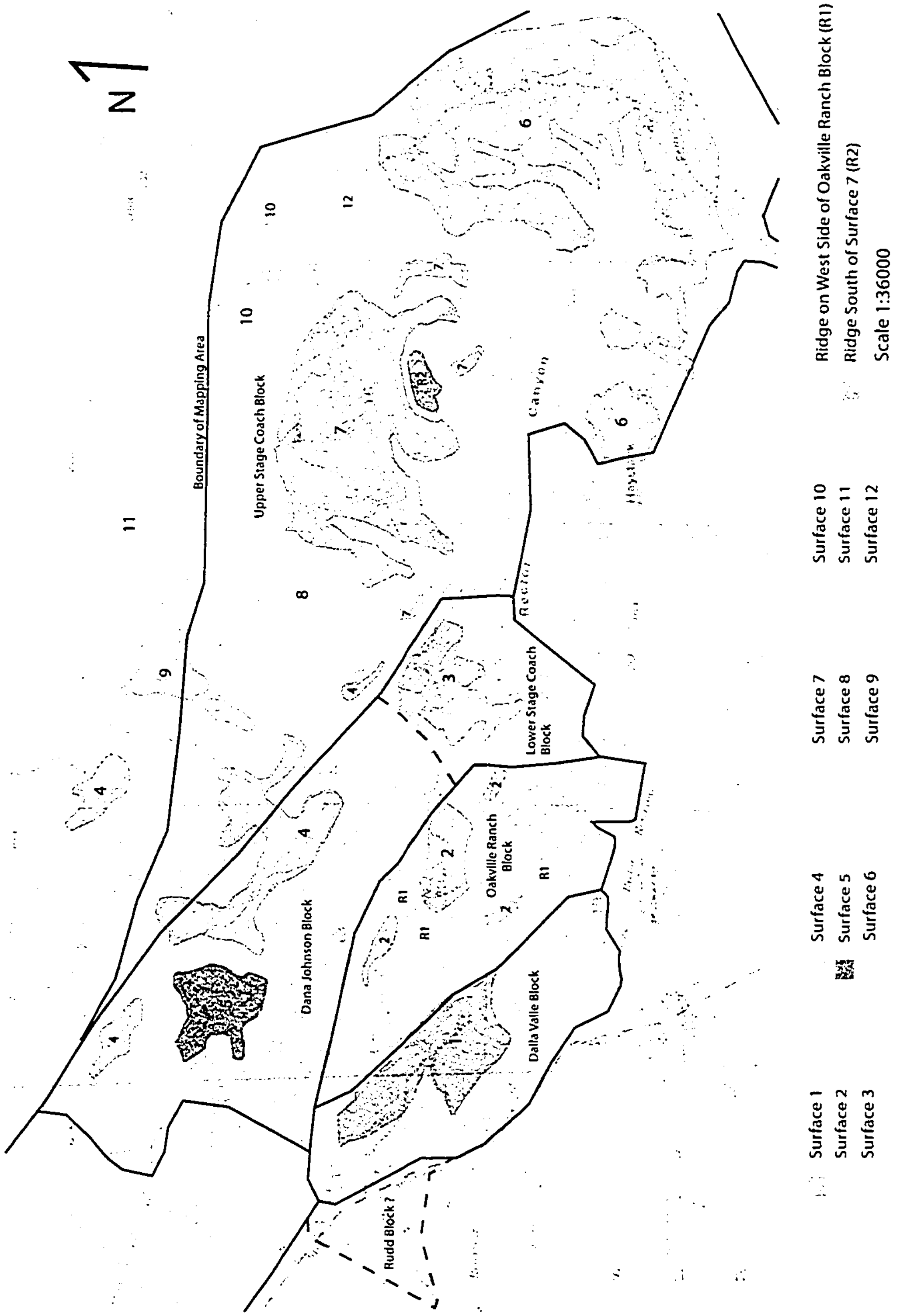


Figure 3. Map of the erosional surface remnants

displacement surfaces below the ground surface. For simplicity, the slip surfaces will be referred to as faults in this thesis.

In the study area, the Sonoma Volcanics at and near the ground surface have undergone spheroidal weathering that has produced thick rinds of weathered material around the relatively fresh interior of unweathered rock. Because weathering rind thickness increases with age, rinds from each of the benched surfaces can be compared. Rinds of approximately equal thickness from different surfaces would support the hypothesis that the surfaces were initially continuous.

Hypothesis

The benched surfaces east of Napa Valley and north of Rector Canyon are proposed to be part of a once-continuous erosional surface that has been deformed and separated by folding and faulting. This research is focused on investigating this hypothesis and clarifying the geologic history of this area.

Scope of Work

A literature review of topics relating to the Sonoma Volcanics, core stone development and weathering, and pediment formation was conducted. An aerial photograph investigation of the area was performed at the USGS library in Menlo Park using photographs from the Yountville collection taken in 1948, 1957, 1958, 1959, and 1973 at scales of 1:20,000 or 1:12,000. Detailed field mapping was performed to identify the geology and to analyze the thickness of weathering rinds.

Figures produced for this study include maps of the erosional surfaces and blocks, a geologic map, stratigraphic columns, a table of weathering rind measurements, and several profiles. Two stream profiles along Rector Creek were constructed to observe changes in stream gradient; abrupt changes in gradient may indicate a unit contact or faulting. These profiles are helpful because the floor of Rector Canyon was inaccessible due to Rector Reservoir and thick vegetation in the canyon. A surface profile along line A-A' is oriented parallel to the slopes of most of the surfaces studied in this investigation. Two geologic cross sections, X-X' and Y-Y', are included to depict one possible interpretation of the structure in this area.

Description of Study Area

Napa Valley, a renowned wine-producing region, is approximately 72 km (45 mi) northeast of San Francisco, California (Fig. 1). Napa Valley lies within the northern California Coast Ranges, a province characterized by ranges and valleys trending north-northwest. The study area is in the Vaca Mountains east of Napa Valley. This area is approximately 16 km (10 mi) north of the city of Napa and covers approximately 23 km^2 (9 mi^2) of hilly terrain bounded on the north by State Route 128 and on the south by Rector Canyon (Fig. 2).

Land within the study area is a mix of state and private property. Access to this area is complicated by the number of individual residential and commercial land owners and the non-uniform parcel shape and size. Attempts to contact property owners by phone, e-mail, and letters were moderately successful. Several properties could not be investigated because the owners refused access or did not respond to the inquiries.

Historic and Current Land Use

Much of Napa Valley has been utilized for agriculture in some fashion for the majority of the last 150 years. According to Jan Krupp (personal communication), the earliest reported land use in the study area was for short-lived German vineyards dating to the 1890's. Other evidence of use includes several stone fences and stone and concrete foundations that were constructed at an unknown date. Today the area is primarily used as vineyards by several wineries but also includes private residences. The study area is in the viticultural area known as the Stag's Leap District. Grapes grown on the proposed erosional surfaces mainly include cabernet sauvignon and merlot, which grow well in the volcanic soils.

To use the proposed erosional surfaces as vineyards, landowners cleared vegetation and boulders that littered the ground surface and soil. A very large pile of the rocky debris removed from the vineyards on the Dana Johnson block can be easily seen from the western side of Napa Valley. On Stage Coach Vineyards alone there are at least 10 large mounds of this rocky waste, the largest of which (Fig. 4) stands 15 to 18 m (50 to 60 ft) tall and is 46 to 61 m (150 to 200 ft) wide. These piles contain fragments ranging from baseball-sized to boulders as large as 3.7 m (12 ft) across. The removal of this material and the preparation of the fields required the use of heavy tractors and bulldozers. Piles of rock removed from the vineyards are found on all the blocks but are

Figure 4. Pile of stones removed from the vineyards on surface 8. Pile is 15 to 18 m (50 to 60 ft) tall and 46 to 61 m (100 to 150 ft) wide.

most noticeable on the Upper Stage Coach and Dana Johnson blocks. In this area, the waste rock is used in many man-made structures, including fences (Fig. 5), footbridges, buildings, erosion control barriers on the perimeter of the vineyards, and road base in private drives and access roads.

Two reservoirs have been constructed in the vicinity of the study area. In 1946, Conn Creek dam and Rector Creek dam were completed. Both dams are earthen dams. The Conn Creek dam, owned by the State Department of Veteran Affairs, formed Lake Hennessey and is north of the study area. The Rector Creek dam, owned by the City of Napa, produced a smaller reservoir known as Rector Reservoir and is at the southern edge of the study area.

The study area is drained by two main streams and their tributaries that flow only during the winter and spring months and after large rain events. The majority of the area

Figure 5. Stone fence on surface 7. The Stage Coach Vineyards are visible behind the stone wall.

is drained by Rector Creek, which is highly entrenched into the Sonoma Volcanics in Rector Canyon. Rector Creek generally flows to the west and is a tributary of the Napa River in Napa Valley. An alluvial fan at the mouth of Rector Canyon has built out onto the floor of Napa Valley. Rector Creek is restricted now by Rector Reservoir. Many tributaries of Rector Creek dissect the Oakville Ranch block and both Stage Coach blocks.

An unnamed canyon between the Dalla Valle and Dana Johnson blocks drains a much smaller region near the northwestern edge of the study area. The northern wall of this canyon is 2 to 3 times higher than the southern wall of the canyon. Several other unnamed streams drain the northern boundary of the study area and empty into Lake Hennessey.

Climate and Vegetation

Napa Valley has a Mediterranean climate characterized by cool, moist winters and warm, dry summers. Average precipitation for the Vaca Mountains is approximately 63.5 to 71 cm/yr (25 to 28 in/yr) (Western Regional Climate Center, 2003). Vegetation differences between the north- and south-facing slopes can be quite marked in the study area. South-facing slopes, particularly on the Lower Stage Coach and Oakville Ranch blocks, have many more open grassy areas with patches of scrubby bushes. North-facing slopes are densely vegetated with bushes and small trees.

Approximately a third of the land in the study area has been put to vineyard. Pertinent geologic information in these areas has been destroyed due to the mixing and removal of soil and bedrock as the land was readied for planting. The service roads built to reach and maintain the vineyards allow access to the relatively undisturbed areas at the edges of the vineyards. Cuts made for the access roads expose the majority of the core stones observed in this area. The remaining two-thirds of the study area is covered by thick shrubbery, dense pockets of low-standing trees, and occasional open meadows. Access to areas that are not close to roads or trails is very limited due to the thick interlocking shrubs. The stream valleys in the study area are overgrown with vegetation, which severely limits access to bedrock exposures.

Previous Work

The Sonoma Volcanics have been mapped by several workers including Osmont (1905), Weaver (1949), Fox et al. (1973), Baldwin et al. (1998), and Graymer et al. (in preparation). These workers map the majority of the Sonoma Volcanics as undifferentiated andesitic to basaltic volcanics. The most recent attempt to map the Sonoma Volcanics (Graymer et al., in preparation) divided the Sonoma Volcanics into several units including an upper rhyolitic member, a middle member composed of several units of ash, pumice, and agglomerate, and a lower member of undifferentiated andesitic flows. However, Graymer et al. mapped nearly the entire thesis area as their lower andesitic member "Tsa," which they described as andesitic to basaltic lava flows. This and other maps currently available are inadequate for the level of detail required for this study.

Quaternary Deposits

Quaternary deposits overlie portions of both the Tertiary volcanics and the basement rock near the study area. To the west of the study area, Napa Valley is filled with interbedded alluvial deposits of the Napa River and the many fans that issue from the mountains east and west of the valley. At the western edge of the study area two such fans have built into Napa Valley. Sediments from these fans are composed almost entirely of material derived from the Tertiary volcanics. Several small bodies of alluvial sediment scattered across the study area are related to activity of small streams.

Multiple landslide deposits have been identified north and east of the study area. These mainly occur in the Coast Range Ophiolite and Great Valley Group (Fox et al., 1973; Sims et al., 1973; Graymer et al., in preparation). Graymer et al. mapped one large landslide to the north of the study area; the head of the slide is at the contact between the Tertiary volcanics and older basement rock.

Basement Rock

Jurassic-Cretaceous Franciscan Complex, Great Valley Group, and Coast Range Ophiolite compose the basement rock in the study area. Great Valley Group exposed north and east of this area consists of marine sandstone, siltstone, and shale (Weaver, 1949; Kunkel and Upson, 1960; Graymer et al., in preparation). Franciscan Complex exposed north of the high ridges bounding the eastern edge of Foss Valley consists of metagreywacke (Graymer et al.). Serpentinite of the Coast Range Ophiolite is exposed at the northwestern edge of the study area (Graymer et al.). To the south of the study area, Great Valley Group protrudes from the alluvium along the eastern edge of Napa Valley. The Great Valley Group along the eastern side of Napa Valley is believed to be exposed at the core of a complexly folded anticline (Baldwin et al., 1998).

Franciscan, Great Valley, and Coast Range Ophiolite rocks are unevenly distributed in the area surrounding the study area, and likely formed a non-planar surface prior to the eruption and deposition of the Sonoma Volcanics. Contacts between the Franciscan Complex, Great Valley Group, and Coast Range Ophiolite are mapped as fault contacts in many locations (Graymer et al., in preparation). These units were deformed by a large number of thrust/reverse faults related to the convergent boundary between the Juan de Fuca and North American plates prior to the passing of the Mendicino triple junction (Fox, 1983).

Tertiary Volcanics

In this area the Tertiary volcanics, known as the Sonoma Volcanics, unconformably overlie the basement rocks. The Sonoma Volcanics is an extensive sequence of andesitic to basaltic lava flows, agglomerates, tuffs, and breccias that are capped in some areas by rhyolitic flows and tuffs. Estimated ages for the Sonoma Volcanics range from late Miocene to late Pliocene/early Pleistocene (Weaver, 1949; Mankinin, 1971; Sarna-Wojcicki, 1976; Fox, 1983). These volcanics are exposed as several disaggregated masses trending approximately NW/SE and are divided by valleys containing younger sediment for over 906 km^2 (350 mi^2) in Napa and Sonoma valleys and north of Calistoga (Fig. 6). The Sonoma Volcanics are presumed to have originally been continuous across the area and subsequently disrupted by folding and faulting. The source area for the Sonoma Volcanics is unknown; one possible vent location is 7.8 km (3 mi) southeast of the city of Napa, but the amount of material that location has contributed is uncertain (Weaver, 1949).

Early Work In 1905, Osmont described a thick sequence of andesitic and basaltic lava flows that he termed the Mark West Andesite. This unit was overlain by a complex set of andesitic and basaltic tuffs with interbedded sands and minor lava flows that he termed the Sonoma Tuff. Osmont also described a third unit, the St. Helena Rhyolite, which overlies the Mark West Andesite and the Sonoma Tuff. In 1922, Dickerson used the label Sonoma Group to refer to all three of Osmont's units (Weaver, 1949).

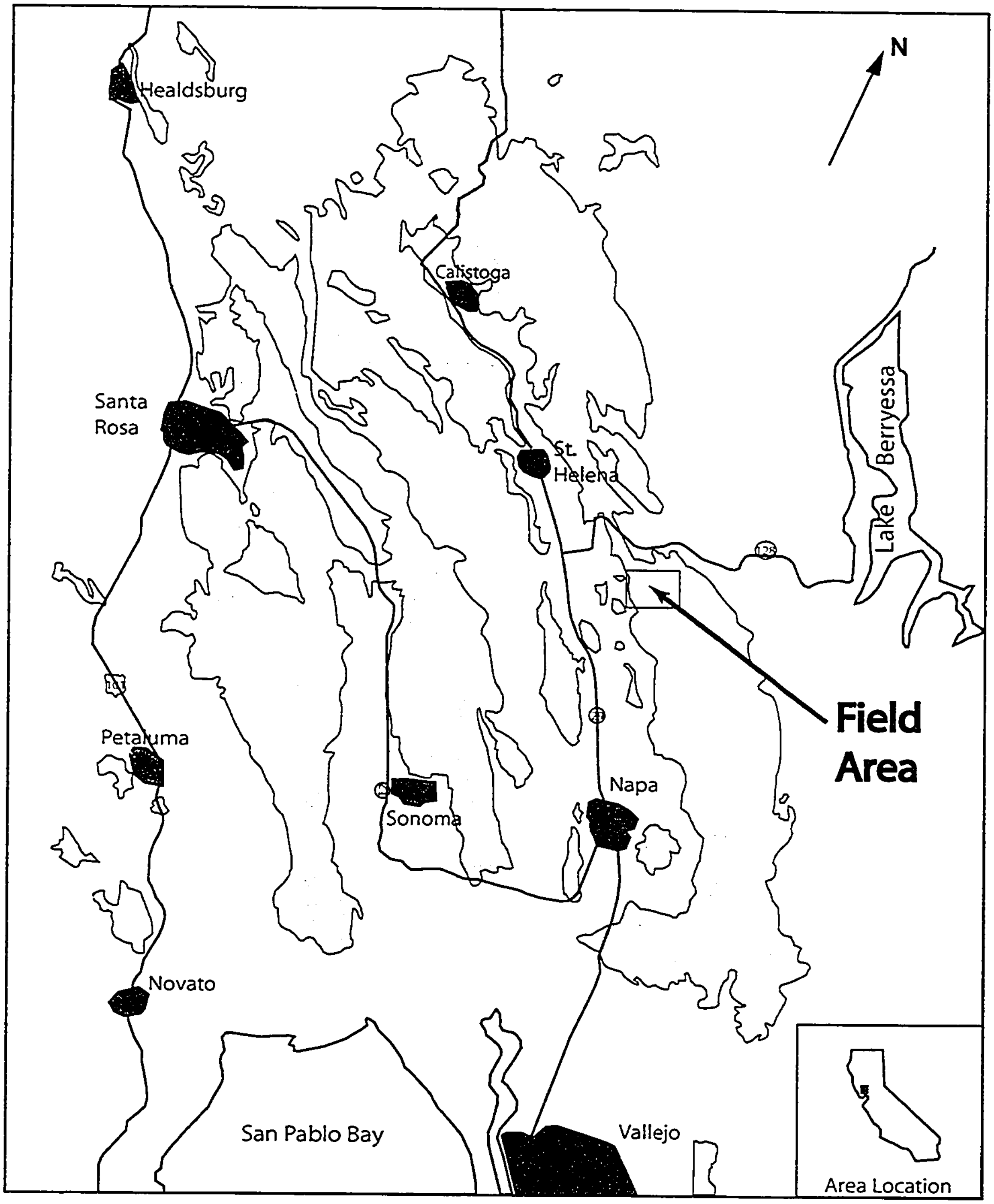


Figure 6. Regional distribution of the Sonoma Volcanics. Figure adapted from Mankinen (1971). Scale 1:408000.

The term Sonoma Volcanics was first used by Weaver (1949). His studies of the Mark West Andesite and the Sonoma Tuff included aerial mapping and detailed field mapping. Weaver also examined the lithologic composition of the units over a large portion of their extent. Weaver (1949) concluded that the lateral changes in the Mark West Andesite and Sonoma Tuff were similar throughout their extent and that it was "...impossible to consider them (the Mark West Andesite) stratigraphically of more importance than the mass of Sonoma tuff." From his findings he considered it best to map the Mark West Andesite, Sonoma Tuff, and the St. Helena Rhyolite as one unit, the Sonoma Volcanics.

Age The Sonoma Volcanics are believed to have erupted during the late Miocene to late Pliocene/early Pleistocene. This age has been determined by stratigraphic position and fossil dating, and more recently by radiometric dating. The base of the Sonoma Volcanics rests unconformably on several formations, indicating its basal surface was topographically irregular. To the east, the base of the Sonoma Volcanics unconformably overlies Franciscan, Great Valley Group, and Coast Range Ophiolite basement rocks (Weaver, 1949; Graymer et al., in preparation). To the west, the basal unit lies unconformably on the Miocene Neroly sandstone and the Pliocene Petaluma Formation (Weaver, 1949; Kunkel and Upson, 1960). To the north, the upper units of the Sonoma Volcanics interfinger with the lower beds of the Merced Formation of Pliocene/Pleistocene age (Kunkel and Upson, 1960). Weaver (1949) found the

Sonoma Volcanics overlain by the Glen Ellen and Huichica Formations, which are believed to be of early Pleistocene age.

Fossil evidence supporting the Pliocene age is from tuff and lacustrine sediments within the Sonoma Volcanics. The fossil remains of plants, euqhids, and diatoms support a Pliocene age (Weaver, 1949; Kunkel and Upson, 1960). Using K-Ar dating, Mankinen (1971) determined ages for the Sonoma Volcanics near Santa Rosa ranging from 2.9 Ma to about 5.3 Ma (Pliocene). Mankinen's 2.9 Ma age was extracted from a tuff at Mount St. Helena which, though not present in the study area, stratigraphically overlies the andesitic flows in the study area. Fox (1983) noted that G. H. Curtis dated rhyolite south of the study area near Mount George at 3.8 Ma. This is likely the youngest age of the Sonoma Volcanics in the thesis area. Fox (1983) reported that K-Ar dates from Wooden Valley southeast of the study site show andesites have ages of 4.9, 5.2, and 5.4 Ma. Rock from the Sonoma Volcanics near but stratigraphically below the 3.8 Ma rhyolite at Mount George yielded a 4.2 Ma K-Ar date (Mankinen, 1971). Based on these results, the age of the Sonoma Volcanics exposed in the study area is approximately 3.8 to 5.4 million years.

<u>Lithology</u> Weaver (1949) worked extensively in the Sonoma Volcanics, specifically on the eastern side of Napa Valley in the Howell Mountains, Vaca Mountains, and Wooden Valley. Near the eastern side of the Vaca Mountains, 24 km (15 mi) southeast of Rector Reservoir, Weaver constructed a stratigraphic column of the Sonoma Volcanics exposed in the western cliffs of Wooden Valley (Table 1). Weaver's

Table 1. Weaver's 1949 stratigraphic section for Wooden Valley approximately 22.5 km (14 mi) southeast of the thesis area.

Thickness		Lithologic Character
Meters	(ft)	
37	(120)	Even-grained brownish-gray porphyritic andesitic flows with interbedded tuffaceous members.
30	(100)	Light-brownish gray, porphyritic andesite, containing numerous augite crystals set in a dark glassy matrix.
12	(40)	Brick-red to yellowish-brown, fine grained tuff of medium hardness and compactness.
12	(40)	Hard, medium- to coarse-grained, reddish gray andesite with a trachytic texture.
49	(160)	Reddish-gray to brown pumiceous tuff showing banding and flow structure and containing layers of pitchstone.
6	(20)	Fine-grained dense-black to dark-gray andesite.
84	(275)	Hard, brownish-gray, coarse- and medium-textured tuff and intercalated beds of fragmental material. Upper portion contains many scoriae.
15	(50)	Vesicular dark-gray to black andesite.
46	(150)	Dark-gray to black banded andesite with well-developed flow structure.
30	(100)	Red to yellowish-brown pumiceous tuff containing fragmental material and bands of pitchstone.
38	(125)	Black to dark-gray, banded andesite with a dense fine-grained matrix containing medium-sized porphyritic plagioclase crystals.
34	(110)	Coarse-textured black andesite with large phenocrysts of plagioclase. Interbedded with these flows are tuffaceous and pyroclastic members and layers of vesicular lava. The base of this member is nearly at the base of the Sonoma Volcanics. This section varies laterally.
393	(1290)	Total

section is rich (>60%) in flows. The Sonoma Volcanics in Wooden Valley and in this thesis area lack the thick tuffaceous and interbedded diatomaceous member known as the Sonoma Tuff, which overlies the flow-rich Mark West Andesite. The Sonoma Tuff is exposed just northwest of Lake Hennessey (Weaver, 1949; Fox et al., 1973; Graymer et al., in preparation).

Weaver (1949) noted that a representative analog of the upper portion of the Wooden Valley sequence can be seen in the walls of Rector Canyon. He also noted that the units mapped in Wooden Valley change in composition, sequence, and thickness to the north and west. Weaver's reference to the walls of Rector Canyon is vague; he does not describe a type location. Along its 4.8 km (3 mi) length, Rector Canyon displays heterogeneous lithology. Only a portion of Rector Canyon was visited during this study, and a definite correlation between the sequence within the canyon and that at Wooden Valley could not be made.

Petrography Weaver (1949) describes most of the Sonoma Volcanics as being andesitic, with some flows approaching basalt or dacite in composition. The groundmass contains mainly sodic labradorite (plagioclase), augite, hypersthene, apatite, and magnetite or is glassy (Weaver, 1949). Phenocrysts are almost exclusively sodic labradorite and augite. Flows may be massive or vesicular, and the vesicular flows may be independent of or grade into the massive facies lower in the unit. Vesicles are usually less than 2 cm in diameter and are commonly elongated. Quartz is a common filling in vesicles or in joints of the flows. The quartz is believed to be derived from the overlying tuffs as water percolated down through the units (Weaver, 1949). This suggests that thick tuffaceous units may have overlain the study area at one time, as seen to the north.

Tectonic Setting and Structure

During the early Tertiary it is likely that the study area and much of the surrounding land was uplifted and emergent as a result of the buoyancy of the subducting Farallon Plate (Swinchatt and Howell, 2004). At the eastern edge of the Sonoma Volcanics, the basal units of the volcanics unconformably overlie Jurassic-Cretaceous rock, while at the western edge the base interfingers with marine Neroly sandstones of Miocene age (Kunkel and Upson, 1960; Fox et al., 1973). Any early Tertiary strata in the study area were completely eroded away prior to the deposition of the Sonoma Volcanics. Fox et al. (1985) and Swinchatt and Howell (2004) suggested that the volcanics formed in an inland extensional setting related to the passage of the northerly migrating Mendicino triple junction. Around 8 Ma, after the Mendocino triple junction had passed, plate motion changed from transform motion to transpression as the relative motion between the North American and Pacific plates rotated approximately 23 degrees (Atwater and Stock, 1998). Transpression is believed to be the mechanism that formed the north- to northwest-trending thrust/reverse faults and folds that are common in the Coast Ranges and this study area.

The late Cenozioc geologic history and structure of the area that would become Napa Valley is a complex issue that has been debated for many years. Napa Valley's current configuration has been attributed to a synclinal trough (Weaver, 1949), down-dropped fault blocks (Kunkel and Upson, 1960), and a basin at the western edge of a series of east-northeast-dipping thrust faults (Baldwin et al., 1998). Recently, the structure around Napa Valley has been redefined as series of west-vergent thrusts or an imbricate fan forming the Vaca Mountains which overlay a ramp-and-flat-style floor thrust terminating in a fault-propagation fold that produced the Mayacamas Mountains (Swinchatt and Howell, 2004). The faults and folds in the study area formed during complex, multi-stage deformation that is still being unraveled by geologists.

Faults Prior to the deposition of the Sonoma Volcanics, Cretaceous and Jurassic sedimentary rocks were deformed over a wide area by thrust/reverse faulting near a subducting plate boundary (Weaver, 1949; Fox et al., 1983). Currently the study site is within a zone of active tectonic deformation associated with the San Andreas fault system. The San Andreas fault is about 64 km (40 mi) to the southwest of the study area. Locally, a small portion of the total right-lateral slip on the San Andreas fault system is accommodated by the Green Valley, West Napa, and several smaller unnamed faults. Shortening features such as the Foss Valley syncline, Mayacama anticline, and northeast-dipping faults indicate that this area has experienced transpression. The west-dipping Soda Creek fault and other west-dipping faults in the study area suggest localized extension within the regional transpressional system.

Green Valley Fault The Green Valley fault is the longest of the right-lateral faults near the study area and bounds the eastern side of the Vaca Mountains. Its most northerly mapped trace is approximately 3 km east of the study area; north of this, landslides conceal the trace. Paleoseismic investigations by Bryant (1992) and Baldwin et al. (1998) found offset soil, suggesting Holocene surface rupture. The Working Group on Northern California Earthquake Potential (WGNCEP, 1996) estimated a slip rate of 6 ± 2 mm/yr for the Green Valley fault. Weaver (1949) found ≤ 150 m of east-side-down dip slip on the Green Valley fault.

Maacama Fault The Maacama Fault is a right-lateral strike-slip fault 30 km northwest of the study area. This fault consists of several parallel faults in a zone as wide as 800 meters. At the southeastern tip of the Maacama fault is a northwest-trending, east-dipping thrust fault known as the Sulfur Springs fault.

Smaller Faults Much of the study area is contained within the Snow Flat-Lake Hennessey and the Atlas Peak-Foss Valley lineament zones of Baldwin et al. (1998). These zones consist of several northwest-trending lineaments of uncertain origin. Weaver (1949) mapped the Rector fault, a minor structure that apparently juxtaposes the lower member of the Sonoma Volcanics against younger rhyolite in a hill protruding from Napa Valley west of Rector Reservoir. Weaver suggested that the Rector fault continues north beyond Conn Creek, but it has not been mapped where it disappears under the alluvium in Napa Valley. Baldwin et al. (1998) suggested that this fault may be a west-vergent splay of thrust faults under the Vaca Mountains.

Soda Creek Fault South of the study area, the west-dipping Soda Creek fault, identified by Weaver (1949), vertically offsets the Sonoma Volcanics east and west of Soda Creek Road. Johnson, in Baldwin et al. (1998), found that the vertical offset was at least 210 meters. Weaver (1949) estimated as much as 213 meters (700 ft) of vertical displacement between the hanging and foot wall in Soda Creek Canyon. Units in the hanging wall of the fault dip more steeply to the east than do units in the footwall, which suggests a component of rotation. The Soda Creek fault is conspicuously aligned with geomorphic features in the study area and likely extends farther north than mapped by Weaver (1949).

Folds The orientation of the folds in the study area and the surrounding region are "optimally oriented to accommodate shortening" according to Baldwin et al. (1998) and are attributed to blind thrusts at depth. Such folds are graphically shown in the schematic cross sections of Swinchatt and Howell (2004). The folds generally trend northwest and may be plunging to the northwest. No major angular unconformities were observed within the andesitic portion of the Sonoma Volcanics in this area. However, south of Rector Canyon are several locations where there are slight variations between the strike and dip of the andesitic and the rhyolitic members of the Sonoma Volcanics. Southwest of the study area, rhyolite, thought to be the upper member of the Sonoma Volcanics, is in contact with units of the Great Valley Group. This bedrock is exposed in an anticline at the foot of the Vaca Mountains, which suggests deformation prior to the end of volcanism associated with the Sonoma Volcanics.

Foss Valley Syncline This fold was first identified by Weaver (1949) and is about 11 km long; its northern termination lies within the study area. The Foss Valley syncline trends northwest through Foss Valley but bends to the west near Rector Canyon. The fold limbs dip between 20 and 30 degrees, and a wide valley has developed in the broad hinge area. The eastern limb of the syncline forms a ridge 792 meters (2600 ft) in elevation and is locally the eastern boundary of the Sonoma Volcanics. The western limb of the syncline reaches elevations of 640 meters (2100 ft); the resistant units in this limb can be seen from Napa Valley. Near the eastern edge of the Upper Stage Coach block the eastern ridge of the Foss Valley syncline is 213 to 244 meters (700 to 800 ft) above the elevation of surface 6; however, at the Dana Johnson block the ridge is virtually absent or may be occupied by the erosional surfaces themselves, suggesting the Foss Valley syncline dies out east of the Dana Johnson Block.

METHODS

A total of approximately six weeks was spent in the field during the summer and fall of 2002 and the spring of 2003 conducting detailed geologic mapping of the study area. The main purpose for mapping the individual units in the study area was to compare the stratigraphic sequences on each of the identified blocks. Similar sequences on the blocks would suggest the blocks were separated by faulting or folding. Faults were mapped during the field investigation or interpreted from the aerial photographs. In most cases, the fault surface could not be identified but its location could be constrained by offset units. In other locations, cliffs or slopes that aligned with fractures in the canyon walls were used as indicators of faulting.

Stream Profiles

Two stream profiles were constructed along Rector Creek. To eliminate small-scale sinuosity, stream profiles were constructed by projecting the elevations of the channel orthogonally onto straight-line segments that parallel the trend of the stream. Where the stream makes large scale course changes a new segment is necessary that follows the new trend more closely. Stream profiles are useful in determining changes in stream gradient caused by recent vertical offset, juxtaposed rock types with dissimilar resistance to weathering, or natural falls at the boundary of stratigraphic units. The stream profiles were also helpful in this study because the bottom of Rector Canyon is inaccessible due to Rector Reservoir, dense vegetation, and steep slopes within the canyon.

Maps

The USGS 1:24000 Yountville topographic map (USGS, 1991) was used to supply the elevation data for the eastern profile, which extends from the eastern shore of Rector Reservoir to the easternmost finger of Rector Creek. The contour interval on this map is 20 feet. At its eastern end, Rector Creek splays into several smaller channels that drain the hills bounding Foss Valley.

The western profile uses Marliave's Plate V (Marliave, 1940). The topographic map used by Marliave (1940) during the initial geologic investigation of the Rector Dam site shows the floor of the canyon hidden on the modern maps. This map uses a contour interval of 10 feet. Marliave's map extends west from the NW corner of section 21 to the mouth of Rector Canyon. This map overlaps coverage of the USGS map in the central region of the canyon but has higher resolution. Coverage on this map does not extend out of Rector Canyon or above 183 meters (600 ft) in elevation.

Core Stones

When core stones were encountered, their location, unit type, weathering type, rind thickness and total number of rinds were recorded. At each site, the rind thickness of up to five core stones was measured; where five were not available as many core stones as possible were measured. The weathering rinds were measured in-situ, thus only the rinds that were exposed were measured. For core stones with thicker rinds on one side than the others, the thicker rind was measured as it likely represents the oldest weathering surface on that stone. Measurements were not taken at the corners of the core stones where rind formation is accelerated due to increased surface area-to-volume.

The thickness of weathering rinds was measured at sample localities where core stones were exposed by recent erosion or agricultural activities. The majority of sample sites are from the Upper Stage Coach block as it contains the most roads and roadcuts. The other blocks are poorly represented due to lack of exposure. Each sample location represents a site where core stones formed in-situ. This assertion is supported by through-going weathered joints, interlocking weathering rinds, uniform rock type, preserved phenocryst ghosts, and phenocryst spacing/orientation.

The thickness of the rinds at different sample sites was compared to determine whether core stones on different surfaces could be used to help differentiate the surfaces by age. Colman and Pierce (1981) have postulated a correlation between rind thickness and age. Rinds of similar thickness on surfaces separated both geographically and structurally would support the idea that the surfaces formed at the same time and were then separated. Conversely, rinds of dissimilar thickness in areas where the separation cannot be attributed to structure may be considered separated by age.

For this comparison it would be ideal to compare rinds from sample sites with similar conditions, such as elevation, rainfall, temperature, slope angle, and aspect in an attempt to keep environmental variation between sites to a minimum. However, relatively few sample sites have core stones exposed at the surface with intact rinds, and even fewer have exactly similar environmental conditions. Structural and tectonic deformation since the formation of the erosional surfaces may have caused complex changes in environmental conditions that cannot be accounted for and may be significantly more important than the slight differences between the sites today. It is beyond the scope of this study to determine past environmental conditions at each site, so the sites will be compared independent of environmental factors. Where there are large differences in rind thickness, the area with thinner rinds is considered to be younger.

While environmental conditions are difficult to determine and compensate for, differences in composition are more easily identified and corrected for. Colman and Pierce (1981) found that, when all other factors are the same, the ratio of rind thickness in fine-grained andesite to rind thickness in coarse-grained andesite is approximately 0.84. Units Fg and Mg and most of unit Fgm meet Colman and Pierce's definition of a fine-grained unit (<30% phenocrysts and an aphanitic matrix). Unit Cg1 and Cg2 have sufficient plagioclase or augite phenocrysts to be considered coarse-grained by Colman and Pierce. This indicates that fine-grained units like Fg, Fgm, and Mg should have rinds that are 84 percent as thick as coarse-grained units like Cg1 and Cg2 that are the same age. Thus, coarse-grained units should be normalized by multiplying their thickness by 84 percent to make up for their faster growth.

Topographic Profile

A profile of the proposed erosional surfaces was constructed along line A to A'. In general, this profile was drawn parallel to the southwesterly dip of the erosional surfaces and is orthogonal to the strike of several faults separating the surfaces. Projecting the surfaces to the profile causes some distortion. Surfaces that appear to connect on the profile may actually be separated laterally. The slope of a surface that is not parallel to the profile is exaggerated. Faults that cross the profile at an angle other than 90 degrees or that change strike as they cross an erosional surface will not project to a single point on the profile. Such faults are plotted as a solid line where they cross line A to A', then as a dashed line representing their position relative to the surface they separate.

OBSERVATIONS

Stratigraphy

Although the volcanic rocks mapped by Weaver (1949) at Wooden Valley (several kilometers southeast of the study area) resemble those within the thesis area, their composition, sequence, and thickness differ. These characteristics vary even within Rector Canyon. The units at the surface of the study area generally correlate best with the upper portion of Weaver's (1949) column. The commonalities between the areas include thick flows overlying tuffs and the presence of augite phenocrysts that Weaver found only in one upper andesitic flow. Textural, thickness, and compositional changes between the two areas make it difficult to correlate the majority of the units Weaver describes to units observed in the study area. Variations within the Sonoma Volcanics are common within the study area, and such local heterogeneities should be expected in the surrounding area as well.

Unit contacts are exposed at very few locations in the study area. Most contacts are hidden by soil cover or vegetation, or are obstructed by the subdued topography on the surfaces. Contacts may be seen locally in roadcuts and in the walls of Rector Canyon. The units at the ground surface in the study area are primarily the resistant andesites rather than tuffs, breccias, or agglomerates.

Although lithologic character and sequence vary within the study area, it is possible to construct a generalized stratigraphic section (Table 2). Because unit thickness changes across the study area, it is not included in this table. An estimate of thickness is

Table 2. General stratigraphic section composed of all units in their relative position to each other within the study area.

Unit Name	Description
Fg	aphanitic andesite
LT	lapilli tuff
Mg	porphyritic andesite
Fgm	porphyritic andesite
B1/Ag1	breccia to agglomerate
T1	clastic tuff
Cg1	porphyritic andesite
B2	tuffaceous breccia
Ss	volcanic sandstone
AT	ash tuff
B3/Ag2	tuffaceous breccia to agglomerate
Ob	obsidian
Cg2	porphyritic andesite
B4	breccia

included in the local stratigraphic sections describing the sequences encountered on the different blocks (Appendix A). Table 2 lists the units identified in their position relative to other units. Not every unit listed here is in every location due to erosion and the non-uniform deposition of the units. These units are shown on Plate 1.

Unit B4, a dark-gray breccia with an ashy matrix, is the oldest stratigraphic unit differentiated from the undifferentiated Sonoma Volcanics mapped by Graymer et al. (in preparation). The top of this unit is locally interbedded with the bottom of unit Cg2. Clasts within this breccia are up to 0.33 m (1 ft) in diameter and are composed primarily of andesite similar in composition to Cg2. This unit is near the base of Rector Canyon below the Lower Stage Coach block and along Silverado Trail at the base of a portion of the Dalla Valle block. This unit may be near the middle of the Sonoma Volcanics.

Unit Cg2 is a dark-gray to black porphyritic andesite with a glassy, fine-grained matrix. Plagioclase phenocrysts 2 to 3 mm in size compose 20-30% of the total volume. The upper portion of this unit is occasionally vesicular. This unit is exposed only in the walls of Rector Canyon west of the center of the Lower Stage Coach block. Unit Cg2 and the agglomerate (Ag2) above it are associated with shallow landslides near the western edge of the Lower Stage Coach block.

Black, dense, glassy obsidian (Ob) is exposed below several other pyroclastic units on the west side of the Lower Stage Coach block, and immediately below unit Cg1 on the Dalla Valle block. Weathered portions of this unit appear frosted. This unit contains rare plagioclase crystals, and is occasionally highly fractured and crumbles like shattered glass.

Units B3, a tuffaceous breccia, and Ag2, an agglomerate, are hard, tan to dark gray in color, and phases of the same general deposit. Clasts up to 0.6 m (2 ft) in diameter are common; clasts coarsen to the west where the unit's composition more commonly is of an agglomerate.

Unit AT is a soft, gray, ash tuff with occasional volcanic clasts. This unit is exposed in Rector Canyon, thins to the west, and pinches out in the cliffs on the west side of the Oakville Ranch block.

Volcanic sandstone, unit Ss, is tan to white. Bedding is generally horizontal, but the unit does contain several scoured channels. Grain size ranges from fine sand to coarse gravel with varying composition. The grains are angular to rounded and are moderately cemented. This unit is exposed in the walls of Rector Canyon. The base of unit Ss is in erosional contact with unit AT. Volcanic sandstone is also exposed in the roadcut on the north side of the Dana Johnson block but it cannot be definitively correlated to unit Ss.

Unit B2 is a hard, reddish-brown to light gray medium to coarse-grained tuffaceous breccia. Clasts within this breccia are up to 0.6 m (2 ft) in diameter and are composed primarily of andesite similar in composition to Cg1. This unit also contains thin beds of scoria and obsidian.

Unit Cg1 is a dark-gray to black, porphyritic andesite with a fine-grained matrix. In several locations on the Upper Stage Coach block unit Cg1 contains enough phenocrysts to be classified as a porphyry. The key features for distinguishing between unit Cg1 and Cg2 are bimodal plagioclase and rare, mafic phenocrysts in unit Cg1. One mode of plagioclase is 3-7 mm euhedral crystals that compose up to 20% of the total volume. Many of these plagioclase are zoned and have tattered edges. The other mode of plagioclase is 1-2 mm crystal fragments that compose up to 25% of the total volume. The upper portion of this unit occasionally contains up to 30% vesicles. Unit Cg1 is the most widely exposed unit in the study area and is the oldest unit exposed on the erosional surfaces. Unit Cg1 can be seen as prominent cliffs in the walls of Rector Canyon east of the Oakville Ranch block. West of the Oakville Ranch block unit Cg1 is difficult to see or even find in outcrop. From the Oakville Ranch block, several geologic units can be seen cropping out occasionally in the walls of the southwest facing cliffs of the Dana

Johnson block; one of these may be unit Cg1. Several kilometers northwest of the study area, at the base of the hill southeast of the intersection of Highway 128 and Silverado Trail, andesite crops out that matches the composition and texture of unit Cg1 very well.

Unit T1 is a light-gray to white, medium-grained clastic tuff. This unit contains many crystal fragments and pumice with volcanic clasts 10 to 13 cm (4 to 5 in) across. Unit T1 is exposed at the northern side of the Dana Johnson block immediately below unit Fgm. T1 may be a variation of unit B1, a breccia immediately above unit Cg1 on the Upper Stage Coach block and below unit Fgm on the Oakville Ranch and Dalla Valle blocks.

Units B1, a coarse-grained tuffaceous breccia, and Ag1, an agglomerate, are both light-gray to pink, and are phases of the same general deposit. Clasts within these units are up to 1 m (3 ft) in diameter and are similar in composition to unit Cg1. Scoria and vesicular andesite are occasionally interbedded within these units.

Unit Fgm, a gray to purple porphyritic andesite, is easily distinguished by its green to reddish-brown augite phenocrysts, which are sometimes as much as 25% of its total volume. The percentage of augite by volume and the size of the crystals change laterally. On the Upper Stage Coach block, augite phenocrysts, 3-4 mm across comprise as much as 25% of the rock volume. However, in the northwestern corner of the Dana Johnson block the augite phenocrysts are only 1 mm across and comprise 15% of the total volume. Plagioclase laths 1-2 mm across comprise 5-10% of the total volume. Unit Fgm is exposed on the Upper and Lower Stage Coach, Dana Johnson, and Oakville Ranch blocks. The southern and eastern edges of this unit are hidden under unit Fg and

Mg on the Upper and Lower Stage Coach blocks. The appearance of unit Fgm at the edge of surface 8 marks the disappearance of unit Cg1 in surface exposure.

Unit Mg is a dark-gray porphyritic andesite with a dense, fine-grained matrix. Phenocrysts include plagioclase (laths and fragments) and rare augite. The plagioclase laths are ≤ 2 mm across and comprise 15% of the total rock volume; in some locations the laths have a preferred orientation thought to be flow structure. Plagioclase fragments are 1 to 2 mm across, comprise 2-5% of the total rock volume, and are subangular to subrounded. Euhedral brown to green augite is 1 to 2 mm across and comprises < 5% of the total rock volume. Vesicles may or may not be present, but are usually less than a few percent of volume. This unit may be a phase of unit Fgm or a separate unit that overlaps the southern end of unit Fgm. It is exposed between unit Fgm and Fg or directly above unit Cg1.

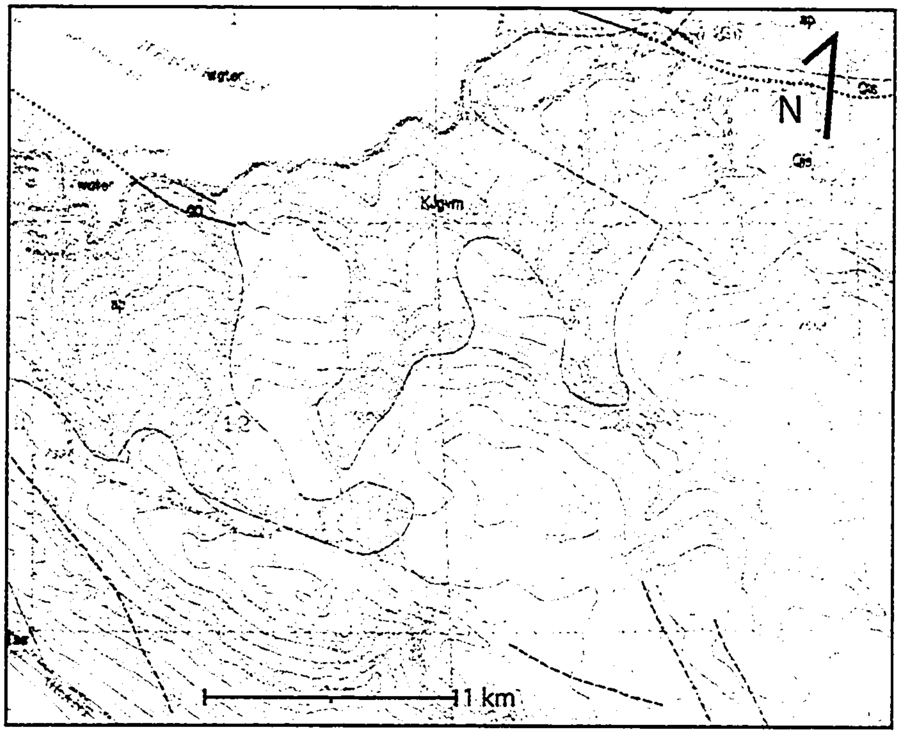
Unit LT is a light-gray to white lapilli tuff with many pumice fragments. This unit is only exposed in two small deposits on the Dana Johnson and Oakville Ranch blocks.

Unit Fg is a dark-gray to blue-gray, dense, aphanitic andesite (composition may approach basalt; a chemical analysis was not performed). Phenocrysts, where present, comprise <5% of the total rock volume and include plagioclase laths and rare brown augite. This unit is exposed primarily in the eastern and central portion of the study area on the Upper and Lower Stage Coach, Dana Johnson, and Oakville Ranch blocks.

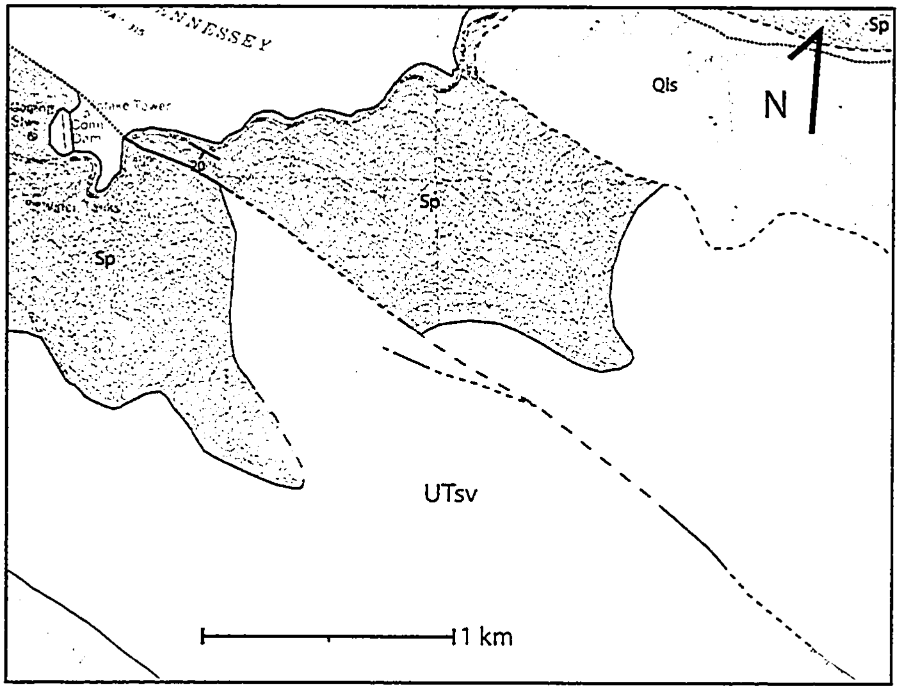
Suggested Changes to the USGS Geologic Map

Graymer et al. (in preparation) mapped unit KJgvm, the mudstone to siltstone member of the Great Valley Group, northeast of the Dana Johnson block and south of Lake Hennessey (Fig. 7). This unit is in fault contact with serpentinite of the Coast Range Ophiolite as seen east of the Conn Dam. Little mudstone or siltstone is exposed along Highway 128 or the access road to the Dana Johnson block; instead, the material mapped as KJgvm appears to be serpentinite of the Coast Range Ophiolite. The unit originally mapped as serpentinite has a slightly greater number of serpentinized blocks than the material originally mapped as KJgvm, but is otherwise very similar in appearance and composition to the unit originally mapped as KJgvm. Unit KJgvm in this location may need to be changed on the USGS (Graymer et al.) geologic map to serpentinite of the Coast Range Ophiolite.

Another suggested change in this area is the contact between the unit originally mapped as KJgvm and the Sonoma Volcanics. The USGS map shows a sinuous contact between these units on the canyon walls, but this contact may be inaccurately mapped. The access road below the hill at 422 m (1386 ft) makes a hairpin turn where the USGS map shows Sonoma Volcanics, but only serpentinite is found in this area. Occasional blocks of Sonoma Volcanics along this access road are most likely transported by landslides and slope wash. Unit KJgvm and the serpentinite originally mapped by Graymer et al. (in preparation) on the upper portion of the Dana Johnson block were not observed in the field and may also be mismapped. Suggested modifications to this area are shown on Figure 7.



A. Original USGS geologic map (Graymer et al., in preparation).



B. Alternate geologic interpretation.

Figure 7. Suggested alterations to the USGS geologic map resulting from field mapping.

Structural Blocks

Upper Stage Coach Block

This is the largest and easternmost of the six blocks in the study area (Fig. 2). The western side of this block is bounded by a fault scarp, Sage Canyon, and several tributaries of Rector Creek. The northern, eastern, and southern boundaries of this block extend beyond the edge of the study area. The Foss Valley Syncline is mapped on the Upper Stage Coach block and terminates at its western edge. Surfaces 4, 6, 7, 8, and 9, which represent two generations of erosional surfaces, and surfaces 10, 11, and 12, which have an undetermined relationship to the other surfaces, are mapped on this block (Fig. 3).

Dana Johnson Block

This block is bounded on the southwest by a large unnamed canyon and fault scarp; on the northeast by a fault scarp, Sage Canyon, and a tributary of Rector Creek; and on the south by a tributary of Rector Creek (Fig. 2). The northern portion of this block extends past the edge of the study area. The southeastern side of the Dana Johnson block slopes down to the southeast towards the Lower Stage Coach block. Surfaces 4 and 5 are mapped on this block.

Lower Stage Coach Block

The Lower Stage Coach block is wedge-shaped and tapers to the southwest (Fig. 2). This block is bounded on the north by a tributary of Rector Creek, on the south by

Rector Canyon, and on the east and west by fault scarps. The interior of the Lower Stage Coach block is offset by many west-dipping faults and at least one east-dipping fault. Surface 3 is the only surface mapped on this block.

Oakville Ranch Block

This block is bounded on all sides by fault scarps and canyons (Fig. 2). The interior of this block is incised by a large tributary of Rector Creek. Remnants of surface 2 and ridge R1 are preserved above the modern system of canyons and gullies.

Dalla Valle Block

The Dalla Valle block is bounded on the northeast by fault scarps and an unnamed canyon and on the west by Napa Valley (Fig. 2). The southern boundary of this block extends beyond the mapping area where it changes character and is occupied by high, steep ridges. The northern portion of this block is generally flat, but the southern portion is highly eroded. Surface 1 is the only surface on this block.

Rudd Block

The term block may not be appropriate for this area as its extent and structure are not well defined (Fig. 2). Little information about the Rudd block was observed at the surface and, in general, was not studied in detail due to limited access. The small outcrop of the Sonoma Volcanics that protrudes from the alluvial fan at the northwest corner of the Rudd block is composed mainly of unit Mg, and a small amount of breccia crops out at its western edge. This sequence is similar to the northwestern corner of the Dalla Valle block.

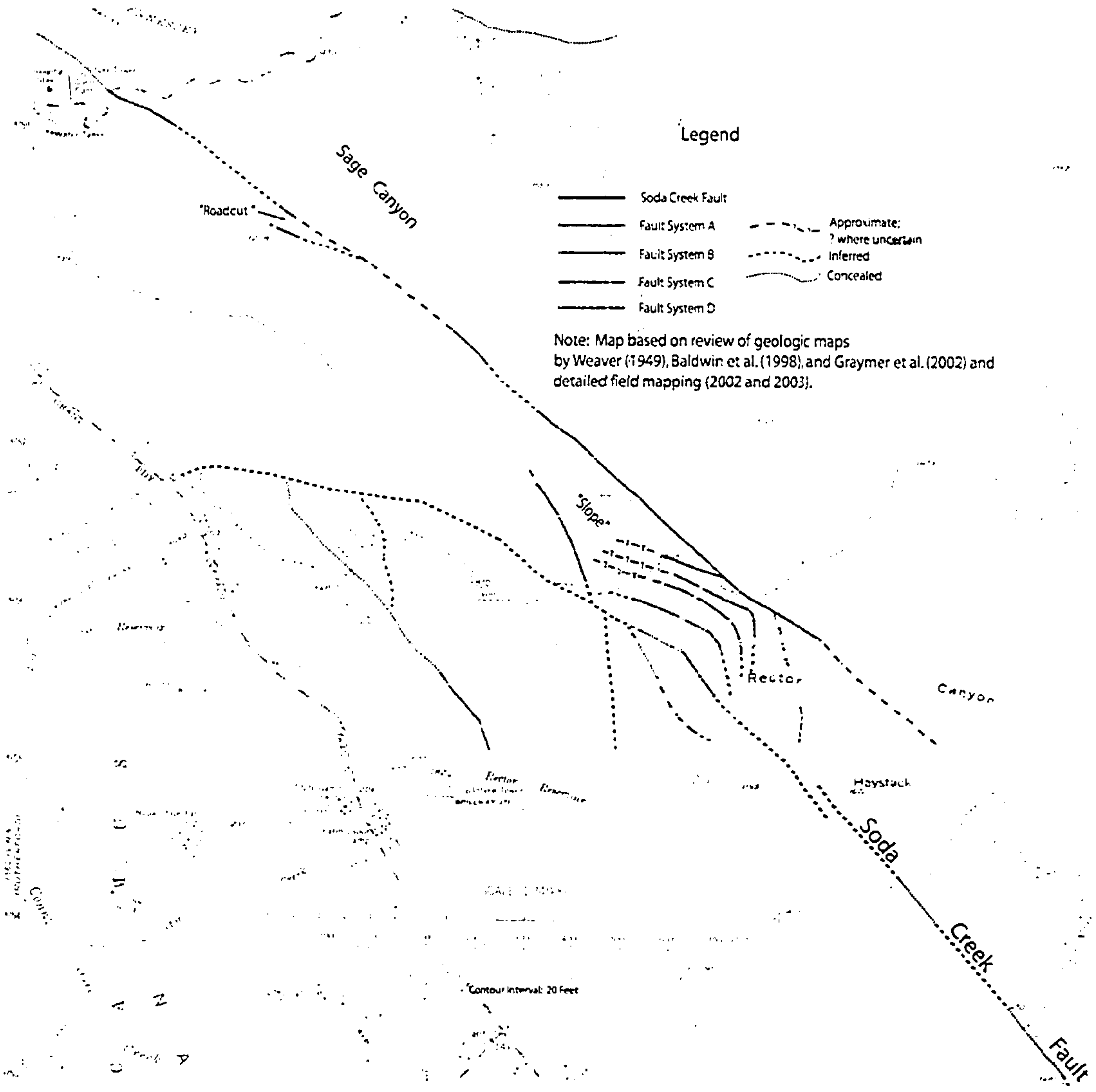
A soil pit southwest of the intersection of Oakville Cross Road and Silverado Trail shows Sonoma Volcanics under 0.5 m (1.5 ft) of soil. The bedrock surface in the soil pit is very undulatory due to the nature of the weathered volcanics. In other soil pits excavated to the east of this site, no bedrock was encountered to depths of 1.2 to 1.5 m (4 to 5 ft). There is insufficient evidence to determine how the Rudd block is related to the surrounding area.

Faults

Faults identified during field mapping are responsible for the step and bench topography in the study area. These faults have been divided into four systems on the basis of the blocks they separate (Fig. 8). Cross sections X-X' and Y-Y' illustrate the stratigraphy and idealized structure within the study area (Fig. 9 and 10).

Fault System A

Fault system A, an approximately 6-km-long, linear fault separating the Dana Johnson and Lower Stage Coach blocks from the Upper Stage Coach block, is the most northerly of the identified faults. A segment of this fault was previously identified in the area between the Upper and Lower Stage Coach blocks by Baldwin et al. (1998) and Graymer et al. (in preparation). Detailed field mapping suggests this fault extends farther to the northwest. A subtle northwest-trending scarp approximately 1.5 to 2.4 meters (5 to



Note: Map based on review of geologic maps by Weaver (1949), Baldwin et al. (1998), and Graymer et al. (2002) and detailed field mapping (2002 and 2003).

Figure 8. Map of fault systems identified in the study area.

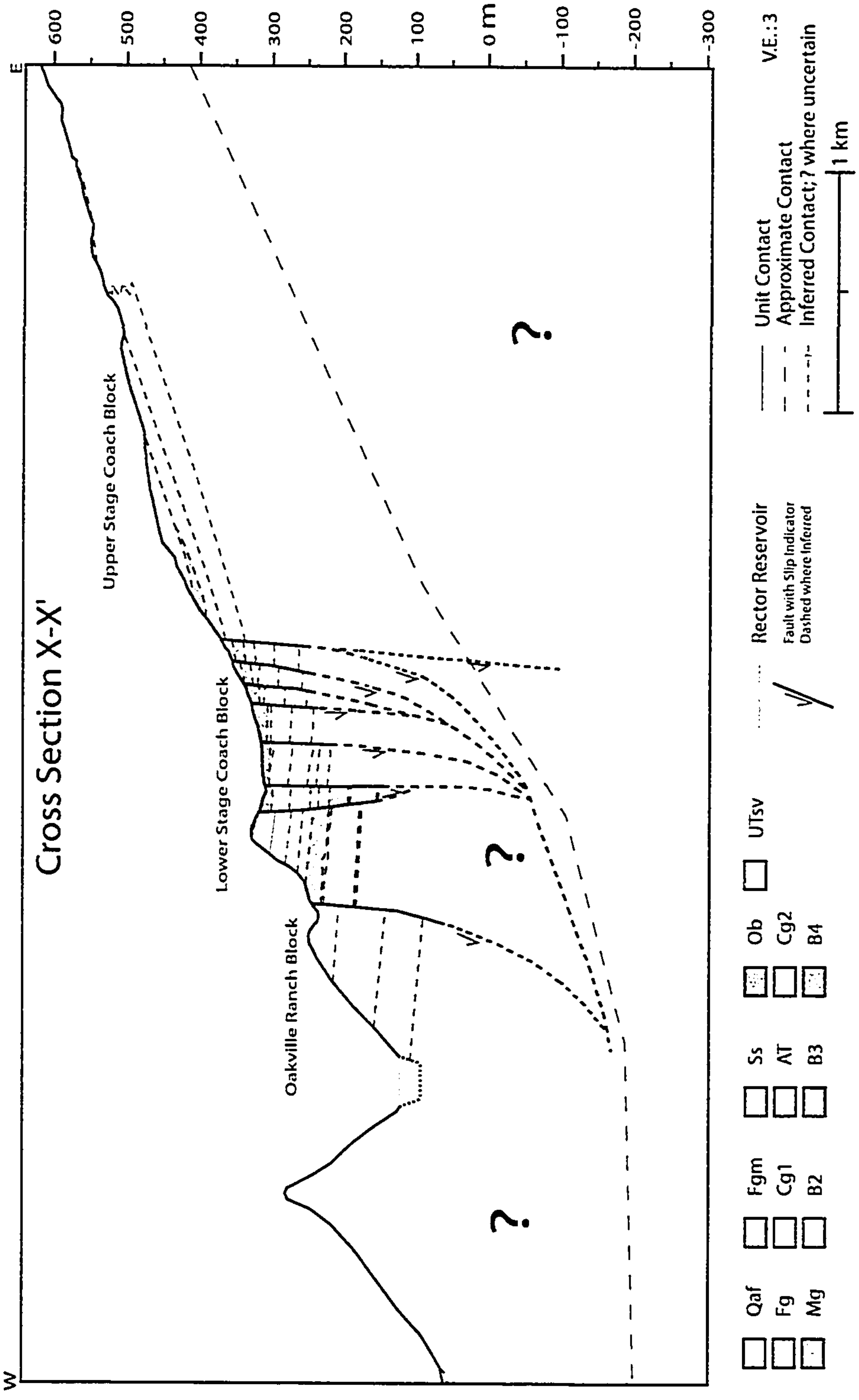


Figure 9. Geologic Cross Section along line X-X'

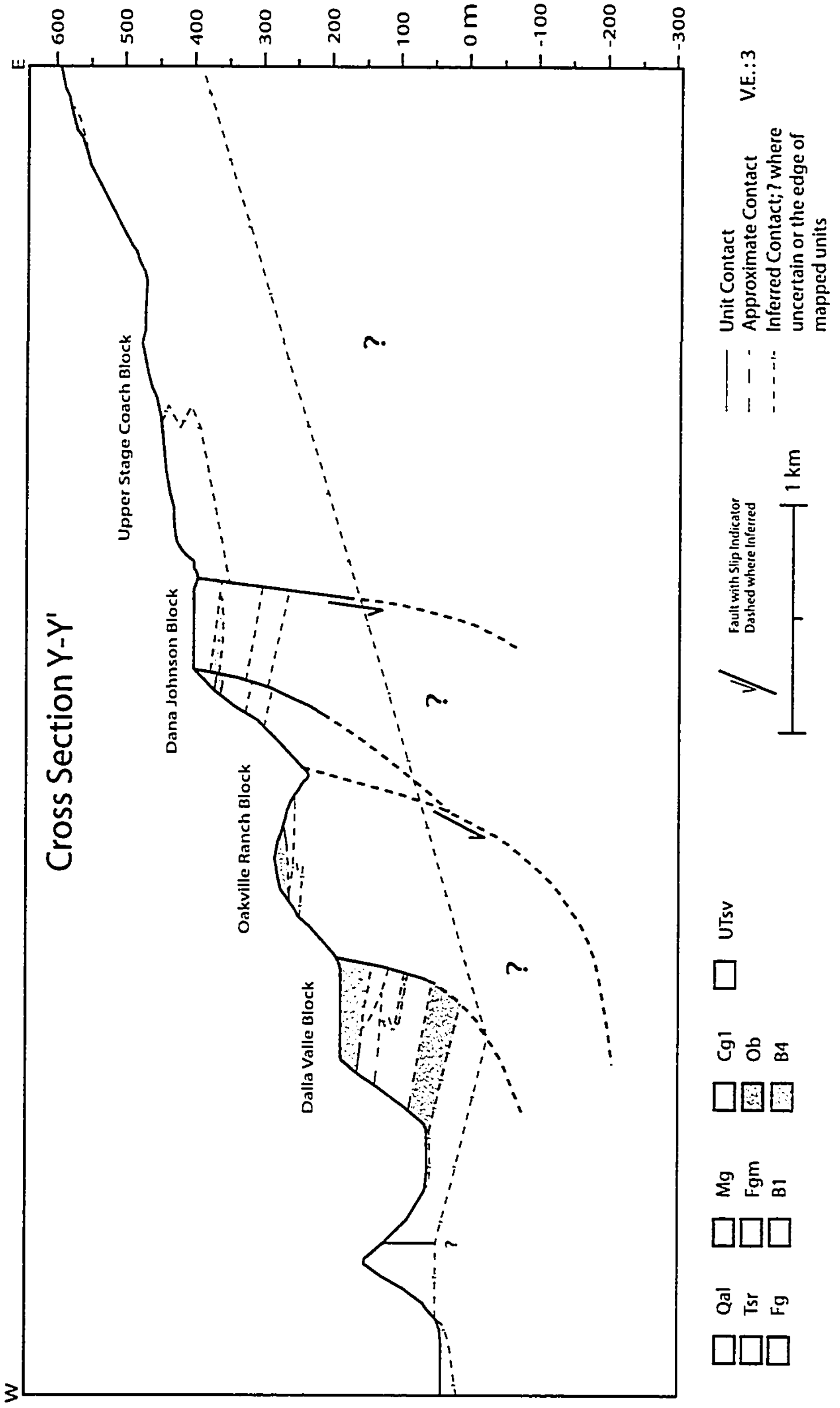


Figure 10. Geologic Cross Section along line Y-Y'

8 ft) high was observed south of the hill at an elevation of 421 meters (1382 ft). This scarp is poorly expressed in the southeast but becomes visible to the northwest where resistant boulders are increasingly exposed. At the western edge of the scarp is an entrenched stream oriented parallel to the fault; however, the fault trace is not visible in the stream channel. The fault also bisects a small hill at an elevation of 402 meters (1320 ft) and juxtaposes units Fgm and Fg with southwest-side-down separation, but no scarp is visible. A large roadcut perpendicular to the fault exposes a series of south- to southwest-dipping faults that juxtapose Sonoma Volcanics and the Coast Range Ophiolite.

The USGS Yountville geologic map (Graymer et al., in preparation) shows another fault that cuts the southern shore of Lake Hennessey approximately 213 meters (700 ft) east of Conn Dam, juxtaposing serpentinite of the Coast Range Ophiolite on the west and Great Valley mudstone on the east. (The rock mapped as Great Valley mudstone may be misclassified, as previously discussed.) This fault is collinear with the fault to the southwest, and is interpreted as a through-going, west-dipping normal fault (Fig. 8).

Fault system A is exposed in a roadcut of the common driveway providing access to the Dana Johnson block from Route 128 (Fig. 8, "Roadcut"). The volcanics exposed in this roadcut are mainly tuffs and volcanic sandstones with minor flows near the top (Fig. 11 and 12). Their composition, sequence, and position place the base of the roadcut approximately 15 meters (45 ft) below the base of unit Fgm. At the northern edge of the roadcut is a brecciated zone with mixed volcanics and occasional serpentinite

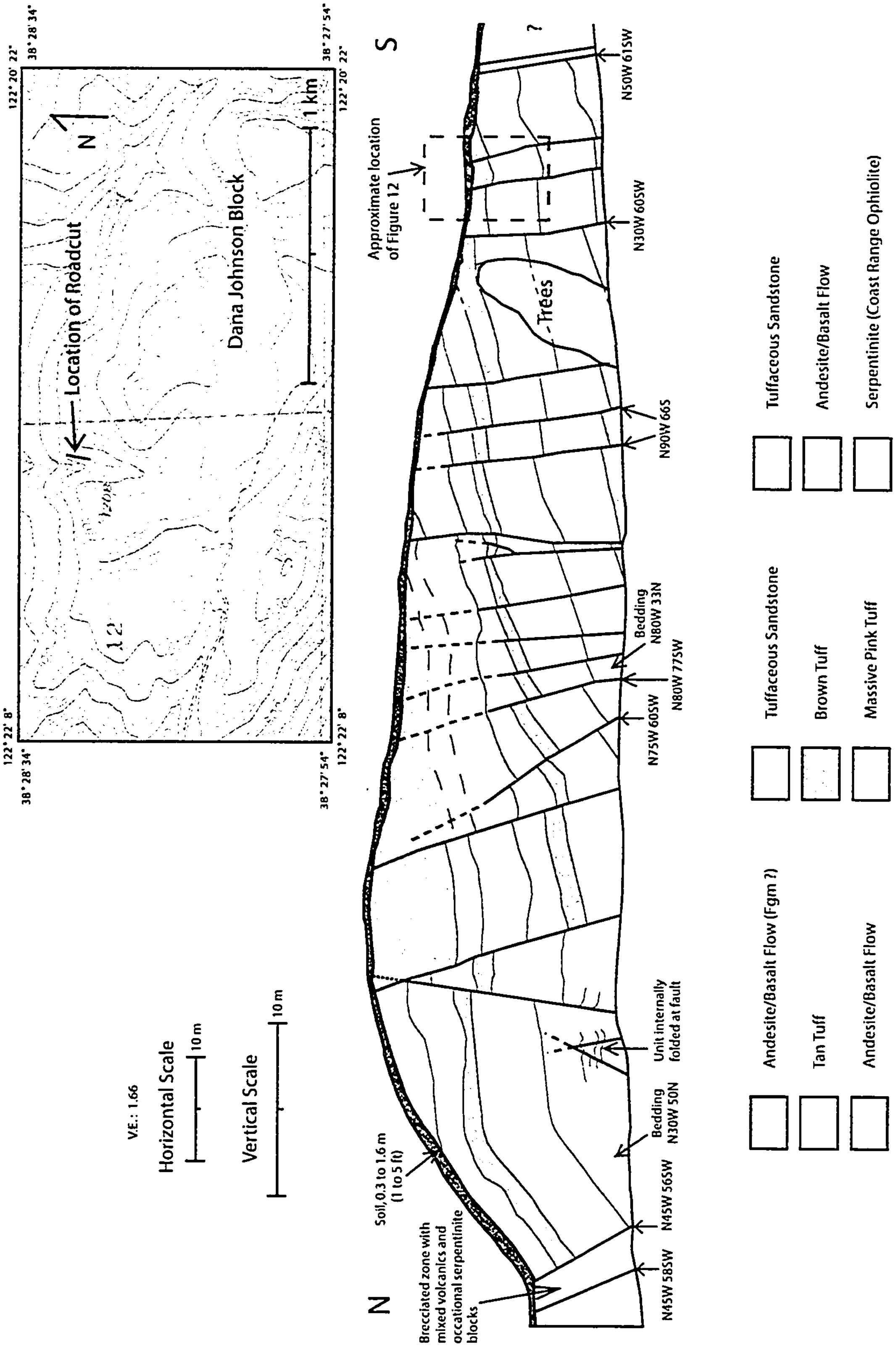


Figure 11. Sketch of the roadcut at the northern edge of the Dana Johnson block.

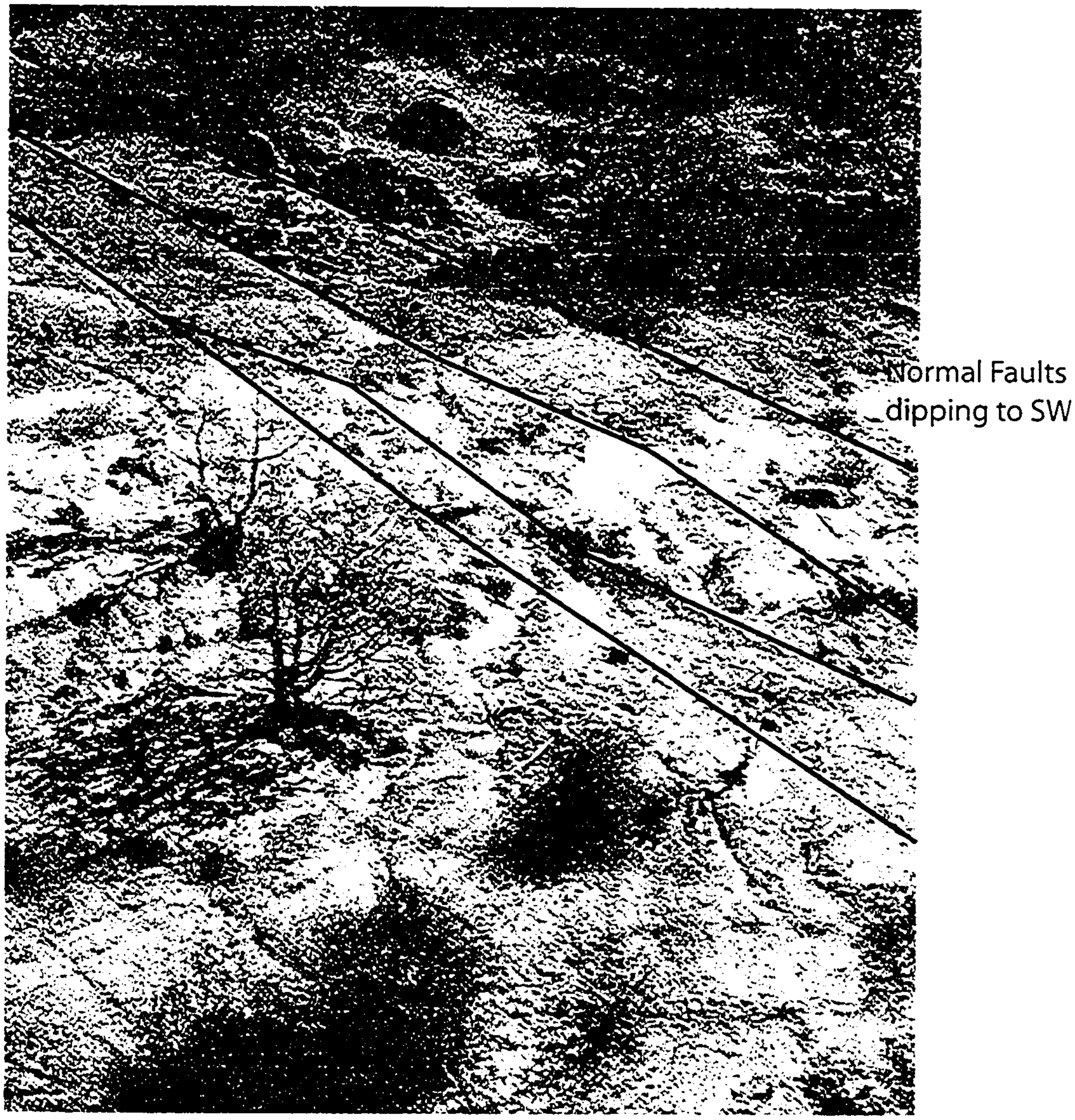


Figure 12. Picture of a portion of the roadcut. Andesite/basalt flow at top, volcanic sandstone at base. Roadcut is fractured by many SW-dipping normal faults. Area of photograph outlined on Figure 11.

blocks between two subparallel faults oriented N45W 58SW and N45W 56SW. Serpentinite lies north of this brecciated zone and Sonoma Volcanics lies south of it. All faults in this roadcut contain approximately 1-3 cm of red clayey gouge that is easily excavated to expose smooth slip surfaces. The volcanic units near these faults are oriented N30W 50NE and dip towards the faults, with decreasing dip to the south. It is not possible to determine the sense or magnitude of slip on the northern faults because the original stratigraphy of the area is unknown.

Numerous minor faults in the roadcut may be splays of the main northern fault. These smaller faults vary in orientation but generally strike N80W to N30W and dip 60° to 75° SW. Dip separation on individual minor faults averages about 0.5 m (1.5 ft), with a maximum of 6.5 m (21 ft). Unit 3, a distinct pink unit, exhibits about 15 m (50 ft) of down-to-the-south dip separation across the length of the roadcut.

Several small reverse faults were identified in the roadcut. These small reverse faults may cut across the normal faults or they may be offset by them, but generally do not cut the entire section. The exception to this is a north-dipping fault near the northern edge of the roadcut with approximately 1.2 meters (4 ft) of dip separation. The reverse faults are likely the result of the complex faulting and stress fields caused by the many splays in the fracture zone.

Fault System B

Fault system B separates the Dalla Valle and Oakville Ranch blocks from the Dana Johnson and Lower Stage Coach blocks. This fault system consists of three strands: a roughly east-west central fault inferred in the arcuate canyon along the boundary between the Dalla Valle and Oakville Ranch blocks and the Dana Johnson block, and two north-northwest-striking faults north of the eastern end of Rector Reservoir (Fig. 8). All three faults are west-side-down normal faults.

The northern wall of the canyon occupied by the east-west central fault diminishes in height to the east and is the product of the fault scarp and erosion. This type of feature is known as a composite scarp. The northern wall of the canyon has as much as 244 m (800 ft) of relief, of which as much as 91 m (300 ft) is due to erosion. The remaining 153 m (500 ft) is the approximate maximum offset on this fault.

While it is easy to argue that the strike of the fault is expressed as the trend of the canyon, the dip is less well defined. Several fault surfaces found on the northern wall (foot wall) near the base of the canyon dip 44° to the southwest. Though shallower than other fault dips determined in the study area, these dips are corroborated by the 40-50° slope of the northern wall of the canyon.

The southern fault, which separates the Oakville Ranch and Lower Stage Coach blocks, is inferred from several lines of evidence. First, a brecciated zone of fractures generally oriented N15E 85NW is observed in the north-south-trending canyon near the east end of Rector Reservoir. Second, stratigraphic units are offset across the trace of the fault (Plate 1). Third, there is a noticeable change in slope west of the ridge at the western edge of surface 3. Fourth, a slight increase in gradient is observed on the western stream profile at point D' (Fig. 13) near the brecciated zone. Fifth, the gully immediately north of surface 3 is deflected to the southwest in this area. These five sites are aligned

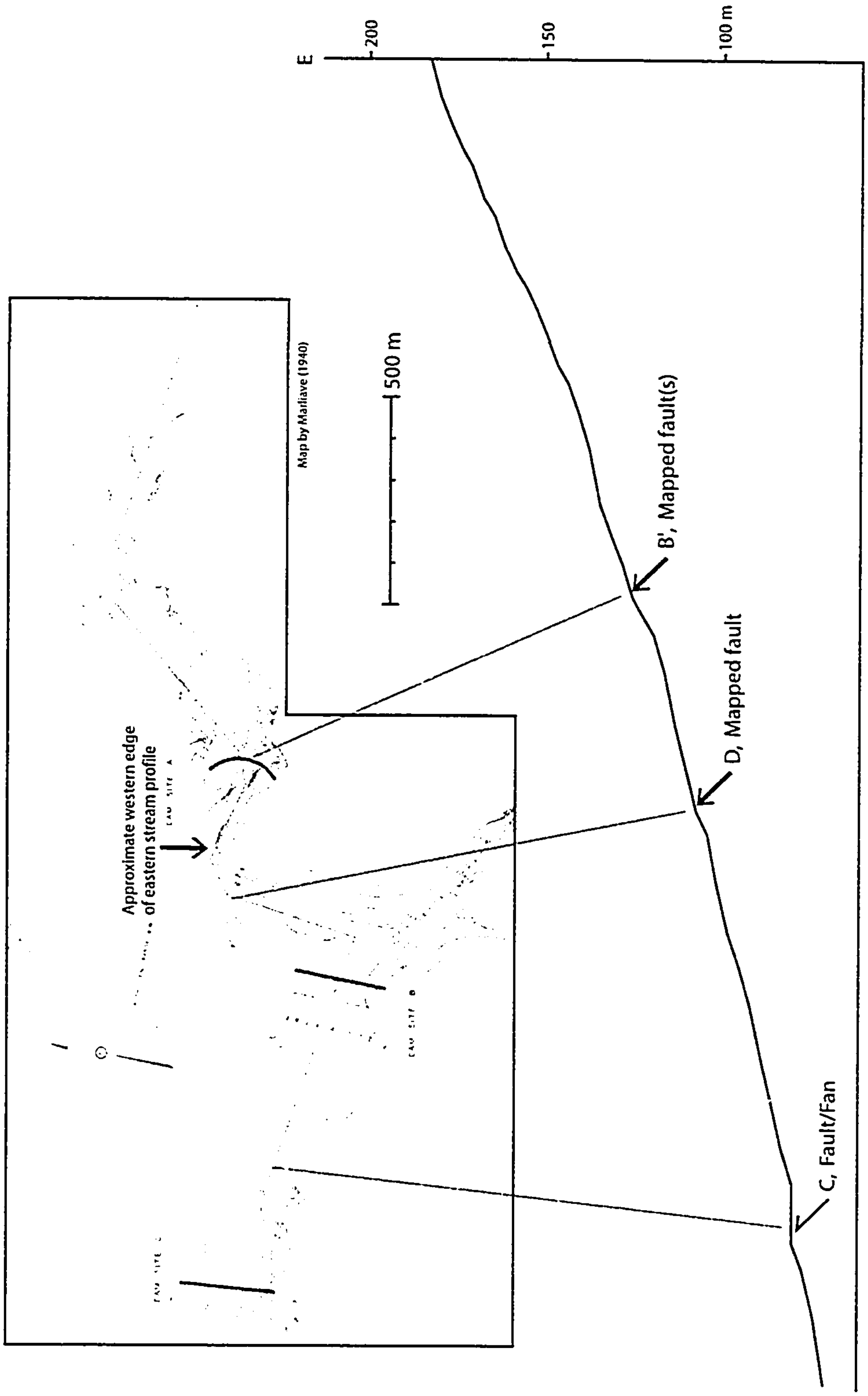


Figure 13. Western stream profile of Rector Creek. Topographic map from Marliave (1940) Plate V.

along a steep normal fault that separates the Oakville Ranch and Lower Stage Coach blocks by approximately 37 meters (120 ft) vertically. The orientation of this fault suggests that it is a conjugate of the northwest-southeast-trending fault or faults separating the Oakville Ranch and Dalla Valle blocks from the Dana Johnson block.

The northern fault shows southwest-side-down offset on the western edge of the Dana Johnson block (Fig. 8). The main fault exhibits a scarp 7-10 m high, but Unit Fg shows separation of >33 m (100 ft). This discrepancy may indicate the presence of subparallel, unrecognized strands in a fault zone.

Fault System C

Fault system C is a series of short faults that cut the interior of the Lower Stage Coach block (Fig. 8). These faults also were mapped by Graymer et al. (in preparation). The faults are not well expressed on the topographic map or aerial photographs, but they are marked by scarps that trend northwest and face southwest. The 3-4.6 m (10-15 ft) high scarps are defined by bedrock outcrops distributed across the eastern part of the Lower Stage Coach block, but vegetation and slope processes have hidden many of the scarps from view. Several west-dipping faults were identified during traverses of the walls of Rector Canyon; however, many may have gone unrecognized.

These closely spaced scarps lower the surface of the Lower Stage Coach block from the east to the west. By themselves, however, fault system C cannot account for the 104 m (340 ft) difference in the elevations of surface 3 and surface 7 (Fig. 3), so other faults may be present but unidentified. Faults of system C may cut across northwestern

Haystack Peak and join the Soda Creek fault, but steep terrain and dense vegetation prevent their detection.

Fault system C has little expression on the eastern stream profile (Fig. 14). Although units in the walls of Rector Canyon are visibly offset by minor faults, the stream profile shows little change in gradient except at point B. The steepened gradient at point B is very near faults mapped on both sides of the canyon by Marliave (1940) and on the north side of Rector Canyon. While few significant features were observed in profile, in plan view Rector Creek is deflected at the eastern edge of the Lower Stage Coach block and parallels the trend of several faults mapped on the block. The units exposed just east of the ridge on the west side of the Lower Stage Coach block are offset along a steep east-dipping fault with up to 34 m (110 ft) of down-to-the-east normal separation. This east-dipping normal fault coincides with east-dipping faults mapped by Marliave (1940).

Fault System D

Fault system D is the inferred boundary between the Dalla Valle and Oakville Ranch blocks (Fig. 8). This fault system is difficult to identify because of burial by slope wash, vegetation, or agricultural activities. Baldwin et al. (1998) map a photo lineament that is parallel to the scarp at the east side of the Dalla Valle block, but its location is as much as 152 meters (500 ft) west of the break in slope. This lineament may be a splay of the main fault that cut the Dalla Valle and Oakville Ranch blocks, but is too far from the main scarp to produce the offset. Evidence of a fault closer to the break in slope is in the

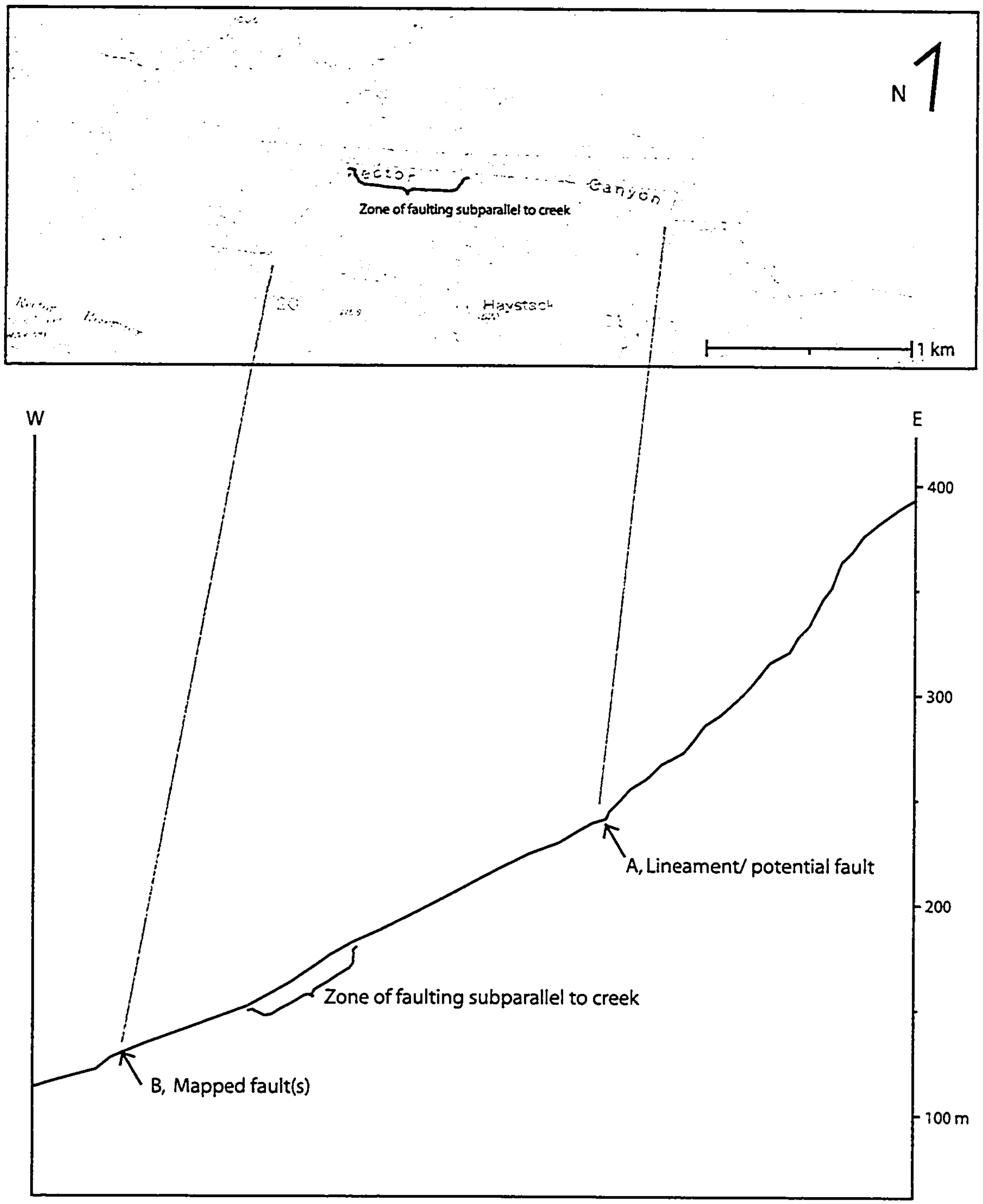


Figure 14. Eastern stream profile of Rector Creek. Index map from Yountville topographic map (USGS, 1991).

northern wall of Rector Canyon approximately 213 meters (700 ft) east of Rector Dam. Barren rock exposed below the high-water line of the reservoir contains fractured and locally brecciated zones, oriented approximately N41W 84SW. The majority of the fractures are filled with white gauge and silica precipitate. Projected northwestward along strike, these fractures align with an eroded gully and parallel the lineament mapped by Baldwin et al. (1998). At the top of this gully, volcanic flows on the west side of the fractures are juxtaposed against welded tuffs and fluvially bedded sandstone and conglomerate on the east. The sandstone is of the same composition and in the same stratigraphic position as the gravelly volcanic sandstone below the western edge of the Lower Stage Coach block and is likely unit Ss. The northwestward projection of this fault is much closer to the scarp at the eastern boundary of the Dalla Valle block than are lineaments mapped by Baldwin et al. This fault may have produced the inflection at point C on the western stream profile (Fig. 13).

The northern portion of the Oakville Ranch block narrows to a thin wedge between fault system B and the main fault of fault system D. The northern end of the Oakville Ranch block has been downdropped approximately 24 m (80 ft) by a splay of fault system D but still remains approximately 37 m (120 ft) above the elevation of the Dalla Valle block (Plate 1).

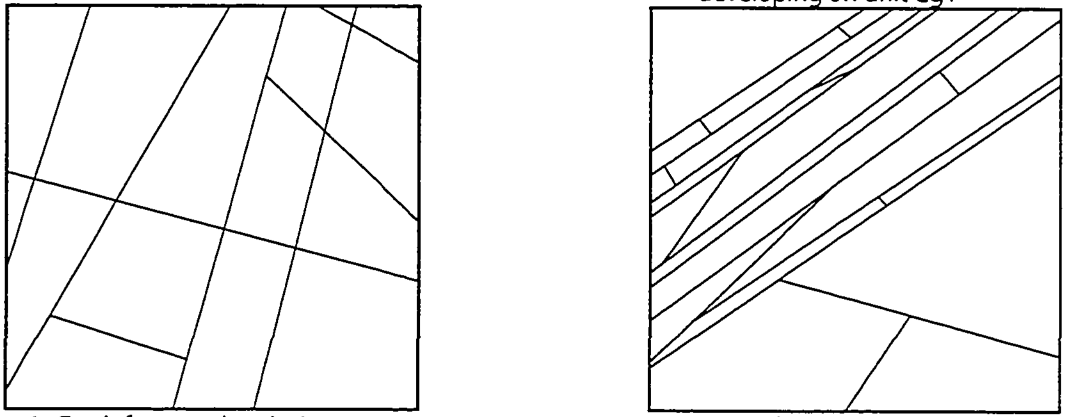
Core Stones

A large number of subrounded to rounded boulders and cobbles protrude from the ground surface and are exposed in the soils of the study area. Many of these are core stones, which are the weathered remnants of jointed bedrock. Within the study area these core stones occur mainly in the flows of the Sonoma Volcanics. Core stones are a common weathering product in this area and are not limited to the study site.

Core stones are formed by spheroidal weathering (Fig. 15), in which chemical weathering is concentrated along the surfaces of fractures and joints within a rock. In the study area, weathering rinds range in thickness from a fraction of a millimeter to 10 or more centimeters. Weathered rinds appear oxidized on their outer edge and are gray nearest the fresh rock, which, in this area, is black or dark gray in color. The boundary between the rind and the fresh rock is usually sharp but may not be planar in cross section. The remaining unweathered portion of the rock at the center of weathering rinds takes the name "core stone" because it is found at the core of the weathered exterior.

There appear to be no criteria describing how thick the weathering rind must be before the interior is considered a core stone. For the purpose of this study, any rock visibly surrounded by weathering products that formed in-situ is considered a core stone.

Weathering rinds may form as minerals near the surface of the rock interact with water percolating along the joints. The oxidation and hydration during chemical weathering convert the minerals to clay; the resultant change in volume separates the weathered rind from the fresh interior of the rock (Easterbrook, 1999). When the weathering front reaches a unit of rock it attacks the edges and corners of the jointed block. Weathering along the initially angular blocks gradually rounds sharp corners producing an oval or spheroidal shape (Fig. 16). During spheroidal weathering, concentric rings of weathered material are separated from the relatively fresh core of the

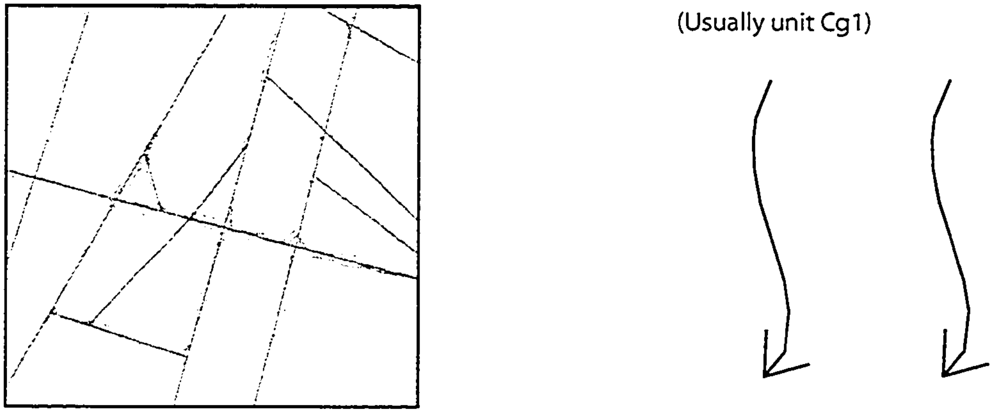


Common rind development:
Concentric rinds detach from core stone.

Single thick undetached rinds developing on unit Cg1

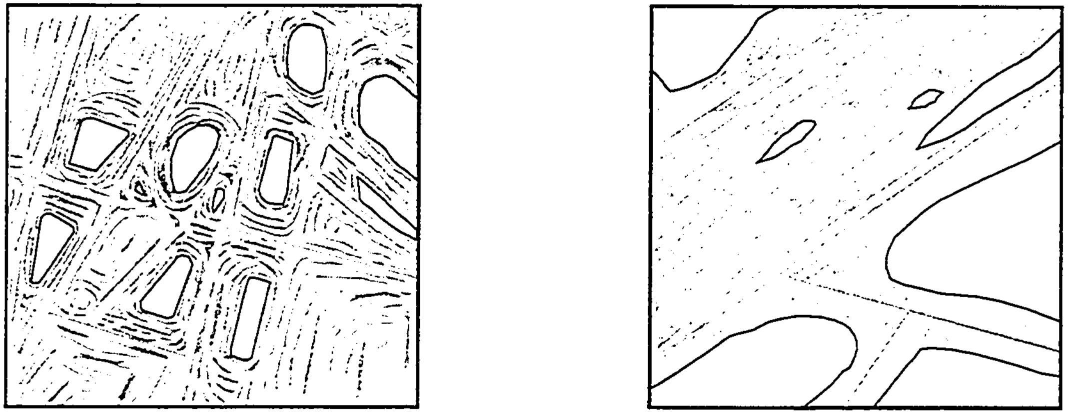
A. Fresh fractured andesite

A. Fresh fractured andesite
(Usually unit Cg1)



B. Young Weathering Profile: Edges of fractured blocks weather producing a rind of altered material around an unaltered core.

Gradual progression between A and B, rinds do not detach



C. Mature Weathering Profile: Multiple rinds have detached consuming some blocks completely and leaving a rounded core of resistant stone within others.

B. Mature Weathering Profile: Portions of unit are completely decomposed to clay but retain evidence of fracture pattern and phenocryst ghosts.

Figure 15. Progression of spheroidal weathering observed in field area.

Figure 16. Young core stones near the initial stage of weathering. Edges have been rounded, and 1 to 2 rinds have detached. The soft rinds have been removed by rain on the face of this roadcut, 300 meters west of Oakville Cross Road and Silverado Trail.

stone being weathered. The detached rinds remain parallel to youngest rind. These weathered shells often look like skins of an onion.

In highly fractured zones, weathering is facilitated by high fracture density that allows water to easily enter the unit. This can be observed in a quarry wall near the eastern fence of Stage Coach Vineyards (Fig. 17), where unit Cg1 is highly fractured except in the northern end of the wall where it is more massive. Weathering was much greater in the zone of dense fractures than in the massive part of the unit due to the increased surface area. Weathering rinds do not always follow the idealized process described above. In many cases the rind on one side of the core stone may be significantly thicker than the others. The difference in thickness of these rinds may be as much as 2 to 3 centimeters. One possible explanation for this is that the side with thinner rinds represents fractures that began weathering at some point after the side with the thicker rind did. Although core stones typically have rounded edges, some rinds preserve the initial angular shape of the rock even after six or seven rinds have formed (Fig. 18). A similar phenomenon occurs as tabular blocks weather to take the shape of a disc with sharp edges. In such rocks the rind will grow faster near the edges of angular stones than in more rounded stones.

In areas where rock has been spheroidally weathered for long periods, it may be totally consumed by chemical weathering. If these areas are not disturbed the delicate rinds may be preserved. When exposed in excavations, well-developed rinds can be seen interlocked with their neighbors; this indicates that these rocks weathered in place from a once-continuous unit (Fig. 19).

Figure 17. Picture of the quarry on the Upper Stage Coach block. Unit Cg1 is completely decomposed in the densely fractured zone on the left. On the right, unit Cg1 is less fractured and larger blocks are preserved.

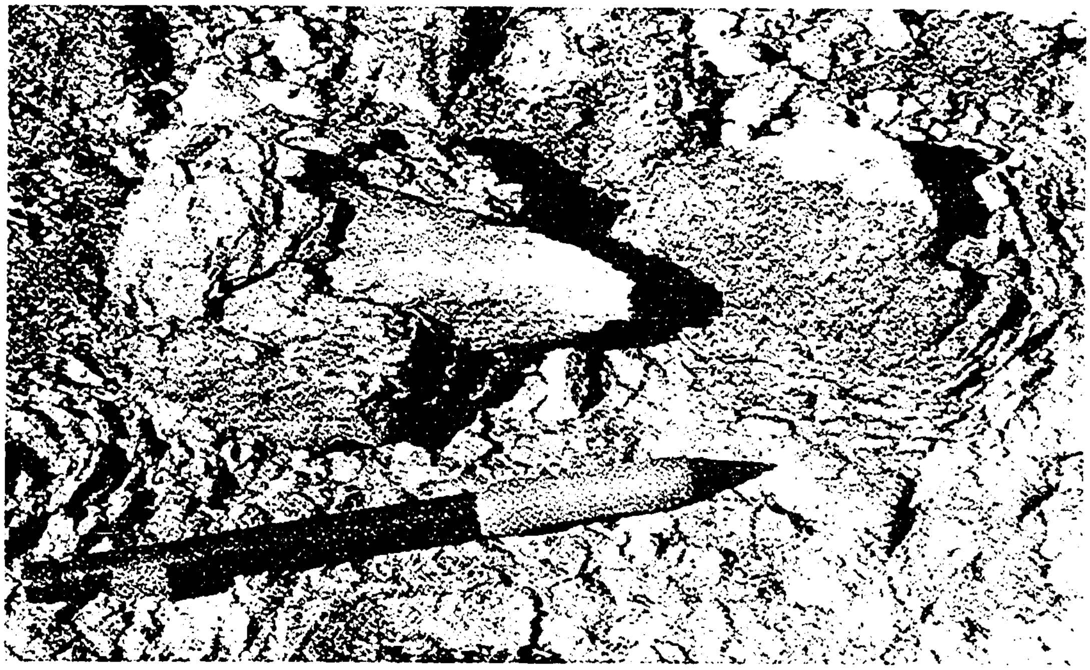


Figure 18. Angular and rounded core stones. Above the pencil, the rinds have preserved or formed an angular core stone. To the upper right of pencil, the rinds have rounded the core stone.

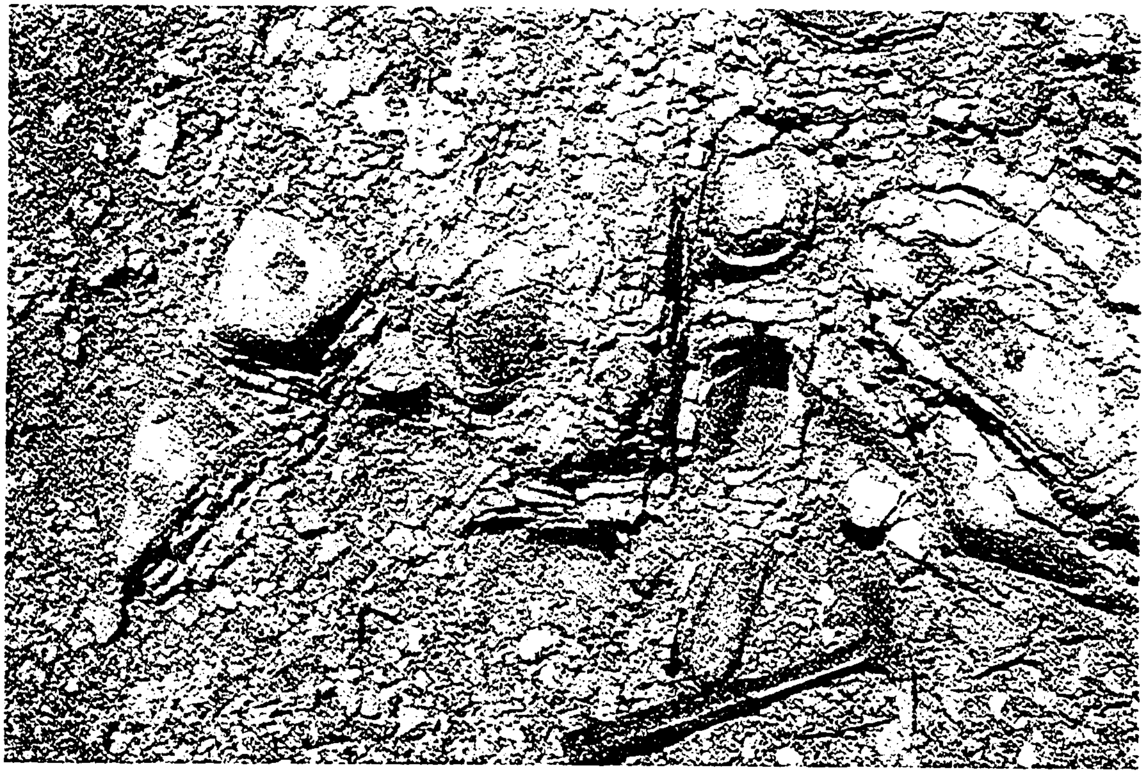


Figure 19. Mature core stones from sample site 27. As many as seven rinds surround the remnant core stones. Rinds interlock, indicating that they formed in-situ. Rinds commonly break into the small chips observed in this figure.

In many places, competent bedrock is exposed at the surface. In other locations, 3 to 6 m (10 to 20 ft) of weathered bedrock and soil overlie competent bedrock. Viewed in profile, the boundary between the zone of spheroidal weathering and competent bedrock is undulatory. Towers of resistant bedrock may be surrounded by weathered bedrock and core stones.

Units Fg, Fgm, and Mg have a very fine-grained and rather uniform interior which facilitates even weathering. Core stones within these units commonly have many rinds. The thickness of each detached rind ranges from about 4 mm to 15 mm. The rinds are usually very fragile and crumble into small fragments when disturbed (Fig. 19). Units Cg1 and Cg2 generally have thicker individual rinds than units Fg, Fgm, and Mg, but the total thickness of the rinds is less. While some core stones in unit Cg1 have multiple rinds like Fg, Fgm and Mg, they also have a second type of weathering rind that is almost exclusive to unit Cg1 and Cg2. This second type of rind leaves blocks of units Cg1 and Cg2 completely decomposed with a single undetached rind. One possible explanation for this second type of rind is that the larger crystal size of Cg1 and Cg2 may cause uneven weathering along the grain boundaries and prevent a through-going surface to propagate, which prevents the rind from detaching. The clays in the undetached rind would then act as a wick, drawing moisture towards the unweathered stone to continue weathering. A second explanation is that the chemical composition of the clays in the core stones with undetached rinds may be different than in core stones with detached rinds, resulting in a lower potential for swell and limiting the ability of the rind to detach.

In areas where unit Cg1 has been completely weathered and hydrated to clay, the joints are preserved and white ghosts of feldspars can clearly be seen. When disturbed by excavation or plowing, the completely weathered remnants break into pieces and appear as gray to yellow clods in a clayey soil. When similar activities occur in weathered portions of units Fg, Fgm, or Mg, many iron-stained chips and angular pieces of the rinds are exposed in the soil.

In areas where moderate erosion has occurred, the rind material may be removed at the surface and washed out of the area. This process leaves behind the core stones which are too large for erosion to remove, and is similar to the process by which desert pavements form through deflation. The remaining material collects as the ground surface is lowered and evolves into a surface littered with rubble. This is very common in the interior of the Upper Stage Coach block where the modern stream channel has dissected the surface and incised into the weathered bedrock (Fig. 20). Where the stream channel has scoured deeply, the zone of weathered bedrock is completely removed, exposing fresh bedrock.

Table 3 lists rind thicknesses measured at 32 sample sites, shown in Figure 21, where core stones were exposed.

Figure 20. Eroded core-stone bearing portion of surface 7. The rounded boulders and cobble are likely core stones that slope wash was unable to remove.

Table 3. Measurements of rind thickness in core-stone bearing localities of the study area. The measurements in bold are outliers and are not used in the comparisons. Underlined average thickness is corrected for 84% growth rate.

Sample #	Unit	Thickness (mm)	Avg. Thickness (mm)	Avg. # of Rinds
1	Mg	46, 48, 49, 49, **59**	48	7
2	Fgm	20, 20, 21, 23, **30**	21	3
3	Cgl	3, 4, 6, 7, 8	6, 4.7	1
4	Mg	**46**, 52, 53, 53	53	8
5	Fg	**42**, 48, 62, 64, 68	60	7
6	Cgl	3, 4, 4	3.75, 3.1	1
7	Cgl	3, 4, 4, 4, 4.5	3.9, 3.3	1
8	Cgl	1, 2, 2, 2	1.75, 1.5	1
9	Cgl	0, 1, 1, 1	0.75, 0.6	1
10	Cgl	7, 7, 8, 8	7.5, 6.3	2
11	Cgl	7, 8, 9, 9	8.25, 7	1
12	Cgl	4, 5, 5, 5, 5	4.8, 4	1
13	Cgl	10, 10, 10, 10, 13	10.5, 8.9	1
14	Cgl	4, 4, 6, 6	5, 4.2	1
15	lost			
16	Cgl	7, 8, 8, 9, 9.5	8.5, 7	1
17	Fg	30, 30, 40, 40, 45	37	4
18	Cgl	23, 25, 31, 32, 36	29, 24.7	4
19	Cgl	18, 25, 25, 25	23, 19.5	2
20	Cgl	24, 25, 30, **41**	26, 22.1	3
21	Cgl	**20**, 26, 27, 27, 27	27, 22.5	3
22	Cgl	11, 12, 12, 14, 16	13, 10.9	1
23	Cgl	13, 15, 19, 20, 20	17, 14.6	2
24	Cgl	35, 35, 35, 37, **52**	36, 29.8	3
25	Fg	48, 50, 51	50	6
26	Fg	**43**, 63, 64, 69	65	8
27	Fgm	47, 47, 47, 49, **66**	47	7
28	Cgl	**35**, 40, 41, 42	41, 34.4	3
29	Cgl	19, 23, **34**	21, 17.6	2
30	Mg	**35**, 52, 53, 53	53	6
31	Mg	**39**, 62, 62, 62, 62	62	6
32	Cgl	**24**, 31, 34, 35, 38	35, 29	2

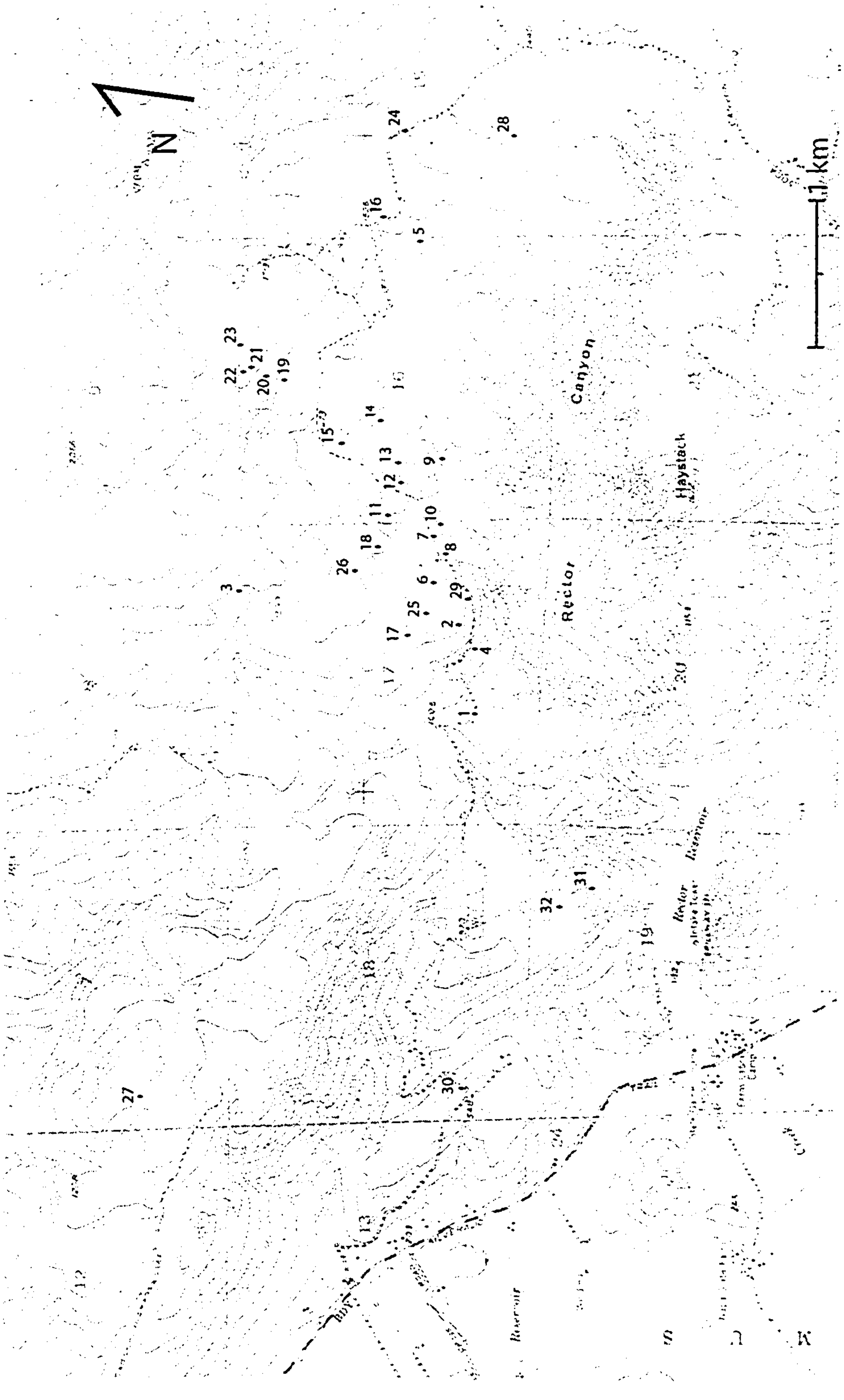


Figure 21. Map of sample sites.

Soils

According to the Soil Survey of Napa County, California (Lambert, 1979) the study area is mantled by well to moderately developed soils of the Boomer, Guenoc, and Hambright series that are derived from igneous parent material, but is mainly classified as rock outcrop. Much of the soil in the study area contains core stones that formed in place.

In the majority of the study area, parent material (weathered bedrock) has not been transported by sedimentary processes, so it is in-situ. Such soils are saprolites. The weathered bedrock in which the soil forms commonly contains core stones. In many places the relict granular texture and jointing of the parent material may still be observed in the soil. According to the U.S. Department of Agriculture, these observations characterize a Cr horizon. Of the three soil series mapped in the study area, only the Boomer series has a Cr horizon. In contrast, the Hambright and Guenoc series are underlain by an R horizon (fractured bedrock) and lack a Cr horizon. The saprolite soils in the study area are inadequately defined as they are currently classified in the Soil Survey of Napa County, California (Lambert, 1979). The Cr horizon is identifiable in most soils exposed at the study site and represents a significantly different profile than one without a Cr horizon (Fig. 22 and 23).

If rind formation rates from other areas in the western United States (Colman and Pierce, 1981) are similar to formation rates here, the soils may have taken hundreds of thousands of years to form. This does not suggest that all the soil present in the study area has formed in place. Because of the topography, slope wash is occurring and soil is

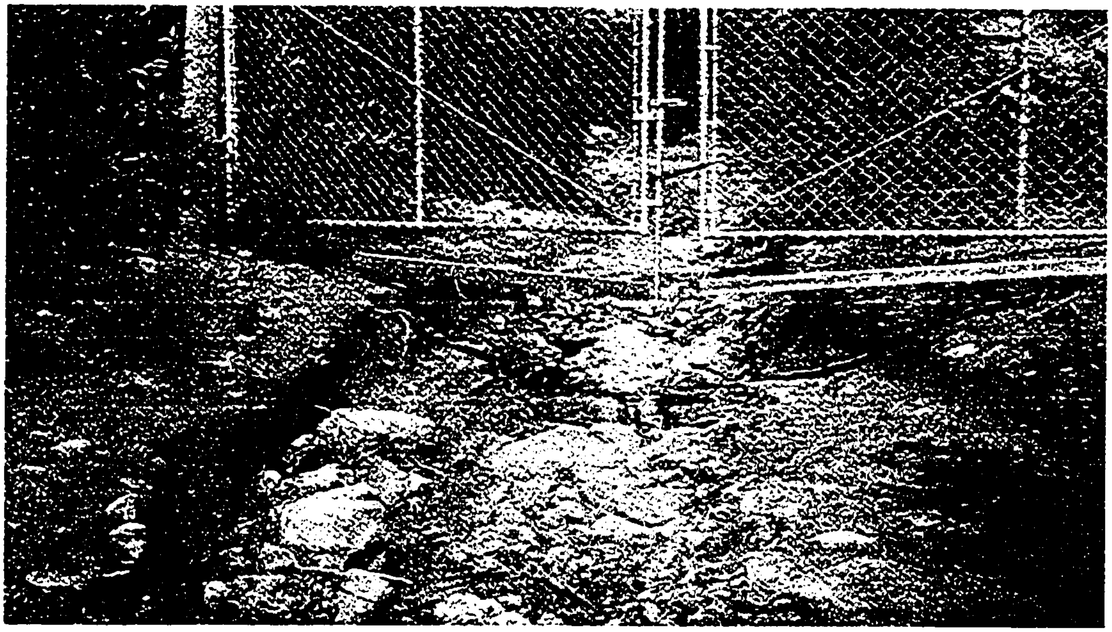


Figure 22. Cr horizon exposed below soil. Erosion occurred during winter storms of 2002 to 2003 season. Erosion removed approximately 1 to 1.5 m of the soil profile.

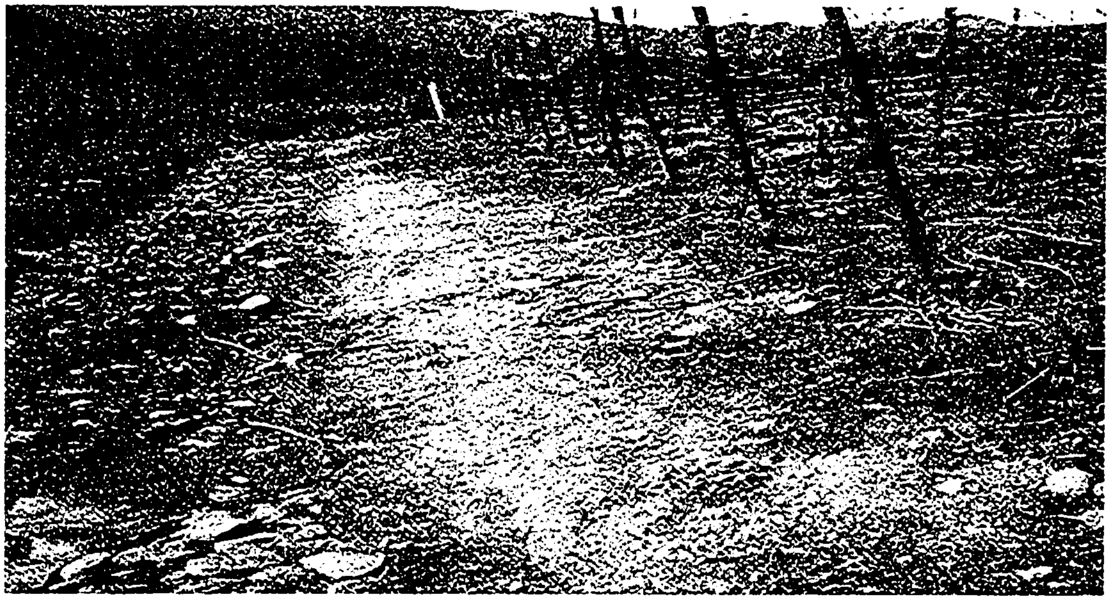


Figure 23. Thin soil over weathered core stones on surface 12 in the Stage Coach vineyards. Light colored material exposed in roadcut is decomposed unit Cg1.

being transported from the hills to lower elevations. This process strips the saprolite soils from some areas and buries them in others. In-situ core stones are almost always mantled by a thin colluvial soil. These areas are classified mainly as rock outcrop by the Soil Survey of Napa County (Lambert, 1979). The thin colluvial soil is typically less than 15 cm (6 in) thick and has a sharp lower boundary. There is commonly a marked color difference between the thin colluvial soil (brown) and underlying core stone-bearing soil (reddish to grayish brown).

DISCUSSION

Rind Analysis

The comparison of rind thickness on core stones within the study area assisted in correlating the age of the weathering surfaces. The concept that rind thickness increases with age suggests that core stones with thinner rinds are from geomorphically younger areas. The rind thickness measured at the sample sites suggests at least two erosional surfaces in the study area. The geomorphology and structure of the area support this interpretation, but also are consistent with an alternate scenario involving three generations of erosional surfaces.

The wide range of rind thicknesses (0-69 mm; Table 3), may indicate a range of ages or growth rates; however, the latter is not considered in this analysis. Variations in rind thickness occur among the samples collected at each site. For example, at site 31 four of the rinds measured were 62 mm thick but one was 39 mm thick. In this case, the 39 mm rind is not representative of the site and thus is ignored. At site 18, thickness ranges smoothly from 23 mm to 36 mm, so all samples were included in the analysis. The cause of this variation is unclear but may be the result of fracturing of large core stones and the subsequent weathering of those fractures.

In and around the gullies and stream networks, fresh bedrock with virtually no rind is usually exposed. In general, the farther from or higher above the channel, the thicker the rinds. Once a stream has incised into the existing erosional surface, topographically higher outcrops will begin to weather and produce rind material. This process could result in rinds of dissimilar thickness in close proximity to each other as small streams incise the erosional surfaces. The thinness of the rinds in the area of sample sites 6 through 16 suggest that these samples are in an area of surface 6 that was eroded after the second oldest erosional surface formed.

In general, rind thickness correlates poorly between different areas of Cg1 on the Upper Stage Coach block. While sample sites 18, 24, and 28 have sizable rinds, many other sites on surface 6 and 7 have unusually thin rinds. This is likely due to erosional variation involving the multiple drainages on surfaces 6 and 7. In some areas, the streams may be confined to gullies; in other areas, small streams may have been effective in lowering the elevation of broad areas.

Figure 24 shows two curves, one of the individual rind thicknesses and a second of the averaged rind thickness of each sample site. While the curves exhibit similar gaps, Colman and Pierce (1981) suggest that rinds measured at a site are best represented by an average of the individual thicknesses. The averaged rind thicknesses show two gaps, one between 53 and 60 mm and a second between 38 and 47 mm. Although few of the sample sites have exactly the same averaged rind thickness, the clusters of points above the second gap and between the two gaps are segregated enough to be attributed to two distinct periods of rind genesis. The gaps in the sequences may indicate periods of uplift during which incision occurred, preventing preservation of rinds that initiated growth during that period. Rinds thicker than about 60 mm began forming on the oldest erosional surface after it was abandoned due to uplift. The rinds between the two gaps began to form after the second-oldest erosional surfaced was abandoned due to further

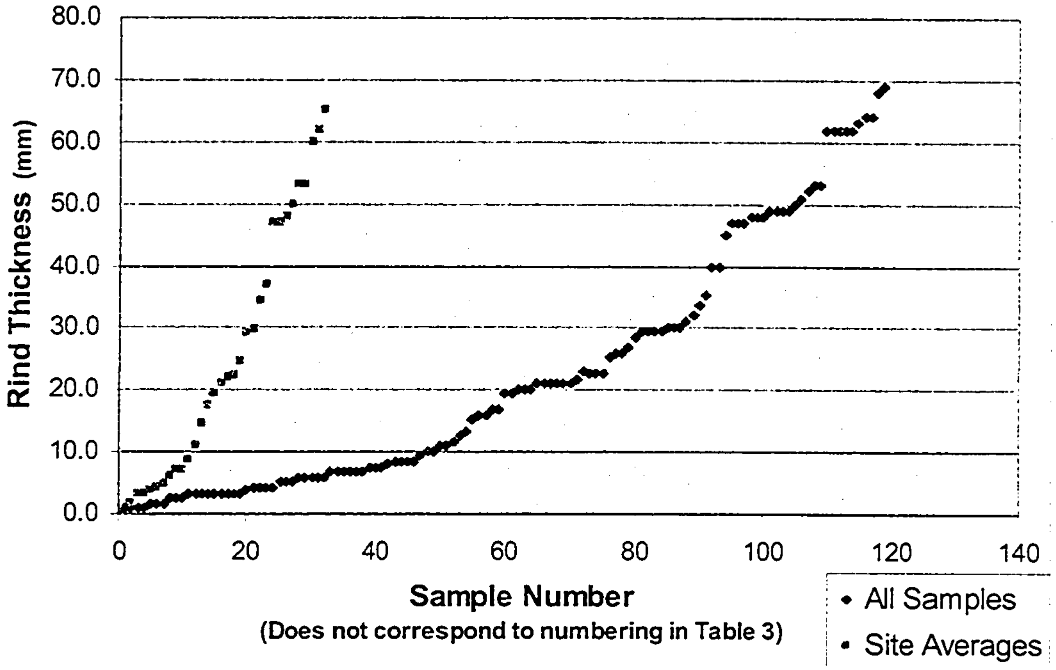


Figure 24. Rind thickness of all samples and the average thickness by site.

uplift in this area. The two 40-mm rinds at sample site 17, which plot within the 38-47 mm gap, may come from areas locally abandoned by erosion during uplift.

Rinds < 38 mm thick cannot be correlated definitely to any particular erosional event or larger surface. They may reflect the changing erosional system that has been at work in this area as it was uplifted to form the Vaca Mountains. The absence of distinct gaps suggests that, after the second oldest erosional surface formed, the erosional system was not allowed enough time to develop broad flat surfaces or it was not competent enough to do so.

Rinds measured in this investigation indicate at least two distinct ages of geomorphic surfaces in this area. Sample sites with rind thickness >60 mm, including sites 5, 26, and 31, represent the oldest erosional surface preserved in this area. The oldest erosional surface is composed of surface remnants 8, 9, R1, and R2. Sample sites plotting between the two gaps, including 1, 4, 25, 27, and 30, represent the second oldest erosional surface. Rind comparisons suggest that surfaces 1, 3, 4, and 7 compose the second oldest erosional surface. Surfaces 2 and 6 are also part of the second oldest erosional surface, but rind data are unavailable for these areas; evidence supporting their inclusion is based on stratigraphy, topography, and geomorphic character. A still younger erosional surface may be present on surface 5, based on its position relative to surface 4; however, no rinds are exposed on the surface.

A possible age range for the erosional surfaces and faulting event was evaluated by adapting formulas used by Colman and Pierce (1981). These calculations are discussed in Appendix B.

Erosional Surfaces

Twenty-five areas were identified as possible surface remnants and were grouped into 14 surfaces based on their occurrence on the structural blocks. Each represents an area of anomalous low relief that is separated from the other surfaces by geomorphic character, elevation, drainages, or structure. The boundaries for each surface are shown on Figures 3 and 25. The identified erosional surface remnants, surfaces 1 through 9 and R1 and R2, are assigned to three generations of surface formation (Fig. 25). Surfaces 10,

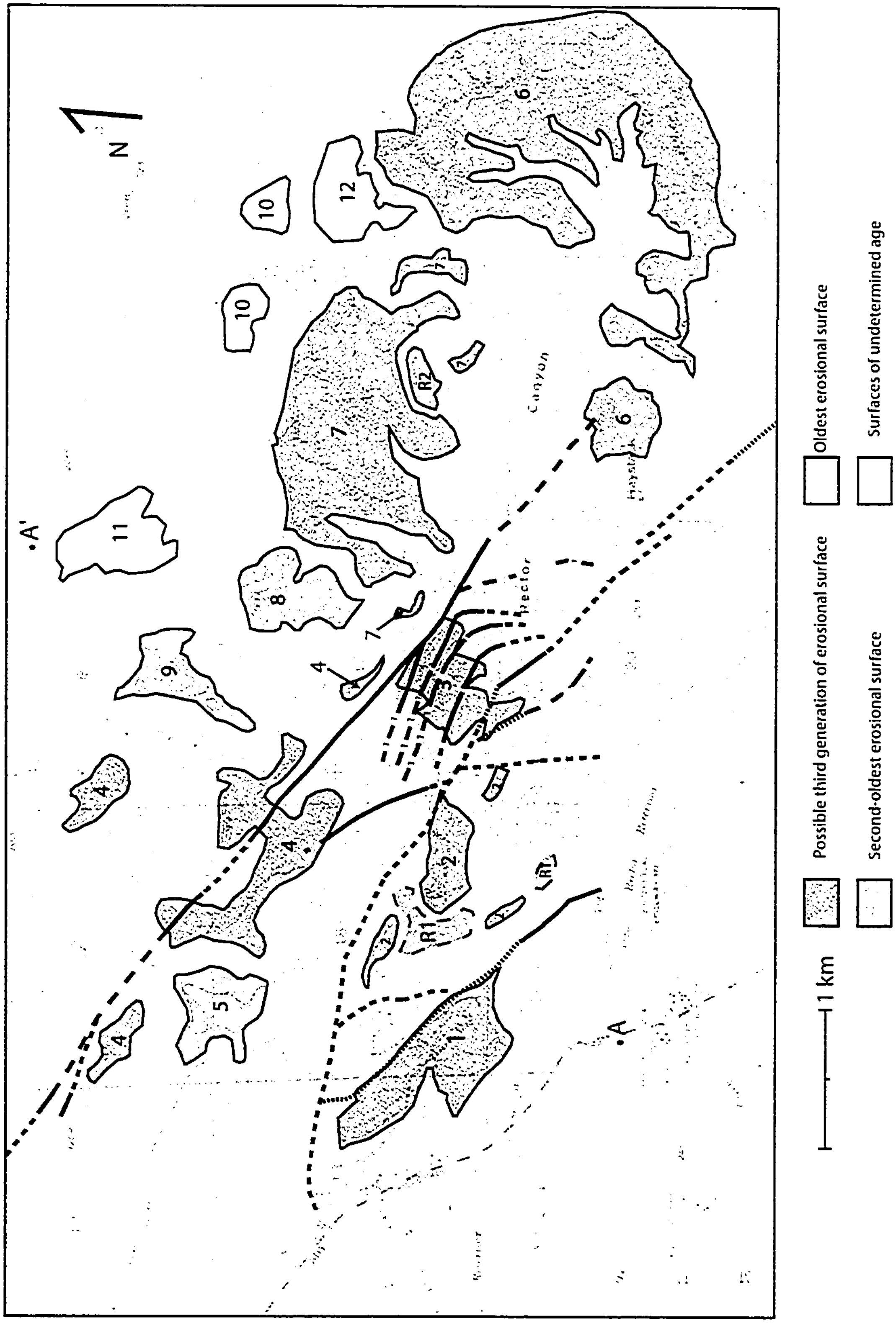


Figure 25. Map of identified erosional surface remnants in field area.

11, and 12 were identified as potential erosional surfaces but their relationship to the three generations of erosional surfaces could not be determined. Figure 26 is a profile of the relative positions of the identified surface remnants and associated fault systems.

Most surface remnants identified in this study are in a relatively unfolded area at the terminus of the Foss Valley syncline. The original extent of the erosional surfaces is uncertain due to significant erosion and deformation in this area. The erosional surfaces encompassed at least the areas contained within the study area, but may have covered a much larger area.

Surface 1

Surface 1 is located on the Dalla Valle block and slopes gently to the west and northwest (Fig. 27). However, units within the Dalla Valle block dip moderately to the southeast on the eastern side of the surface. Units on the western edge of the Dalla Valle block dip 50° (Weaver, 1949) to 30° (Baldwin et al., 1998) northwest. Baldwin et al. (1998) suggested that these dipping units are part of an anticline; however, surface 1 on the Dalla Valle block is relatively flat and shows no signs of being folded. As surface 1 is not folded, this erosional surface is younger than the folding event.

Rind analysis indicates that surface 1 is part of the second-oldest erosional surface. This assignment is corroborated by the generally good preservation of surface 1, which distinguishes it from the more dissected remnants of the oldest erosional surface (8, 9, and R1; Fig. 25).

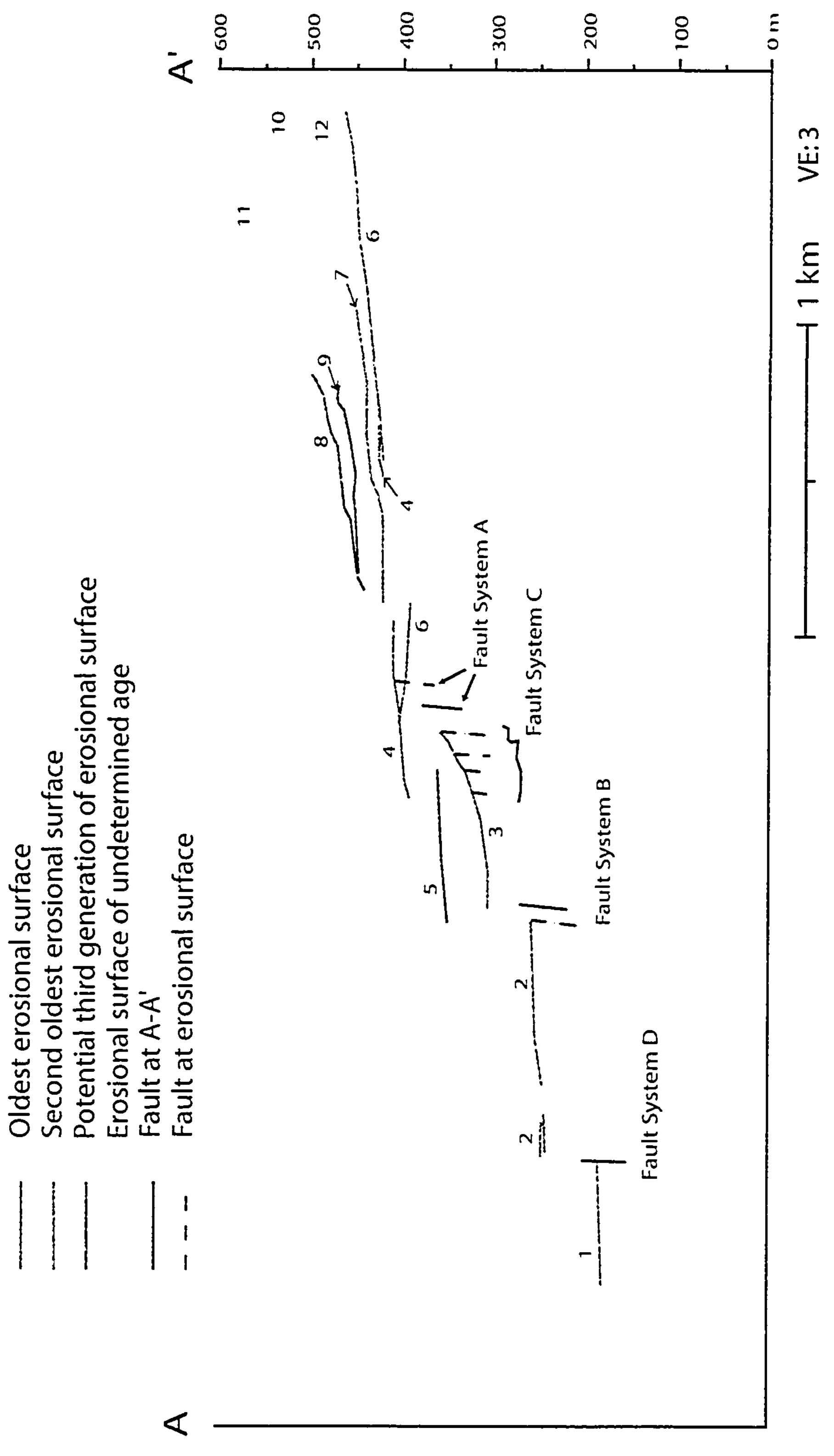


Figure 26. Surface profile along line A-A'. Erosional surfaces projected onto profile.

Hills protruding from valley floor.
(Toes of collapsed blocks, toppled blocks, or folds?)

Figure 27. View to the south of the Dalla Valle block and surface 1. Separation between surface 1 and Napa Valley is 76 to 91 m (250 to 300 ft). Edge of the Dana Johnson block in foreground.

Two valleys south of surface 1 and north of Rector Reservoir have destroyed any evidence of surface 1 in that area. It is unclear how surface 1 is geomorphically or structurally related to the 274 m (900 ft) ridge south of Rector Reservoir. It is possible that surface 1 simply did not extend that far south and that the 274 m (900 ft) ridge was a high point during the formation of surface 1. It is also possible that structural evidence separating these features has been hidden or erased by recent geomorphic or structural processes.

Surface 2

Surface 2, mapped on the Oakville Ranch block, is composed of four surface remnants separated from each other by a tributary of Rector Creek and ridge R1. The slope between ridge R1 and the remnants of surface 2 is erosional in nature, indicating that surface 2 is younger than ridge R1.

Surface 3

This surface occupies the relatively flat interior of the Lower Stage Coach block but is also mapped on a portion of the moderately-steeply dipping eastern side of the block because fault system C offsets the surface in several places. Analysis of rinds at sample sites 1 and 4 indicates that surface 3 is a remnant of the second-oldest erosional surface.

Surface 4

Surface 4 is mapped on both the Upper Stage Coach block and the Dana Johnson block and has been deeply incised by Sage Canyon. Fault system A crosses surface 4 but offsets only the southeastern portion of this surface. Surface 4 slopes to the south-southwest and exhibits about 33 m (100 ft) of elevation change across Sage Canyon. Analysis of rinds at sample site 27, near the northwestern boundary of surface 4, indicates that surface 4 is a remnant of the second-oldest erosional surface.

Two small benched surfaces below the southwestern edges of surfaces 8 and 9 protrude from the canyon wall and are mapped as surface 4 on Figures 3 and 25. The bench below surface 9 is connected to the eastern side of surface 4 by a narrow strip on the canyon wall that slopes more gently than other portions of the canyon wall. Fault planes were not identified at the eastern edge of these remnants and bands of vegetation do not appear to be disrupted in this area, suggesting that the two small benches are not offset fragments from surfaces 8 and 9 at the top of the canyon.

Surface 5

Near the center of the Dana Johnson block, wedge-shaped surface 5 is topographically lower than surface 4. The northern side of surface 5 is marked by a slope that abruptly rises to the hill at 422 meters (1386 ft). The eastern boundary of surface 5 is gentler than the northern boundary but there is a definite break in slope. Soil cover and alluvium on surface 5 obscure bedrock and core stones in this area. Surface 5 appears to be an erosional surface younger than the second-oldest erosional surface in the surrounding hills. This is the only remnant of a third generation of erosional surfaces.

Surfaces 6 and 7

Surfaces 6 and 7 surround Rector Canyon in the interior of the Upper Stage Coach block. On the surface profile (Fig. 26) surfaces 6 and 7 are separated vertically by approximately 30 meters (100 ft). This apparent separation is an artifact of either the position of the profile or the dip of the erosional surface caused by folding in this area, and is not related to faulting. The unit composition (Cg1) and surface morphology are very similar on both surfaces.

Surfaces 6 and 7 have been heavily incised by Rector Creek and a complex system of gullies and rills has formed. The access road to the Stage Coach Vineyards crosses multiple modern stream drainages that have incised 6 to 9 m (20 to 30 ft) below the rounded concordant divides on surfaces 6 and 7.

While all the rinds measured on these surfaces plot below the 38-47 mm gap in the rind analysis, the position of surface 7 below surface 8 and ridge R2 indicates that broad tops of the drainage divides on surfaces 6 and 7 are remnants of the second-oldest erosional surface.

Surfaces 8 and 9

Surface 8 rises on average 30 meters (100 ft) above surface 7. This ridge is composed of thick flows of unit Fg and also contains the easternmost extent of unit Fgm.

To the northwest, an unnamed canyon separates surface 8 from a conspicuous ridge, surface 9, of approximately the same elevation and slope. Parallel bands of trees, other tonal changes, and rock outcrops can be seen on both sides of the canyon on aerial photos and in the field. Access was not available to the upper portion of surface 9, but unit Fg probably caps the hill above unit Fgm. Baldwin et al. (1998) also mapped matching tuffs at the base of the canyon that probably are stratigraphically below unit Fgm.

Surfaces 8 and 9 are not separated from surfaces 4 and 7 by faults, suggesting that they formed prior to 4 and 7. The analysis of rinds at sample site 26 indicates that surfaces 8 and 9 represent the oldest erosional surface in the study area.

Surface 10

Northeast of surface 7, the topography slopes up to surface 10 (Fig. 28). Modern geologic maps show a single 20° southwest-dipping attitude (from Weaver, 1949). Thus, it is difficult to determine the structure of the northern side of the Upper Stage Coach block. It is unknown if the slope north of surface 7 is due to the Foss Valley Syncline, additional normal faults that have down-dropped surface 7, thrust/reverse faults that have elevated surface 10, or the natural edge of the erosional surface. Small outcrops of unit Fg or another aphanitic flow are exposed at surface 10. If the unit is Fg, it would suggest that folding or faulting is responsible for its position relative to unit Fg south of surface 7.

Analysis of rinds at sample sites 19 through 23, at the western side of surface 10, are comparable in thickness to rinds on surfaces 6 and 7, so surface 10 may be part of the second-oldest erosional surface.

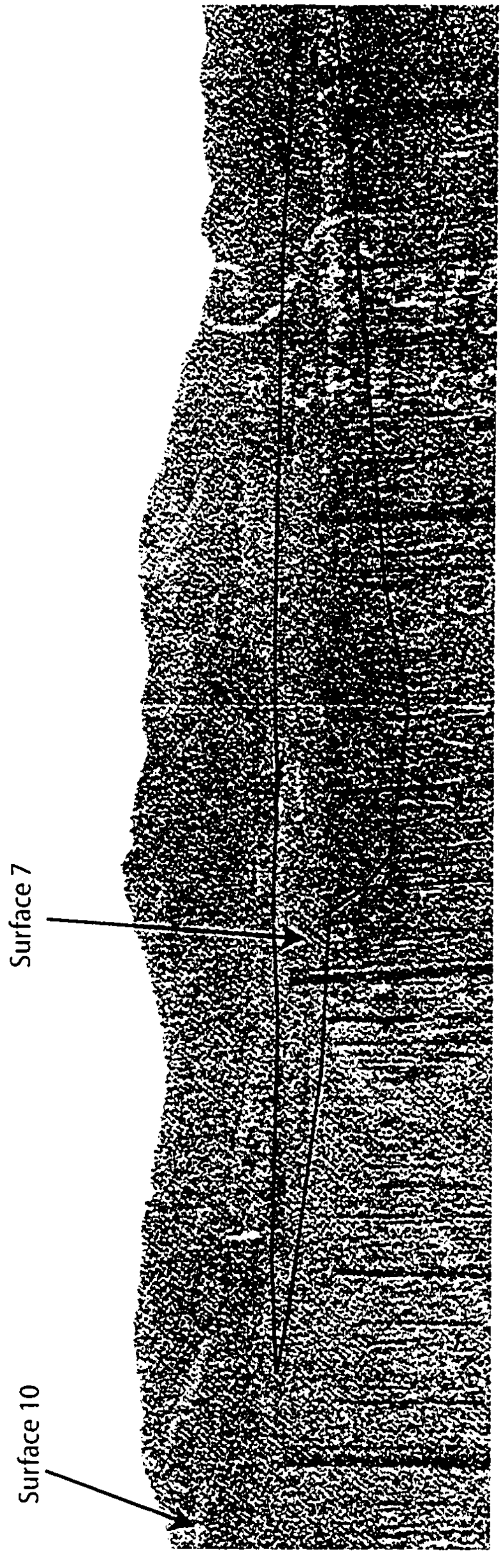


Figure 28. View from surface 8 east to surfaces 7 and 10.

Surface 11

Surface 11 is north of the boundary of the study area and was not visited due to access problems. This surface is anomalously flat and may be related to other surfaces in the study area. The vegetation pattern suggests that surface 11 may be composed of unit Fgm. Small trees at the outcrop of unit Fgm in the canyon between surfaces 8 and 9 are also seen at the perimeter of surface 11. Geomorphically, surface 11 appears similar to surfaces 8 and 9.

Surface 12

This area on the Upper Stage Coach block is bounded on the east, south, and west by moderately steep slopes approximately 18 m (60 ft) in height and to the north by a moderately steep slope approximately 30 m (100 ft) in height. While rind thickness measured on the eastern side of this surface is among the thickest measured in unit Cg1, a significant amount of erosion and deposition have occurred on this surface, leaving its association to the other surfaces in question. This surface may be part of the oldest erosional surface because it is topographically higher than neighboring surfaces 6 and 7.

Ridge R1

Several hills, referred to as R1 on Figures 3 and 25, rise 12 to 18 m (40 to 60 ft) above surface 2. The separation between the ridge top and surface 2 on the Oakville Ranch block appears to be erosional, suggesting that the ridge top and the interior of the

Oakville Ranch block have different ages. Analysis of rinds at sample site 31 indicate that R1 represents eroded remnants of an older surface, equivalent to surface 8 and 9.

Ridge R2

South of surface 7, an elongate exposure of unit Fg includes ridge R2 (Fig. 25) at 463 meters (1520 ft). The upper portion of this ridge is a small remnant of the oldest erosional surface. Units at the ridge are nearly horizontal appear to be unfaulted, which suggests that they are near the axis of the Foss Valley syncline and that the position of R2 above surface 7 is related to erosion.

Mendocino Plateau

Fox et al. (1983) discusses an undulatory to subplanar erosional surface, the Mendocino Plateau (Fig. 29), that may be related to erosional surfaces identified in the study area. However, the Mendocino Plateau is 35 to 40 km west of the study area and extends south from Fort Bragg to Mount Tamalpais, and east from the coast to the Russian River valley. The Mendocino Plateau is identified by rounded to tabletop hills and ridges in the central part of the plateau and accordant summits in the heavily dissected southern part of the plateau. The plateau formed after 6 Ma (Fox, 1983). The eastern edge of the Mendocino Plateau separates the relatively undeformed Sebastapol block from the deformed Santa Rosa block (Fox, 1983). Napa Valley and this thesis area are within the Santa Rosa block.

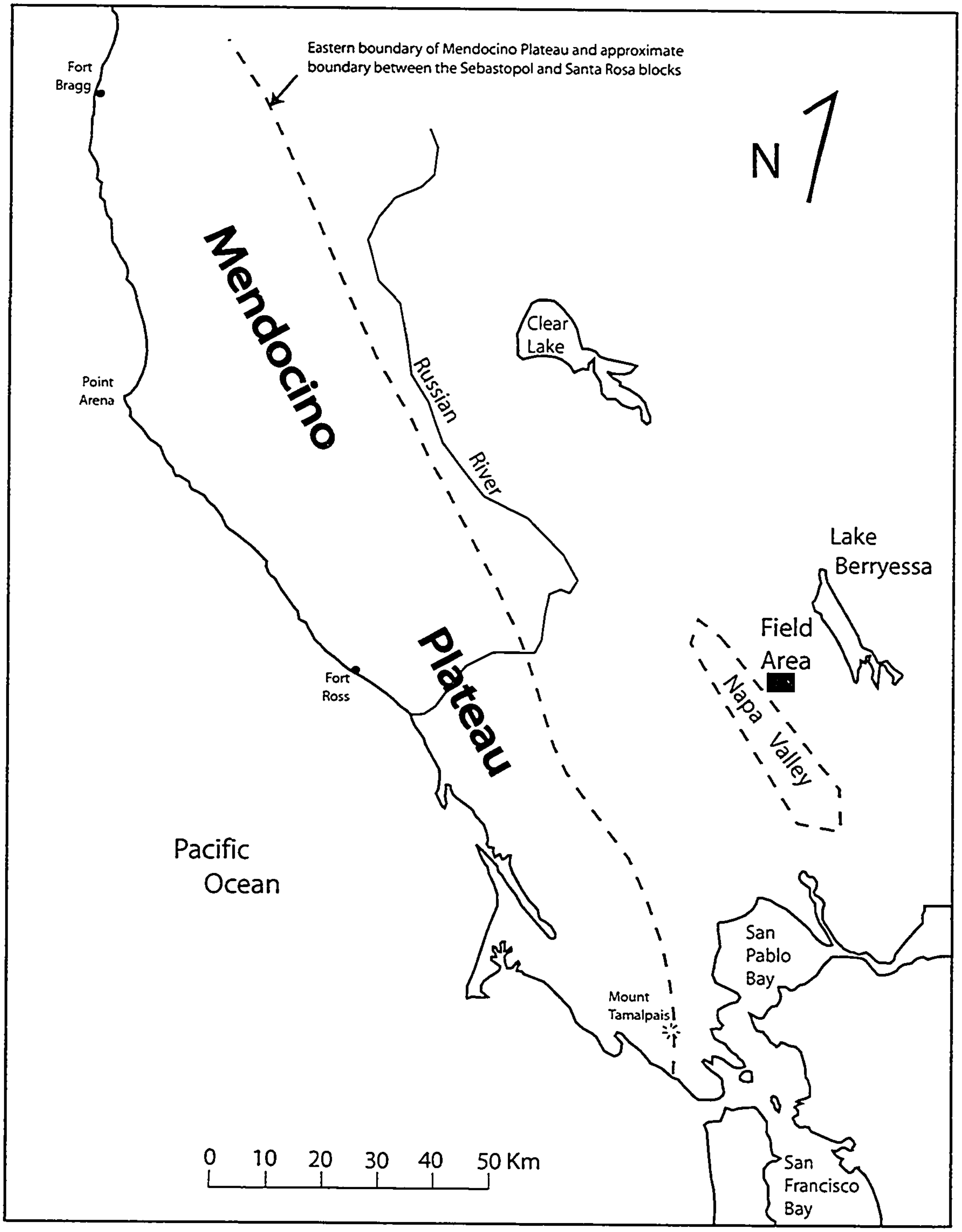


Figure 29. Location of Mendocino Plateau in relation to field area. Figure adapted from Fox's (1983) Figure 10. Scale 1:1022000.

There is little evidence to suggest that the Mendocino Plateau extended as far east as the study area. It is possible that during the period of tectonic quiescence in which the Mendocino Plateau formed, a similar erosional surface, whether connected to the Mendocino Plateau or not, could have formed in the study area. Swinchatt and Howell (2004) support the hypothesis that the erosional surfaces identified in the study area formed separately from the Mendocino Plateau. They suggest that the surfaces are remnants of a localized pediment that formed on the western flank of the Vaca Mountains during uplift.

Sloping Ramp

The southern part of the Dana Johnson block is a long slope that abuts the Lower Stage Coach block to the south (Fig. 2) and lies between fault systems A and B of this study (Fig. 25). The surface of this slope dips on average 15 degrees to the southeast. Resistant units in the wall of the canyon separating the Oakville Ranch and Dana Johnson blocks appear folded and increase in dip near crest of the slope, then parallel the surface of the slope, similar to a monocline.

This slope could be explained in two ways. (1) The uniform slope of the surface and the change in dip of the units seen in the canyon wall west of the slope suggest that it may be the result of as few as two splays. The sloping ramp connects the upthrown and downthrown blocks and is bounded on either side by subparallel faults (portions of fault system A and B). (2) The slope is the result of offset along a series of splays or fault slices, each of which accommodates a portion of the total vertical displacement. This is similar to the series of faults within fault system C on the Lower Stage Coach block. Stream incision at the foot of the slope and other slope processes may have obliterated the scarps related to these splays.

Structural and Geomorphic Evolution

Baldwin et al. (1998) and Swinchatt and Howell (2004) suggested that east-northeast-dipping thrust/reverse faults related to transpression are responsible for much of the folding and deformation in the hills east of Napa Valley. Baldwin et al. (1998) also suggested the Green Valley fault to the east and the Maacama fault to the northwest have produced a restraining stepover that uplifted the Vaca Mountains. Although the Sulfur Springs thrust at the southeastern end of the Maacama fault may be related to west-vergent thrusts under the Vaca Mountains (Baldwin et al. 1998), it does not appear that such faulting has produced surface rupture in the study area. However, as noted by Swinchatt and Howell (2004), thrust faults near the eastern side of the Vaca Mountains and the hills protruding from Napa Valley (Figure 27) may instead be evidence of a mega-landsliding.

While the presence of several reverse faults mapped by Baldwin et al. (1998) near the southwestern edge of the Lower Stage Coach block is questionable, the presence of reverse faults is not unexpected in the study area. This area has experienced shortening evident in the folded Sonoma Volcanics, and thrust or reverse faults may be present at depth. The fault systems identified in this study may contain a limited number of reverse faults that help take up any differential movement within or between the blocks, as suggested by Marliaves's trench logs (1940).

The boundaries of the structural blocks could be either moderate- to high-angle normal faults or mega-landslides that daylight to the west. My preferred explanation is that the step-and-bench topography is due to slip on the four fault systems that appear be related to the northern extension of the Soda Creek fault.

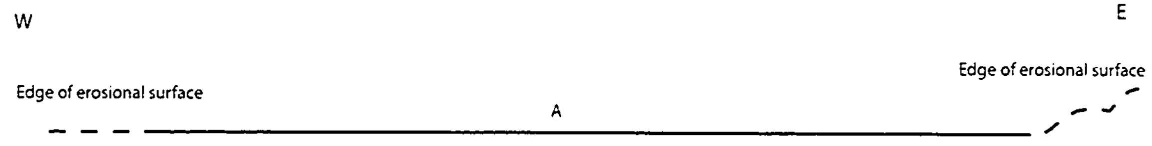
Surface 4 is mapped across fault system A (Fig 25). In the study area it is not uncommon for erosional surfaces of the same age to be separated by faulting because normal faulting generally occurred after the erosional surfaces formed. However, the units exposed at the ground surface of surface 4 are dissimilar across fault system A: unit Fg is exposed at the surface of surface 4 on the Dana Johnson block south of the fault and unit Fgm, a stratigraphically lower unit, is exposed on the Upper Stage Coach block north of the fault. This indicates that offset on fault system A occurred prior to the formation of surface 4.

A scarp along part of fault system A, near the hill at an elevation of 421 meters (1382 ft), suggests that the system has reactivated after the formation of surface 4. One explanation of partial scarp preservation is that the fault experienced two phases of displacement. The first occurred prior to the formation of surface 4 and the second occurred after surface 4 formed. The first event on this fault could have occurred at any time between the final eruption of the Sonoma Volcanics and the abandonment of the oldest erosional surface. If the abandonment of the oldest erosional surface is associated with the initiation of uplift in this area, the first event on the normal fault may have been structural settling following uplift. The reactivation event on the southern portion of this fault is potentially the same event that offset the Soda Creek fault and the many faults mapped in this area that separate the erosional surfaces. This is only one possibility but it does support the geologic history of this area as presented.

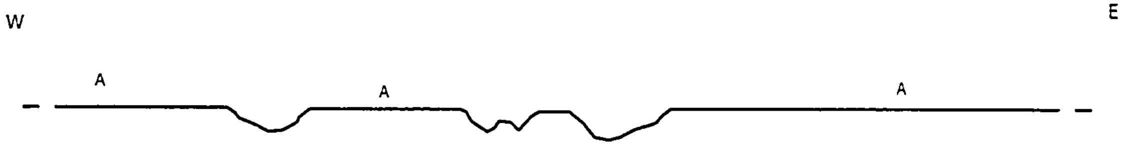
The geologic history of the area after eruption of the Sonoma Volcanics is outlined below and depicted in Figure 30. The scenario described here is in general accordance and entirely compatible with the geologic history of Napa Valley described and illustrated by Swinchatt and Howell (2004).

1. The Sonoma Volcanics erupted during the late Miocene to late Pliocene/early Pleistocene. The upper part of the andesitic portion of the Sonoma Volcanics, including all the units in the study area, was deposited around 5.4 to 3.8 million years ago, confining the age to the late Miocene and Pliocene (Mankinen, 1972).
2. During the eruption of the Sonoma Volcanics, minor folding exposed Great Valley Group bedrock west of the study area.
3. Rhyolite, the uppermost member of the Sonoma Volcanics, intruded and erupted onto the lower member of the Sonoma Volcanics. Fox (1983) reports that G. H. Curtis dated rhyolite at Mount George to be 3.8 million years old. Dikes of rhyolite are exposed at the ridge line of the hills south of Rector Reservoir. Rhyolite also caps several ridges and hill tops south of the study area. Southwest of Rector Reservoir, rhyolite is in depositional contact with Great Valley Group exposed in the valley floor.

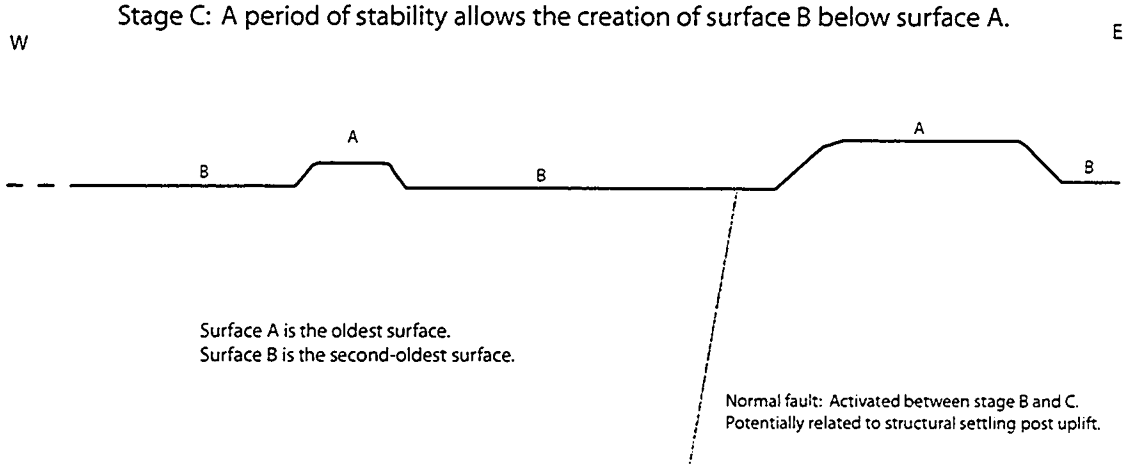
Stage A: Stream system planes-off surface A from an initially uneven surface.



Stage B: Initiation of uplift causes incision into surface A.



Stage C: A period of stability allows the creation of surface B below surface A.

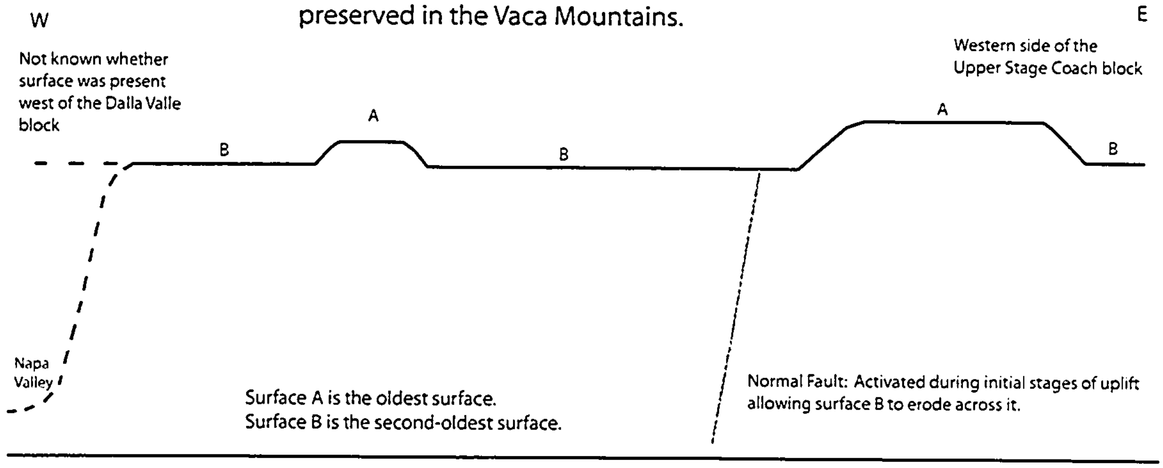


Surface A is the oldest surface.
Surface B is the second-oldest surface.

Normal fault: Activated between stage B and C.
Potentially related to structural settling post uplift.

Figure 30. Idealized view of surfaces and blocks before and after collapse.

Stage D: Surfaces uplifted above Napa Valley and preserved in the Vaca Mountains.



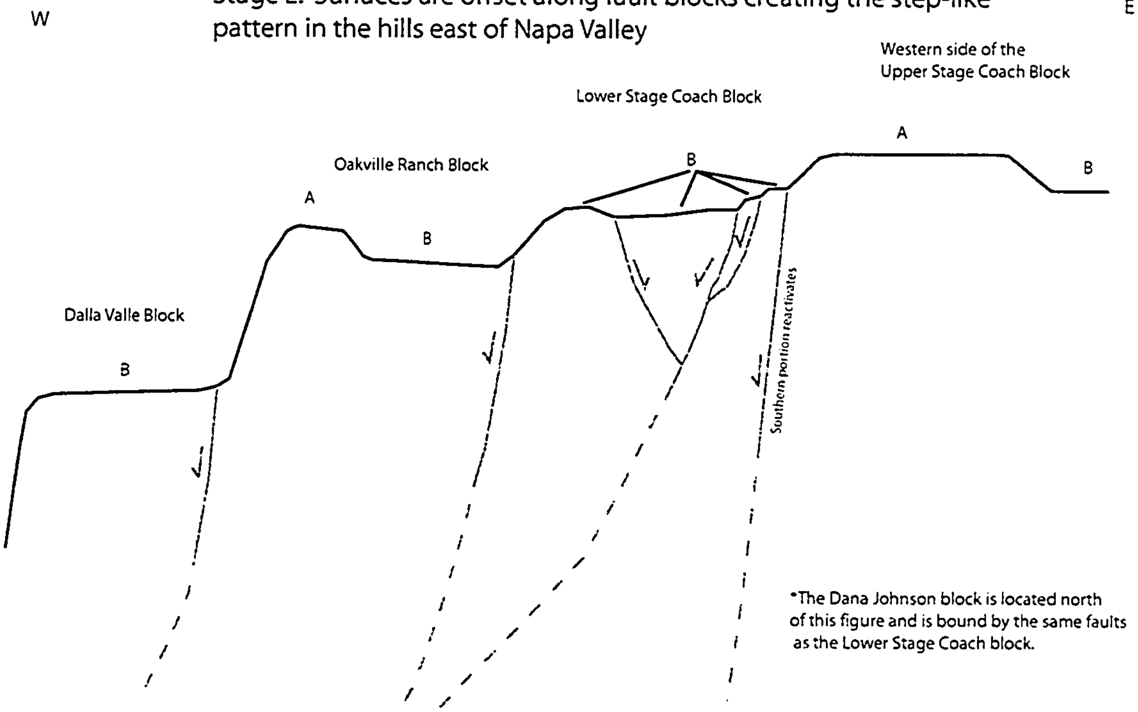
Not known whether surface was present west of the Dalla Valle block

Western side of the Upper Stage Coach block

Surface A is the oldest surface.
Surface B is the second-oldest surface.

Normal Fault: Activated during initial stages of uplift allowing surface B to erode across it.

Stage E: Surfaces are offset along fault blocks creating the step-like pattern in the hills east of Napa Valley



*The Dana Johnson block is located north of this figure and is bound by the same faults as the Lower Stage Coach block.

Unknown whether faults shallow then daylight in Napa Valley as toes of mega-landslide or continue as steeply dipping normal faults and connect to a fault system below.

Figure 30, continued.

4. Erosion planed off a surface to form an area of subdued topography (Stage A; Fig. 30).
5. Slight uplift of this area or a change in stream grade caused incision into the erosional surface in step 4. This incision abandoned the erosional surface in step 4, leaving remnants above the new base level (Stage B; Fig. 30).
6. Soon after or even during the uplift in step 5 the normal fault at the western edge of the Upper Stage Coach block was activated (Stage C; Fig. 30). This juxtaposed unit Fg and Fgm in the area that became surface 4.
7. Erosion began to form a second surface 12 to 30 meters (40 to 100 ft) below the elevation of the older surface in step 4 (Stage C; Fig. 30). This younger surface was separated from the older erosional surface by steep cliffs or gentle slopes. The variance in separation between the first and second erosional surfaces suggests the area was uplifted and tilted.
8. At some point after the surface in step 7 was abandoned, a third generation of surfaces formed (surface 5).
9. Folding and thrust/reverse faults related to northeast/southwest oriented compression uplifted and weakly folded the erosional surfaces in the process of building the ranges east and west of Napa Valley. Erosional surfaces in the Vaca Mountains were preserved (Stage D; Fig. 30).
10. The western portion of the Vaca Mountains was down-dropped or collapsed across several west-dipping faults. The master fault in this system is the west-dipping Soda Creek fault. Within the study area, the Soda Creek fault splays

northward from Rector Canyon. The movement along this fault system lowered resisting forces acting on the fault in step 7, reactivating the southern portion of this fault. The northern portion of this fault failed to reactivate. This faulting formed the step-and-bench topography in the study area (Stage E; Fig. 30). (This event occurred between 190,000 and 2,500 years before present (Appendix B).)

11. Streams began to incise into the Vaca Mountains east of Napa Valley, forming steep canyons in the study area. Smaller streams incise into the erosional surfaces, stripping areas near the drainages of weathered bedrock.

CONCLUSIONS

The benched surfaces stepping up into the Vaca Mountains east of Napa Valley represent three generations of erosional surfaces that formed due to episodic uplift of the region. The oldest erosional surface remnants consist of surfaces 8, 9, R1, and R2. The second-oldest erosional surface remnants include surfaces 1, 2, 3, 4, 6, and 7. The youngest potential erosional surface remnant is surface 5. The ages of surfaces 10, 11, and 12 could not be definitively assigned. The step-and-bench topography and the six structural blocks are the result of west-side-down offset along fault systems A through D. These faults are splays of the northward extension of the Soda Creek fault. While an alternate conclusion, supported by Swinchatt and Howell (2004), is that the displacement surfaces termed here as faults may be slip surfaces of a mega-landslide, at the scale of this study, it is impossible to differentiate between a fault and a slip surface of a 10-mile long mega-landslide.

The variable thickness (0-69 mm) of rinds on core stones may indicate erosional surfaces of different ages. Rinds 60-70 mm thick are present on the oldest erosional surface, and rinds 47-53 mm thick are present on the second-oldest erosional surface. Thinner rinds are present on surfaces that began weathering during or after the erosional surfaces were uplifted into the Vaca Mountains and as streams began incising into the surfaces. Two gaps identified in the set of rind thicknesses measure may represent periods of uplift during which incision occurred.

Future Investigations

This investigation leaves several questions unanswered. What river system(s) eroded the erosional surfaces? What are the ages of the erosional surfaces? What are the ages of the faulting events? Do remnants of the surfaces exist outside of the studied area? What is the relation between the fault blocks in the Vaca Mountains and the hills protruding from Napa Valley?

Further investigation of the hills protruding from Napa Valley would be most helpful in determining whether the blocks in the study area are indeed part of a massive landslide resulting from the collapse of the western side of the Vaca Mountains as proposed by Swinchatt and Howell (2004). A geophysical investigation of the subsurface will be necessary to identify faults and the base of the alluvium in Napa Valley. More surface mapping south of the thesis area could determine whether the erosional surfaces extend in that direction. Other conspicuous flat-topped hills and ridges northeast of the city of Napa may be the southern extension of the erosional surfaces. Ages of the erosional surfaces and the faulting will need to be dated independently. Cosmogenic isotope dating would be an option for the erosional surfaces, although the alteration of the rock to rind may result in a younger age.

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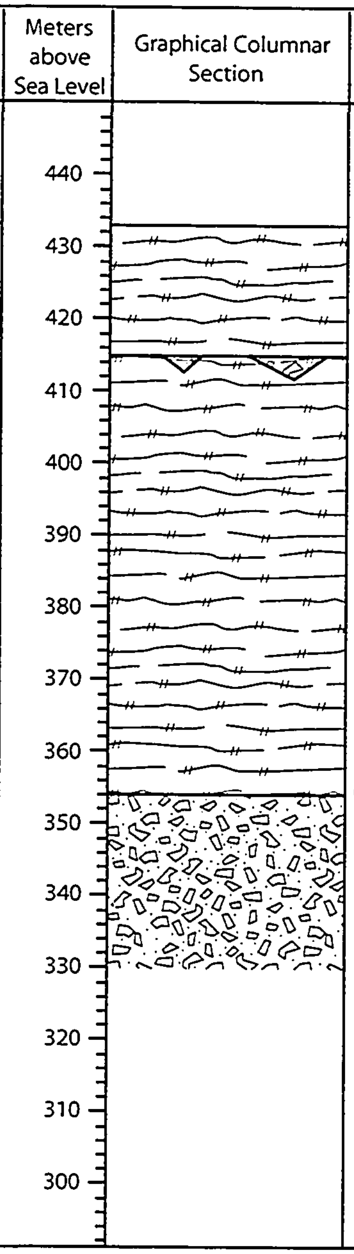
APPENDIX A

Stratigraphic Sections

Stratigraphic Section 1

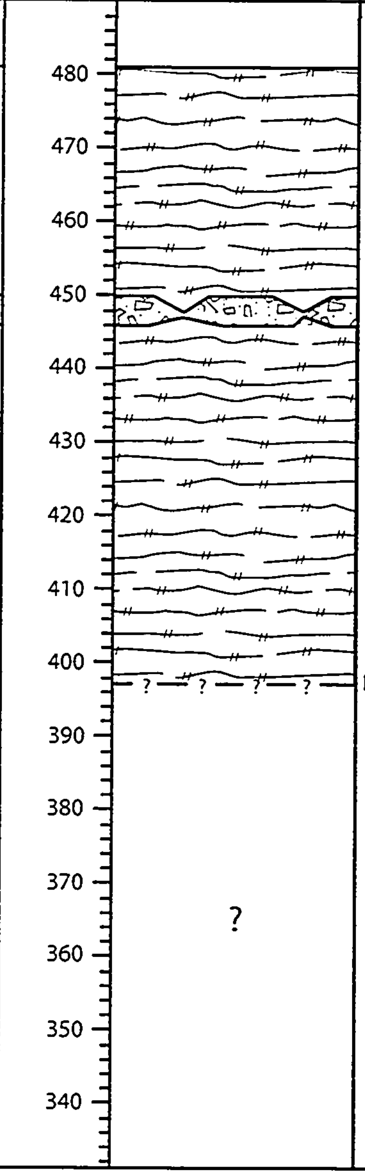
Location: The hill top at 433 m (1420 ft) on the Upper Stage Coach Block about
91 m (300 ft) south of sample site 8



Unit Name	Thickness in Meters	Description
		Core stones not observed at the surface here but are present 91 m (300 ft) to the north.
Fg	18 (60 ft)	Dark gray-gray dense fine-grained andesite, <5% 1 to 2 mm plagioclase laths by volume. Matrix appears slightly granular to glassy.
Cg1	61 (200 ft)	Dark gray-black porphyritic andesite. Phenocrysts: 15 to 25% by volume 3 to 7 mm zoned euhedral-subhedral plagioclase, 20% by volume 1 to 2 mm plagioclase laths. Upper portion is vesicular, may also locally have 1.5 to 3 m (5 to 10 ft) of breccia at top.
B2	?	Contact may not be planar. Hard, reddish brown- light tan, tuffaceous breccia. Clasts up to 0.6 m (2 ft) composed of porphyritic andesite similar in composition to Cg1, scoria, and obsidian.

Stratigraphic Section 2

Location: 482 m (1580 ft) hill on the south side of Surface 7

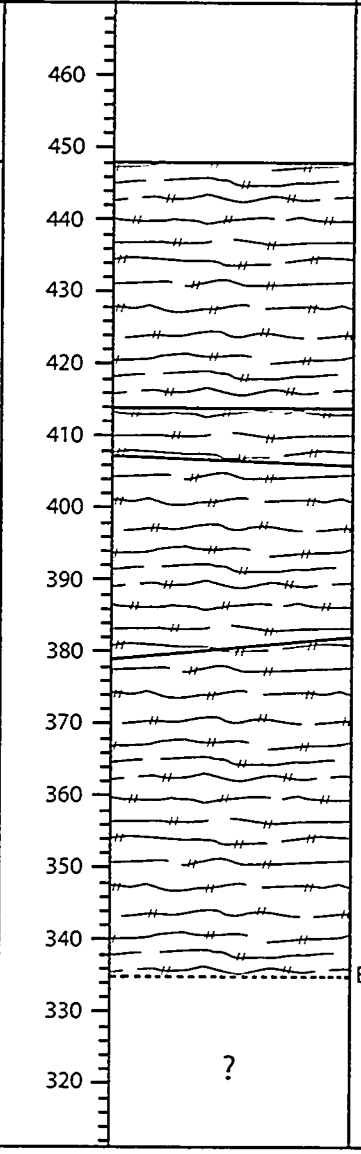


Unit Name	Thickness in Meters	Description
		Core stones found at surface.
Fg	31 (100 ft)	Dark gray-gray, dense fine-grained andesite, <1% 1 mm plagioclase laths, may contain rare brown mafics (augite). May contain subparrallel fractures.
B1	4 (13 ft)	Light gray-pink tuffaceous breccia, fragments 40-60% of volume, vary in size up to 0.6 to 1 m (2 to 3 ft). Outcrop thickness is variable.
Cg1	?	Dark gray-black, porphyritic andesite. Phenocrysts: 15% to 20% by volume 3 to 7 mm zoned euhedral-subhedral plagioclase, 20% to 25% by volume 1 to 2 mm, subhedral plagioclase. Upper 10 m may be vesicular.
		Not exposed

Stratigraphic Section 3

Location: Surface 8, approximately 183 m (600 ft) north of sample site 17

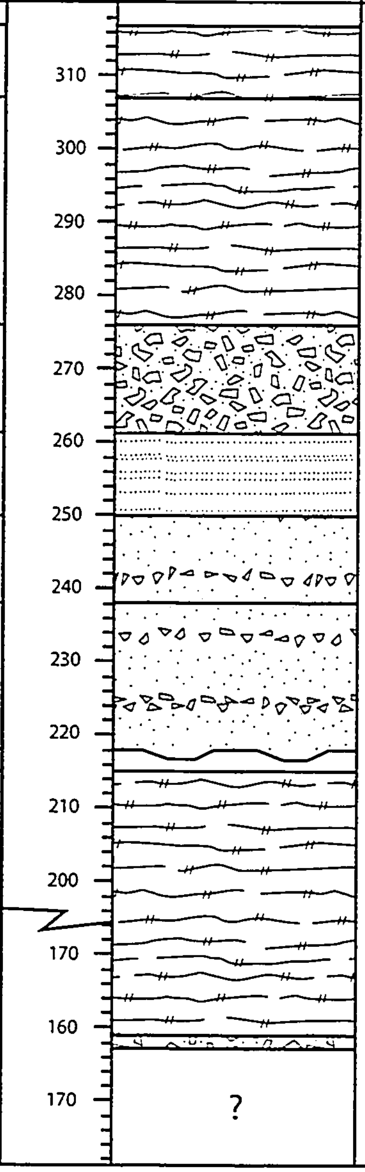
Meters above Sea Level / Graphical Columnar Section



Unit Name	Thickness in Meters	Description
Fg	34 (112 ft)	Core stones not at surface here, but are present 183 m (600 ft) to the south. Dark gray-gray dense fine-grained andesite, <5% 1 to 2 mm plagioclase laths by volume. Matrix appears slightly granular to glassy.
Mg	7 (22 ft)	Gray porphyritic andesite, phenocrysts are mainly plagioclase laths 1 to 2 mm composing 10% of the total volume. Laths commonly have a preferred orientation.
Fgm	29 (95 ft)	Gray porphyritic andesite, commonly weathers purple. Phenocrysts: 15% to 30% by volume euhedral-subhedral green-reddish brown augite 1 to 6 mm, < 5% plagioclase laths 1 to 2 mm. Vesicular layers may be encountered anywhere within unit. Unit thins to the southeast.
Cg1	?	Dark gray-black porphyritic andesite. Phenocrysts: 15 to 25% by volume 3 to 7 mm zoned euhedral-subhedral plagioclase, 20% by volume 1 to 2 mm plagioclase laths. Upper portion is vesicular, may also locally have 1.5 to 3 m (5 to 10 ft) of agglomerate at top. Base uncertain in this area.
?	?	

Stratigraphic Section 4

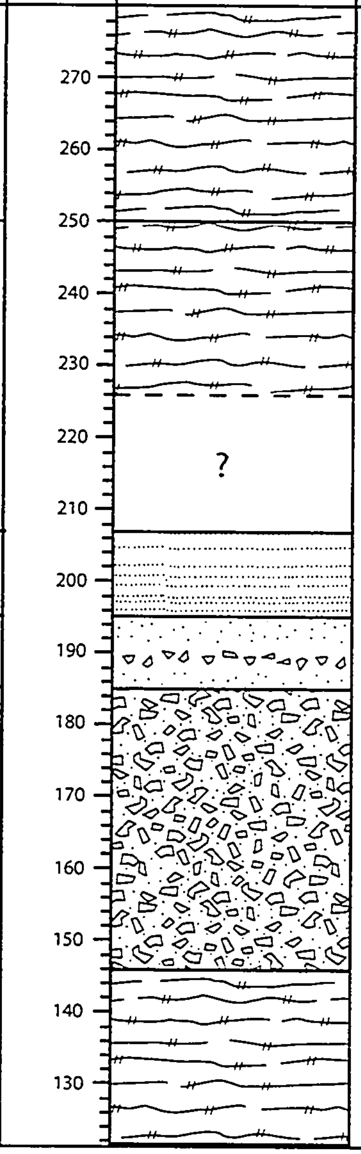
Location: Representative of the southwestern corner of the Lower Stage Coach block.



Unit Name	Thickness in Meters	Description
		Bedrock is relatively fresh at the surface.
Mg	10 (33 ft)	Dark gray porphyritic andesite, dense matrix, phenocrysts: 15% of volume 1 mm plagioclase laths have preferred orientation, 2% to 5% 1 to 2 mm plagioclase fragments, occasional subhedral augite <5% of total volume.
Cg1	31 (105 ft)	Dark gray to gray porphyritic andesite. Matrix is slightly glassy, phenocrysts: 15% of volume 3 to 4 mm zoned subhedral plagioclase 15% of volume 1 to 2 mm subhedral plagioclase. Where exposed in Rector Canyon the outer 5 to 8 cm (2 to 3 in) of this unit may be highly weathered to a light gray or white, interior of unit is still dark gray. Although altered to a lighter color the material is still competent enough to resist crumbling as would be expected if it were a normal weathering rind.
B2	15 (50 ft)	Hard, reddish brown-light gray, tuffaceous breccia. Clasts up to 0.6 m (2 ft) composed of porphyritic andesite similar in composition to unit Cg1, scoria, and obsidian.
Ss	11 (35 ft)	Tan volcanic sandstone/conglomerate, contains bedded channel deposits of sand, silt, gravel, and clasts of andesite and tuff. Unit is moderately cemented but can be carved with hammer.
AT	12 (38 ft)	Soft, dark gray ash tuff with occasional andesitic fragments up to 0.3 m (1 ft).
B3	20 (66 ft)	Dark gray, tuffaceous breccia with fragments <0.6 m (2 ft).
Ob	~3 (10 ft)	Black obsidian, occasional plagioclase crystal up to 2 mm. Parts of this unit are highly shattered and crumble into pebble-sized fragments.
Cg2	55 (180 ft)	Dark gray-black porphyritic andesite, matrix is glassy, phenocrysts: <5% of volume rounded-subrounded 2 to 3 mm plagioclase, 10% of volume 2 to 4 mm subhedral plagioclase, 10% <1 mm anhedral plagioclase laths. The subhedral and anhedral plagioclase have preferred orientation.
B4	2 (6 ft)	Dark gray breccia, clasts up to 0.3 m (1 ft), consisting mainly of andesite similar in composition to Cg2.
?		

Stratigraphic Section 5

Location: 280 m (920 ft) hill at southwest side of the Oakville Ranch block



Unit Name	Thickness in Meters	Meters above Sea Level	Graphical Columnar Section	Description
Mg	30 (100 ft)	270 260		Core stones exposed at surface. Dark purplish gray porphyritic andesite, phenocrysts: 1% to 4% anhedral 2 to 3 mm plagioclase crystals, 10% to 15% of volume 1 mm plagioclase laths/fragments, 1% subhedral augite crystals. Slight preferred orientation for plagioclase. Vesicles common in lower half of unit.
Cg1	?	250 240 230		Dark gray porphyritic andesite, matrix slightly glassy. Phenocrysts: euhedral-subhedral 5 to 6 mm zoned plagioclase 15 to 20% of total volume, unzoned 1 to 2 mm subhedral plagioclase 15% of total volume. Inferred
?	?	220 210	?	Vegetated, not accessible.
Ss	12 (40 ft)	200		Tan-gray volcanic sandstone, bedded channel deposits sand, gravel, clasts of tuff, moderately cemented.
AT	10 (33 ft)	190		Gray, hard tuff with cobble-sized clasts of various andesitic composition, tuff, and scoria.
B3/Ag2	39 (128 ft)	180 170 160 150		B3: Dark gray tuffaceous breccia, clasts <0.6 m (2 ft). Ag2: Dark gray agglomerate, clasts of various andesitic composition. Clasts protrude from soil along outcrop.
Cg2	?	140 130		Dark gray porphyritic andesite. Phenocrysts: 15% of volume 3 to 4 mm plagioclase, 10% of volume 1 mm plagioclase laths.

APPENDIX B

An Exercise in Age Calculation

Using rind development formulas created by Colman and Pierce (1981), an estimated age of the formation of Napa Valley (Baldwin et al., 1998), and the geologic history of the study area suggested in this thesis, a range of ages for the faulting events and core stones can be calculated. Colman and Pierce (1981) have successfully used weathering rind thickness to determine numerical and relative age dates for core stones found at several locations in the western United States. The purpose of their research was to develop a formula to calculate the age of weathering. To calibrate the equation, age dates are first needed from a different dating method. Colman and Pierce chose glacial moraines that had already been correlated to glacial periods by other age dating techniques. The rind thickness of several thousand andesite and basalt clasts was measured at the various locations. The rate of formation of the weathered rinds is expressed as the following equation:

$$d = kt^{1/n} \qquad (1)$$

d = rind thickness
k = a constant representing environmental conditions
t = time
n = rind formation exponent

The exponent n is used to approximate the natural decrease in rind growth with time as the fresh material is increasingly insulated by the rind. Colman and Pierce (1981) suggest an exponent of $n = 2$ best describes simple diffusion reactions observed in obsidian hydration reactions. Because rinds of crystalline igneous rocks form by oxidation, hydrolysis, and diffusion processes, an n value of 2 is probably a maximum value for the exponent (Colman and Pierce, 1981).

$d = kt^{1/2}$ (2)

Using the logarithmic form of equation 1, Colman and Pierce (1981) constructed a plot of rind thickness versus time. The x-intercept on their graph is located at 7,000 years rather than at the origin. Colman and Pierce found that in the early years of formation core stones weather along one curve, then after 7,000 years a second curve better fits the dates observed in the samples.

Because none of the surfaces in the mapping area have been dated previously, it is not possible to use this method. Although this equation cannot be used to date the surfaces, the work of Colman and Pierce (1981) provides some general guidelines for relative age dating of rinds from different locations. When the age and rind thickness from two core stones are compared it is possible to calculate the rind thickness ratio. This ratio combines equation 2 from both samples; if the constant k is the same for both areas equation 3 results:

$(d_1/d_2) = (t_1/t_2)^{1/2}$ (3)

d_1 = rind thickness of sample 1
d_2 = rind thickness of sample 2
t_1 = age of sample 1 rind
t_2 = age of sample 2 rind

$(d_1/d_2)^2 = (t_1/t_2)$ (4)

$(d_1/d_2) = (t_1/t_2)$ (5)

Because equation 3 is a power function with exponent $n = 2$, the rind thickness ratio (d_1/d_2) is probably the minimum age ratio. Squaring the ratio (Equation 4) gives an estimate of the maximum age ratio for the two deposits. Colman and Pierce (1981) suggest that a simple linear relationship (Equation 5) between rind thickness and age may provide an estimate of the minimum age ratio of the two samples. An example taken from Colman and Pierce shows the utility of these ratios.

"[samples from] Pinedale and Bull Lake terminal moraines near West Yellowstone have *rind thicknesses* of 0.40 and 0.78 mm respectively, for a ratio of about 2, and a ratio squared of about 4. Their ages, independently determined by Pierce and others (1976), are about 35,000 and 140,000 yr, respectively, for an age ratio of 4.0." The actual age ratio is within the range calculated by their formula.

Age limits for the equations of Colman and Pierce (1981) are thought to be from 10,000 to 500,000 years, but the upper limit may be extended to approximately 1 m.y. if the rinds are well preserved. The minimum age of 10,000 years is the lower limit because of the difficulty measuring very thin rinds and the x-intercept of the curve. The upper limit of 0.5 to 1.0 m.y. is limited by the equation and their ability to accurately measure rind thickness; Colman and Pierce found that rind weathering decreases with age, and they could not resolve the small changes in thickness with a low degree of error. This may not be as much of a problem in this study area. Rind thicknesses measured by Colman and Pierce were on the order of a few millimeters at most, while rind thickness measured in this thesis are orders of magnitude higher and are commonly 6-7 cm thick. Measurements in this area are not limited by the small differences in rind thickness of Colman and Pierce. As such, it may be possible to correlate relative ages of rind that are much older than 0.5 to 1.0 Ma. However, it is not clear if the formula introduces large or unforeseen errors when extrapolating ages older than 1 million years.

Roadcuts at the eastern edge of the Lower Stage Coach block expose a soil profile that includes an upper colluvially derived layer and a lower layer that may have formed in-situ. The upper layer of unsorted slope wash is composed of sandy clays containing subangular clasts of andesite, each with an undetached weathering rind approximately 3 mm thick. Below those deposits, across a sharp but undulatory contact, is an older soil containing core stones of composition similar to the clasts in the overlying soil. Rind formation in the lower unit is very advanced, ranging from 4 cm in thickness to complete decomposition. At the base of the roadcut and within the second layer, weathered core stones appear to interlock. These features are either the upper portion of the weathering bedrock or a large boulder that has weathered within the colluvial soil. These interlocking core stones have a composition similar to bedrock in this area, and are most likely the upper portion of the weathered bedrock.

The upper colluvial layer is deposited near the scarp of one of the normal faults that down-dropped the Lower Stage Coach block. The west-dipping normal faults in this area would form west-facing scarps, allowing slope wash to collect at their base and on top of the older ground surface. Rinds found on clasts in the upper soil layer would presumably have begun forming after the clasts were deposited. Any fragile rinds previously formed around the core stone would have detached during transport. The youngest rind that had not yet detached from the transported clasts is slightly problematic in this determination. Core stones usually retain a small portion of the youngest rind at their exterior; these are usually 1 mm or less in thickness. Because the rind found in the colluvial layer is usually about 3 mm thick and is softer than the partial rinds found on extracted core stones, there may have been as much as 2 mm of rind growth since emplacement in the colluvial layer. By using the formula created by Colman and Pierce (1981), the age ratio between these two deposits can be calculated.

To calculate this ratio, a few assumptions must be made that may not be an accurate estimation of the system. (1) Rinds in the upper layer were less than 1 mm thick (the lower limit that can be accurately measured) at the time of deposition. (2) Rinds in both soil sequences develop at the same rate. (3) The upper soil was deposited shortly after faulting occurred.

For this calculation, 2 mm will be used as the average rind thickness of the upper soil and 40 mm as the average rind thickness of the lower soil.

Minimum Age Ratio = $40/2 = 20$

Maximum Age Ratio = $(40/2)^2 = 400$

Rinds in the lower soil are at least 20 but not more than 400 times older than rinds in the upper soil. The age difference between these two soils may help determine the age of the faulting event. Unfortunately the age of the weathering surface is very poorly constrained and the age of the rinds in the lower soil is not known. An example follows of how this calculation might work if there was an estimated age of the weathering surface.

For this example, assume that the core stones began weathering after the youngest dated unit, a rhyolitic flow, was deposited. The rhyolitic flow was dated by C. H. Curtis (in Fox, 1983) at 3.8 Ma. This is the maximum age of the rinds.

Minimum Age Ratio = $40/2 = 3{,}800{,}000/X$

Maximum Age = $X = 190{,}000$ years

Maximum Age Ratio = $(40/2)^2 = (3{,}800{,}000/X)^2$

Minimum Age = $X = 9{,}500$ years

X is the possible age range of the rinds in the upper soil and the age of the normal faulting event.

The equations above indicate that the normal faulting in this area may have occurred anywhere from 190,000 to 9,500 years ago.

Baldwin et al. (1998) and Swinchatt and Howell (2004) suggested that the Vaca Mountains on the east side of Napa Valley began to rise approximately 1.0 million years ago. Previously in this investigation it was suggested that the separation of the oldest and second oldest surfaces may be the result of the initiation of uplift of the Vaca Mountains. If this is true, then the age of the second surface would be about 1 million years old. It would be prudent to use an age of 1 million years in the above calculations as well because the sample site is on the second oldest surface.

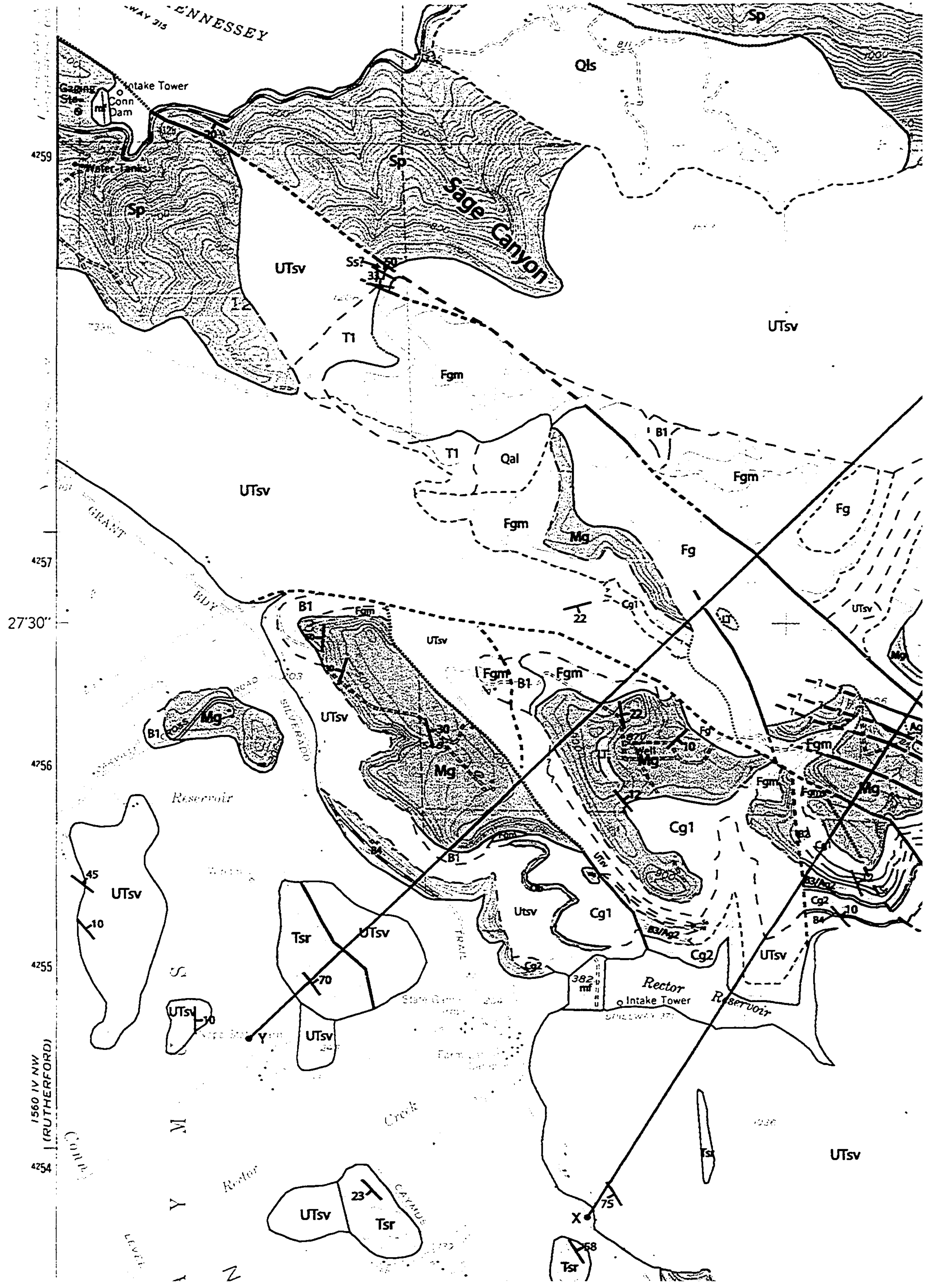
Minimum Age Ratio = $40/2 = 1{,}000{,}000/X$

Maximum Age = $X = 50{,}000$ years

Maximum Age Ratio = $(40/2)^2 = (1{,}000{,}000/X)^2$

Minimum Age = $X = 2{,}500$ years

The calculations above indicate that the normal faulting on the splays in the Lower Stage Coach block may have occurred anywhere from 190,000 to 2,500 years. Because these splays likely are related to the larger normal faults in this area, it may be possible to extrapolate the ages calculated here to the age of the Soda Creek fault.


HENNESSEY
WAY 315
Sp
Qls
Intake Tower
Gaging Sta.
mf
Conn Dam
Water Tanks
Sp
Sp
Sage Canyon
UTsv
Ss?
50
33
T2
T1
Fgm
UTsv
B1
Fgm
T1
Qal
UTsv
Fgm
Mg
Fg
Fg
GRANT
BDY
Cg1
22
B1
Fgm
UTsv
UTsv
Fgm
B1
Fgm
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B1
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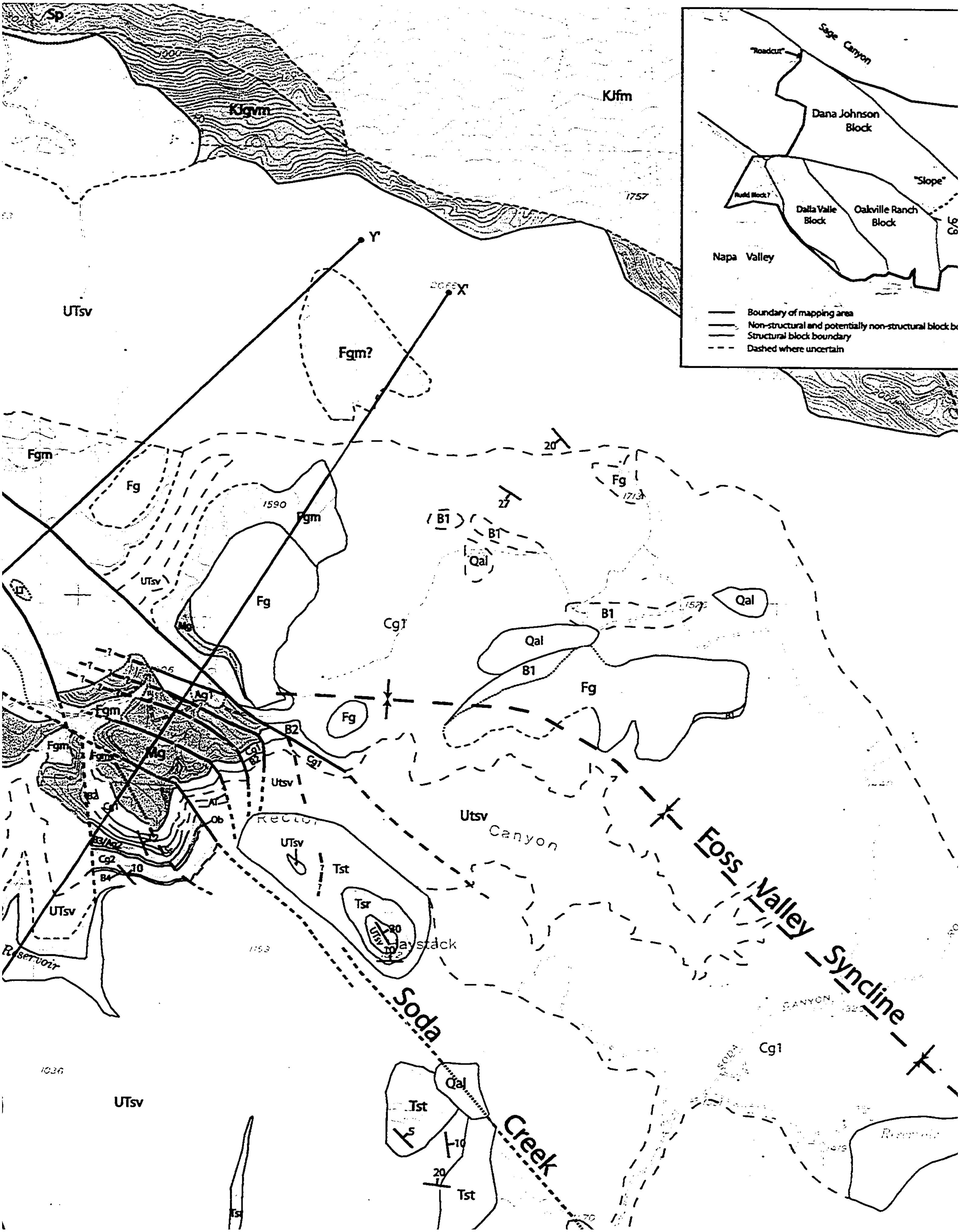
Mg
22
870
Well
10
Mg
Fg
12
Fgm
Fgm
Mg
Ag
Reservoir
B4
B1
Cg1
Bd
Cg1
45
UTsv
10
Tsr
UTsv
Utsv
Cg1
B3/Ag2
B3/Ag2
Cg2
10
B4
Cg2
UTsv
70
Cg2
382 mf
Rector
Intake Tower
Reservoir
UTsv
10
Y
UTsv
Creek
Tsr
UTsv
X
75
UTsv
23
Tsr
Tsr
58
Rector
4259
4257
27'30"
4256
4255
4254
1560 IV NW (RUTHERFORD)

Sp
KJqvm
KJfm
1757
Y'
X'
UTsv
Fgm?
Fgm
Fg
20
Fg
27
1713
1590
Fgm
B1
B1
Qal
UTsv
Fg
Cg1
Qal
B1
Qal
B1
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Mg
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Cg1
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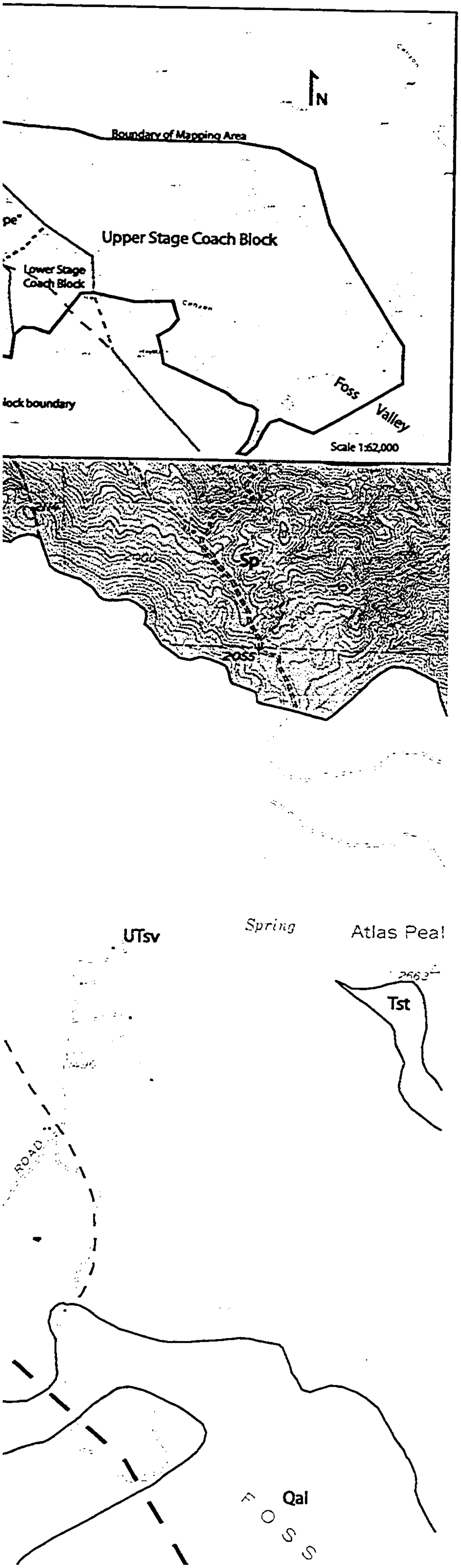
B3/Ag2
Cg2
10
B4
UTsv
Reservoir
Utsv
Canyon
Rector
UTsv
Tst
Tsr
UTsv
20
10
Haystack
Foss Valley Syncline
1153
Soda Creek
CANYON
Cg1
SODA
Reservoir
1036
UTsv
Qal
Tst
5
10
20
Tst
Tsr
Sage Canyon
"Roadcut"
Dana Johnson Block
"Slope"
Rudd Block?
Dalla Valle Block
Oakville Ranch Block
Napa Valley
Boundary of mapping area
Non-structural and potentially non-structural block bo
Structural block boundary
Dashed where uncertain



Units

Recent Deposits

mf Artificial Fill

Quaternary Deposits

Qal Alluvium (Quaternary)

Qls Landslide (Quaternary)

Qaf Alluvial Fan (Quaternary)

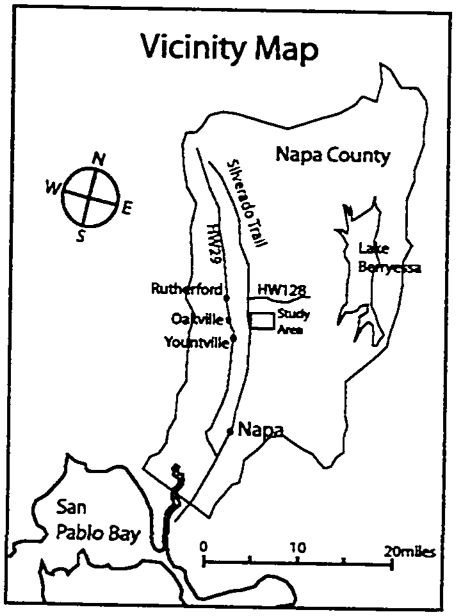
Sonoma Volcanics (Tertiary)

Tsr Rhyolite Member

Tst Tuff Member

UTsv Undifferentiated Member

- **Fg** Andesite (fine-grained)
- **LT** Lithic Tuff
- **Mg** Andesite (porphyritic)
- **Fgm** Andesite (porphyritic)
- **B1/Ag1** Agglomerate/ Tuffaceous Breccia
- **T1** Tuff
- **Cg1** Andesite (porphyritic to porphyry)
- **B2** Tuffaceous Breccia
- **Ss** Sandstone
- **AT** Ash Tuff
- **B3/Ag2** Breccia/ Agglomerate
- **Ob** Obsidian
- **Cg2** Andesite (porphyritic)
- **B4** Breccia



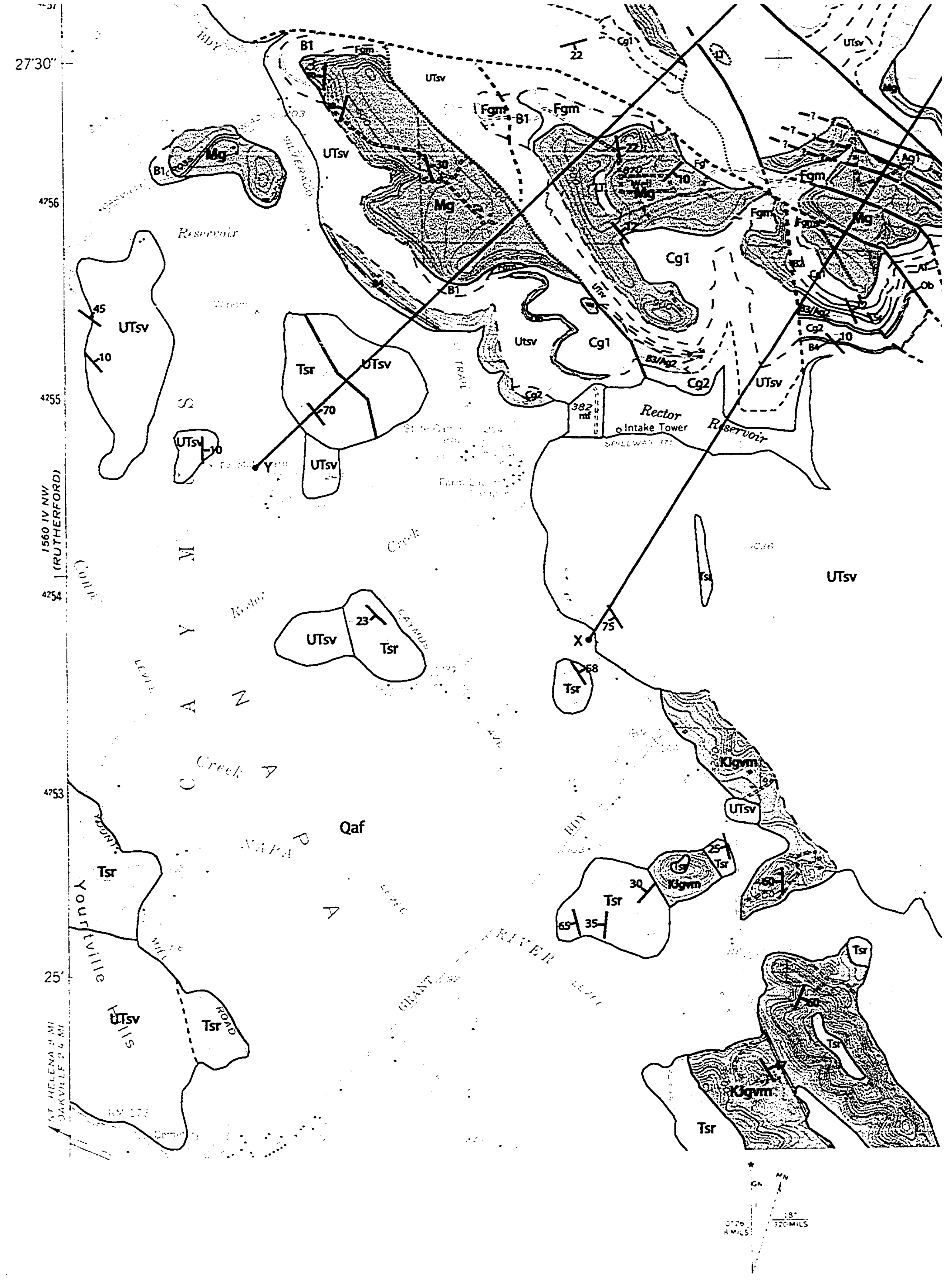
Great Valley Group (Jurassic to Cretaceous)

KJgvm Siltstone, sandstone, and shale

Franciscan Complex (Jurassic to Cretaceous)

KJfm Metegreywacke

Coast Range Ophiolite (Jurassic)


27'30"
4256
4255
4254
4253
25'
1560 IV NW (RUTHERFORD)
ST. HELENA 9 MI
OAKVILLE 2.4 MI
B1
Fgm
UTsv
Mg
Cg1
Cg2
Fg
Ag1
B3/Ag2
B4
Utsv
Tsr
Qaf
Klgvm
Ob
Well
Reservoir
Rector
Intake Tower
Reservoir
SPILLWAY 371
382 mf
Creek
Creek
NAPA
RIVER
CANYON
NAPA
Yountville Hills
ROAD
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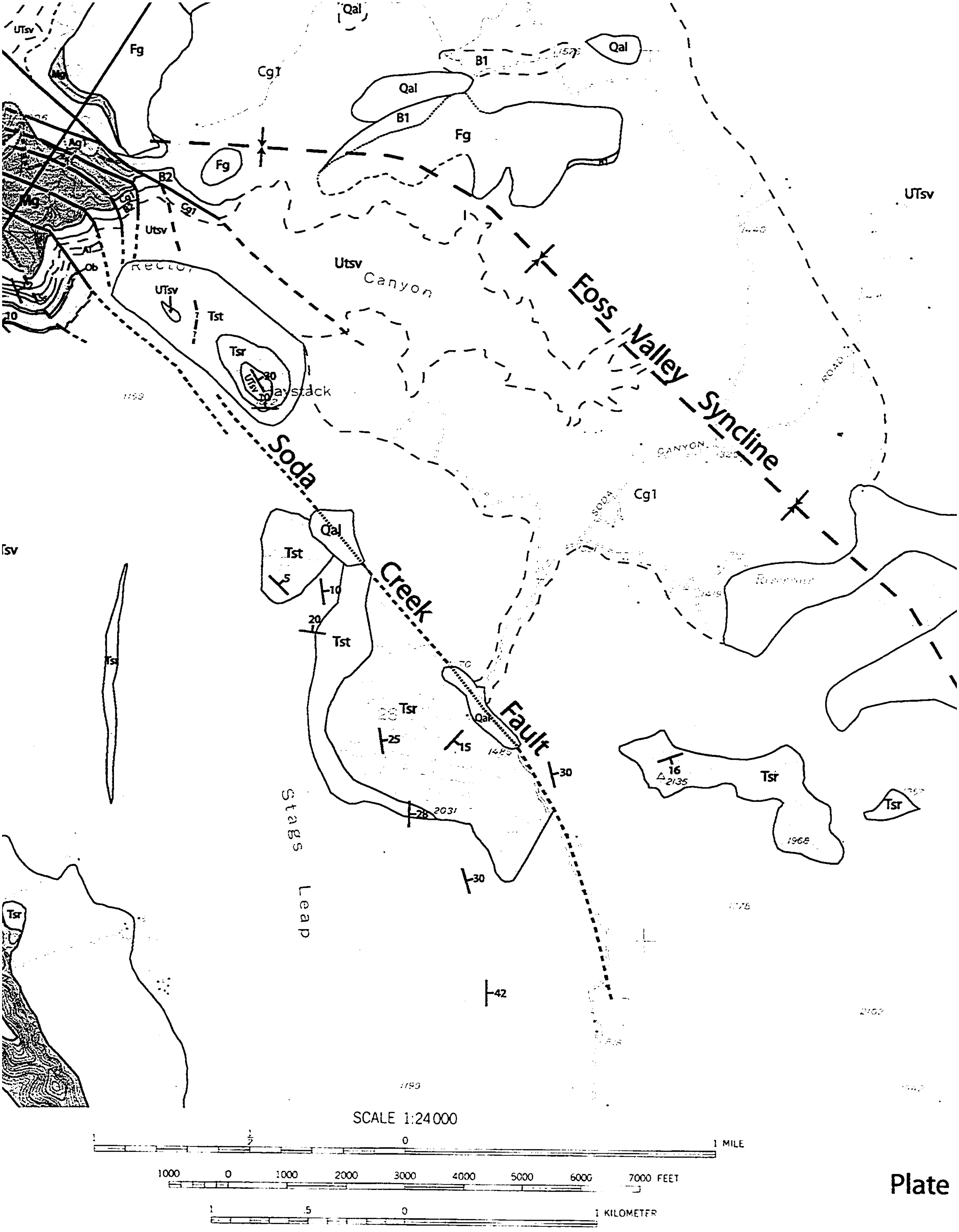
GN
MN


Qal
UTsv
Fg
Cg1
B1
Qal
Mg
Ag1
Fg
B2
Cg1
Mg
B2
Cg1
Utsv
Al
Ob
Rector
Canyon
Utsv
UTsv
Tst
Tsr
UTsv
20
10
Haystack
Foss Valley Syncline
UTsv
CANYON
SODA
Cg1
Soda Creek Fault
Tsv
Qal
Tst
5
10
20
Tst
Tsr
Tsr
25
15
Qal
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16
2135
Tsr
Tsr
1968
28
2031
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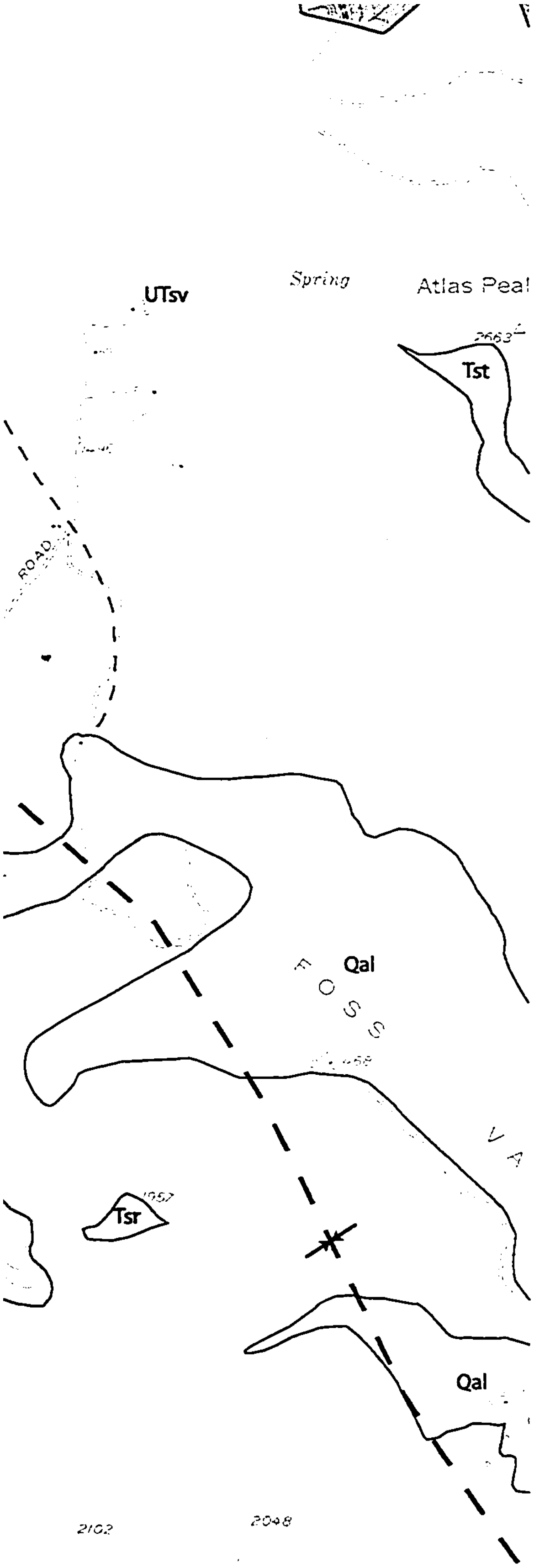
42
Stags Leap
Tsr
SCALE 1:24000
1 ½ 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
Contour Interval: 20 Feet

Plate



Fgm	Andesite (porphyritic)
B1/Ag1	Agglomerate/ Tuffaceous Breccia
T1	Tuff
Cg1	Andesite (porphyritic to porphyry)
B2	Tuffaceous Breccia
Ss	Sandstone
AT	Ash Tuff
B3/Ag2	Breccia/ Agglomerate
Ob	Obsidian
Cg2	Andesite (porphyritic)
B4	Breccia

Great Valley Group
(Jurassic to Cretaceous)

KJgvm	Siltstone, sandstone, and shale

Franciscan Complex
(Jurassic to Cretaceous)

KJfm	Metegreywacke

Coast Range Ophiolite
(Jurassic)

Sp	Serpentinite

Contacts

Concact
Approximate; ? where doubtful
Inferred
Concealed

Fault

Fault
Approximate; ? where doubtful
Inferred
Concealed

Mapping contact between differentiated and undifferentiated Sonoma Volcanics

Approximate axis of Foss Valley Syncline

Strike & dip symbol

47

Note: Map based on review of geologic maps by Weaver (1949), Baldwin et al. (1998), and Graymer et al. (2002) and detailed field mapping (2002 and 2003).

Plate 1: Geologic Map of a Portion of the Yountville Quadrangle

By: Christopher A. Jones