REGIONAL PALEO-TOPOGRAPHIC SETTING OF THE LOVEJOY BASALT, NORTHERN CALIFORNIA

A Thesis

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Master of Science

in

Geosciences

By

Quinn Leon Street

Spring 2009

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APPROVED BY THE DEAN OF THE SCHOOL OF
GRADUATE, INTERNATIONAL, AND INTERDISCIPLINARY STUDIES:

____
Susan E. Place, Ph.D.

APPROVED BY THE GRADUATE ADVISORY COMMITTEE:

____
Terence Kato, Ph.D.

____
Todd Greene, Ph.D.

____
Russell Shapiro, Ph.D.

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ABSTRACT

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The age, chemical composition, stratigraphic position, and probable vent source of the Lovejoy Basalt of northern California have been studied at several localities, but the flow patterns and original distribution remain poorly understood. This study attempts to further understand the nature of the paleo-topographic surface upon which the basalt flowed, the substrate geology at the time of eruption, and the original extent of the flows prior to erosional degradation.

Outcrops at widely separated localities throughout the regional area were visited and are described in order to emphasize differences and similarities in their geologic setting. At each location, the relative intensity of the magnetic susceptibility of the basalt, a direct product of magnetite/titanomagnetite content, was measured and recorded to assess possible regional correlations as well as to test whether or not magnetite settled out of suspension along the course of the exceptionally long flow. The

results of the data were inconclusive, yet hint at the possibility of characterizing individual flows based on relative magnetic susceptibility values.

Westward to northwestward oriented flow direction indicators, including stretched vesicles, tube vesicles, pipe vesicles, and flow grooves, were measured along the basal surface of the Lovejoy Basalt at Oroville Table Mountain. They were found to be approximately perpendicular to linear features on the upper surface.

X-Ray Fluorescence analysis of basalt cobbles underlying the Lovejoy Basalt indicates either previously unmapped mid-Miocene age conglomerates at Oroville Table Mountain or a longer eruption period for Lovejoy Basalt than previously assumed.

New cross sections showing topographic obstructions help define the original distribution of the basalt. A greater degree of channelization than previously assumed was likely present and the possibility of more than one vent cannot be excluded. The maximum extent of the original northward distribution might be further defined by examining the northward termination of Lovejoy Basalt clasts in the Red Bluff Formation.

CHAPTER I

INTRODUCTION

Statement of the Problem

Fine-grained aphyric to slightly porphyritic tholeiitic basalts referred to as "Lovejoy Basalt" are widely distributed in the northern Sierra Nevada range and northern Sacramento Valley of California. Although the age, chemical composition, stratigraphic position, and probable vent source have been studied at several localities, the original distribution and flow patterns of the basalt are not well understood.

Purpose of this study

This study will attempt to understand the nature of the erosional surface upon which the basalt flowed, the substrate geology at the time of deposition, and the original extent of the flows prior to later erosional degradation. Outcrops at widely separated localities throughout the regional area are described in order to emphasize differences and similarities in their geologic setting.

The Lovejoy Basalt commonly displays prominent inverted topography, allowing examination of underlying rock units which have been locally preserved by the erosional resistance of the overlying basalt. In some cases, these underlying rock units are not mapped, due to scarcity of surface exposure, yet are significant in that they represent an isochronous surface which existed just prior to the eruption of the basalt during the Mid-Miocene. Where visible, these subcrops assist in understanding the nature of the surface which served as the substrate for the Lovejoy Basalt.

Fieldwork involved searching for and describing subcropping stratigraphic units, documenting structural features of the basalt which provide insight into the nature and directional transport of the flows, and taking measurements of the magnetic susceptibility of a wide distribution of outcrops to assess possible regional correlations.

Laboratory work involved X-Ray Fluorescence analysis of what appear to be rounded Lovejoy Basalt cobbles found in conglomerates directly underlying the Lovejoy Basalt at Oroville Table Mountain.

New cross sections in the area between Little Grass Valley and the Sacramento Valley provide insight into the nature of the distribution of channelization by showing topographic obstructions. Also, possible correlation was found between linear features on the surface of Oroville Table Mountain and flow direction of the lava.

The goal of this paper is to incorporate observations and measurements with previously published literature so as to provide tools and insights which may assist in the process of determining the original distribution and regional substrate geology of the Lovejoy Basalt.

CHAPTER II

LITERATURE REVIEW

Previous Studies

The Lovejoy Basalt was first studied from a geological perspective as early as the 1880's (Pettee, 1880). It was originally named the 'older basalt' by Turner (1893) because it was the oldest basalt flow in the area he was studying. His paper mentioned the Onion Valley, Mooreville Ridge, Oroville Table Mountain, Red Clover Valley, North Fork Feather River, and Big Chico Creek areas as being occupied by the 'older basalt.'

Numerous studies have been published over the years which contribute general observations regarding the basalts appearance, age, chemical composition, stratigraphy, and regional distribution. Most reports agree that the dark black, glassy, mostly aphyric, basalt typically displays prominent columnar jointing and reaches thicknesses up to 500 feet. Studies on the California Coast Range near Vacaville (Redwine, 1944; Weaver, 1949; Siegel, 1988) correlated the Putnam Peak Basalt to the basalt at Oroville Table Mountain and across the valley at the Orland Buttes (Fig. 1).

A doctoral thesis by Creely (1954) categorizes the 'older basalt' as part of the "Superjacent Series," or relatively flat-lying, undeformed, upper-section of the Sierra Nevada mountain range. The paper mentions the distinctive linear joint patterns found on the surface of the basalt at Oroville Table Mountain as well as the primary mechanical erosive processes associated with the basalt.

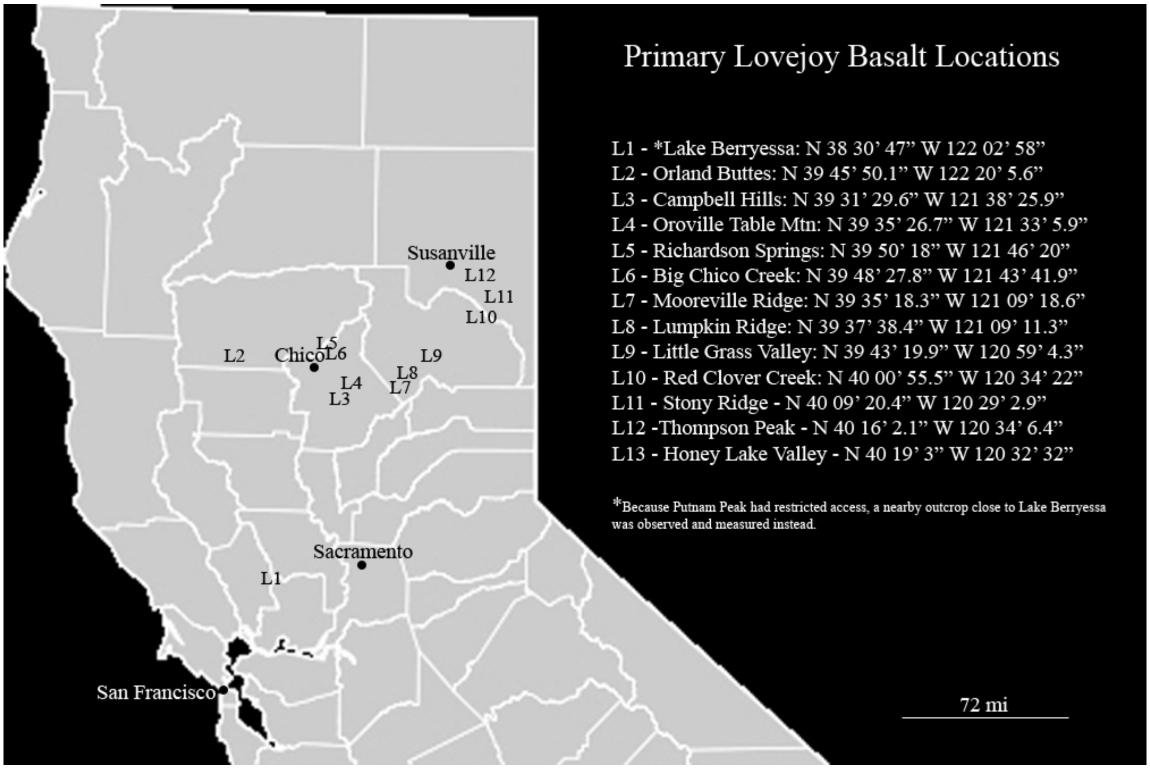


Figure 1. Regional map showing the approximate locations of Lovejoy Basalt outcrops visited during this study. The basalt at Lake Berryessa (L1) can be considered to be correlative with the nearby Putnam Peak Basalt.

In 1959, Durrell named the widespread Tertiary basalt the Lovejoy Formation, after Lovejoy Creek in the vicinity of some of the easternmost known outcrops. Over the years, this name has gained general usage. Many now refer to it simply as the Lovejoy Basalt, which is how it will be referred to throughout this paper.

The first study of the magnetic properties of the Lovejoy Basalt was conducted in 1963. The remnant magnetization was measured and analyzed, resulting in the interpretation that the Lovejoy Basalt had erupted over a relatively short period of time during a period of reversed polarity, and that all of the known outcrops are correlative (Gromme, 1963). Later magnetic studies involving AMS (anisotropy of magnetic susceptibility) as well as additional remnant magnetization measurements confirmed these interpretations and showed that at least two of the Lovejoy Basalt flows have contrasting remnant magnetization orientations (Coe, 2005).

The morphology of the Lovejoy Basalt in the subsurface of the Sacramento Valley is described in a M.S. Thesis by Van den Berge (1968). With the help of well log data from numerous oil companies operating throughout the valley, it was shown that the Lovejoy Basalt once occupied a great deal of the Sacramento Valley and was later covered by volcaniclastic and fluvial deposits.

It is now fairly well accepted that the Lovejoy Basalt erupted from the Thompson Peak area near the town of Janesville, Ca and flowed approximately southwest down the paleo-slope of the ancient Sierra Nevada (e.g. Roberts, 1985; Wagner, 2000; Garrison, 2004). Both the bulk and trace elemental composition of all known Lovejoy Basalt outcrops are very similar to those of the Columbia River Basalt group to the northeast (e.g. Doukas, 1983; Roberts, 1985; Wagner, 2004). The regional distribution is largely thought to be an approximately 6,000 square mile triangular area in northern California in which Thompson Peak, Orland Buttes, and Putnam Peak represent the apices (Tobia, 1997), although exactly how much of this area was originally covered by Lovejoy Basalt is not known with certainty.

Until recently, the age of the Lovejoy Basalt remained elusive and controversial. Over the years there have been a series of contradictory ages proposed, based on stratigraphy (e.g. Turner, 1893; Creely, 1955) and radiometric age dating (e.g. Dalrymple, 1963; Roberts, 1985; Page, Sawyer, and Renne, 1995; Wagner, 2004).

Misinterpretations in the field are responsible for contradictory ages based strictly on stratigraphic evidence. One example is a large block of basalt within the Eocene Ione Formation underlying Oroville Table Mountain which had somehow slumped down into the deposit giving the illusion that it was the underlying rock unit (Lindgren, 1911). Several misinterpretations occurred at the type locality, Red Clover Creek, in which the Lovejoy Basalt appears to overlie the significantly younger andesitic mudflows of the Delleker Formation. This stratigraphic relationship was cleared up only recently when it was determined that the Delleker Formation was deposited into deep channels that were previously cut into the Lovejoy Basalt (Garrison, 2004).

The discrepancies in ages reported by K-Ar radiometric dating are thought to be due to loss of argon gas in the feldspar crystals (Kato, personal communication; Tobia, 1997). A more sophisticated radiometric age dating technique involving Ar-Ar performed on Lovejoy Basalt samples later resulted in ages of approximately 16 Ma for the Lovejoy Basalt (Roberts, 1985; Page et al., 1995; Wagner, 2004), which are now widely agreed upon. A similar Ar-Ar test was previously performed on plagioclase phenocrysts in andesitic mudflows directly underlying the Lovejoy Basalt at Oroville Table Mountain, yielding dates which restrict the age of the Lovejoy Basalt to less than 14 Ma (Wagner, 1990). Nonetheless, the Langhian age of the mid-Miocene is the accepted general age for the Lovejoy Basalt.

Deformational History

Whenever attempting to imagine its original geomorphology, it is important to keep in mind that the Lovejoy Basalt has undergone significant erosion and, in some places, deformation and displacement, since its eruption in the mid-Miocene. Multiple stages of uplift and exhumation have helped shape modern Sierra Nevada morphology and the present Lovejoy Basalt morphology. Although the entire range behaves mostly as a rigid block (Wakabayashi and Turner, 2001), there are some major differences between the northern Sierra Nevada and the southern Sierra Nevada insofar as tectonic movement, exhumation, and volcanism.

Numerous studies have shown that the motion of the Sierra Nevada microplate relative to the North American craton approximately parallels the NW-SE trend of the San Andreas Fault, although the motion ranges from a more northerly direction in the south to a more northwesterly direction in the north (Wakabayashi and Turner, 2001). It should be noted that this is also the trend of the proposed dike at Thompson Peak as well as the feeder dikes in the Columbia River Basalt province (Garrison, 2004). In addition to this inter-range variation, there is a greater abundance of Cretaceous basement rocks preserved in the southern Sierra Nevada and a greater abundance of volcanic extrusions younger than 4 Ma in the northern Sierra Nevada (Wakabayashi and Turner, 2001). It is difficult to say how or even if these variations are related, although the substrate for the Lovejoy Basalt was certainly influenced by the northern Sierra Nevada geomorphology.

Various methods have been used by geologists to estimate the amount of exhumation that has occurred in the Sierra Nevada during each of the significant periods of uplift it has undergone. Some of these techniques include comparing the differential tilt of strata at the eastern margin of the Central Valley, comparing gradients of Tertiary stream deposits, reconstructing old drainages from deposits preserved in paleo-channels, as well as paleo-botanical studies (Wakabayashi and Turner, 2001). Although each of the pre-Miocene tectonic events played a significant yet indirect role, it was the Late-Cenozoic deformational events which had the most effect upon the paleo-geomorphology of the Lovejoy Basalt.

The first major period of uplift during the Late Cretaceous to Late Paleocene post-dates the last plutonic intrusions of the Sierra Nevada and pre-dates Eocene strata deposition, during which time the granitic basement rocks experienced up to 19 Km of exhumation in the north and up to 23 Km of exhumation in the south (Wakabayashi and Turner, 2001). This event largely set the stage by providing the regional topography which would later be eroded and become the shallow gradient of the ancestral Sierra Nevada during the time of eruption of the Lovejoy Basalt.

Evidence for Eocene to Early Miocene uplift is primarily found in the angular unconformities between Eocene strata and overlying Miocene volcanics. An example can be observed at Oroville Table Mountain where the dip of Eocene sedimentary strata is more steeply inclined than the overlying mid-Miocene Lovejoy Basalt. The difference, however, is only a few degrees, indicating that post-Eocene tilting may have been relatively small.

Although some relatively insignificant events of uplift and erosion occurred between the Eocene and Miocene, the topographic relief of the Sierra Nevada had been greatly reduced by the time Eocene strata was deposited, at least in the central and northern parts of the range (e.g. Lindgren, 1911; Creely, 1955; Durrell, 1966).

Late Cenozoic uplift of the Sierra Nevada initiated approximately 4.3 to 6 Ma (Wakabayashi and Turner, 2001). This period had the most dramatic effect upon modern Sierra Nevada morphology. Because the Lovejoy Basalt is the capstone of much of the northern range, it is this period of uplift which most dramatically deformed, displaced, and eroded the Lovejoy Basalt. During this time, the greatest uplift occurred along the eastern side of the range, just west of the frontal fault system, causing a gentle westward tilting of the entire Sierra Nevadan block (Durrell, 1959; Wakabayashi, 1999).

In most places where it remains, the Lovejoy Basalt occupies the highest topographic space in the area. Exceptions include some high outcrops of granitic rocks near Mooreville Ridge (Wakabayashi, 1999), a high exposure of metamorphic basement rocks just to the northeast of Oroville Table Mountain, Late-Cenozoic volcanic deposits to the east, such as the Thompson Peak basalt, as well as the Tuscan/Tehama volcaniclastic deposits which overlie the Lovejoy Basalt in the Big Chico Creek area and in the subsurface of the Sacramento Valley (Van den Berge, 1968).

Because the Lovejoy Basalt is assumed to be a relatively continuous flood basalt unit, extruded during a short period of time by geologic standards, it is considered to be a significant stratigraphic marker in the Sierra Nevada, and as a result has been used, although somewhat unsuccessfully, to check the validity of the rigid tilt-block model of Late-Cenozoic Sierra Nevada uplift (Wakabayashi, 1999).

According to Wagner (1990), most large-scale gradient changes along the Lovejoy Basalt flow in the Sierra Nevada are probably due to paleo-slope, not post-eruptive deformation. However, if the degree of channelization and paleo-topography of the basal surface is more exaggerated than previously thought, it could help explain why the inclination of the Lovejoy Basalt would overestimate Sierra Nevada uplift in the rigid tilt-block model.

The total estimated Late Cenozoic uplift in the Feather River area of the northern Sierra Nevada is between 1400 and 1800 meters. However, significant east-down faulting initiated around 600,000 years ago in a deformed zone east of Little Grass Valley counteracted some of the uplift. Total vertical separation of the Lovejoy Basalt in this area, known as the frontal fault system, is at least 600 meters (Wakabayashi, 1999). Vertical displacement in the Honey Lake fault zone is reported to be between 900 and 1000 meters (Page, 1995). Other significant tectonic deformation includes broad downwarping and minor faulting between Grizzly Ridge and the Diamond Mountains, westward flexure in the Chico monocline area, and several normal faults within the range displacing the Lovejoy Basalt between 10 and 100 meters (Page, 1995).

Lovejoy Basalt in the Coast Range and in the subsurface of the Sacramento Valley has also been subjected to tectonic forces during the late Cenozoic. An E-W trending pressure system has been inferred in the Sacramento Valley based on structural features formed less than 2.5 Ma (Harwood, 1987). It is difficult to say how much the Lovejoy Basalt outcrops located on the Coast Range have been uplifted, or at all, since their extrusion.

Along with being tilted and separated by tectonic processes, the last 14 million years of erosive events have removed or covered the majority of the original Lovejoy Basalt, leaving an array of discontinuous outcrops throughout the northern Sierra

Nevada and a few sparse outcrops on the foothills of the Coast Range. Subsurface data shows that a great deal of Lovejoy Basalt remains underneath the younger deposits of the northern and central Sacramento Valley.

General Description and Tectonic Setting

The Lovejoy Basalt is distinctive in many ways from the multitude of other Late Cenozoic volcanic rocks in the northern Sierra Nevada. Chemically decomposed material appears brownish-grey and relatively indiscrete, but freshly exposed material is usually darker in color and much glassier than other basalts in the area. Unlike many other local volcanic rocks, it usually has the appearance of being completely aphyric. With close examination, however, one can often see small, dark, reflective crystals of either titanomagnetite or other iron-oxide minerals floating in the groundmass. Many outcrops, particularly to the east, display significant phenocrysts of plagioclase as well as less prominent olivine and garnet phenocrysts. The olivine and garnet phenocrysts have been previously referred to as xenocrysts (Garrison, 2004), perhaps to indicate the likelihood that the minerals were not formed within the cooling lava, but were later incorporated from surrounding material during emplacement. Supporting evidence for this conclusion, however, has yet to be presented.

Another distinguishing feature of the Lovejoy Basalt is its tendency to form prominent inverted topography and extensive mesas, such as can be found at Oroville Table Mountain, Lumpkin Ridge, Mooreville Ridge, Stony Ridge and other localities. Although other local basalt flows have also formed large areas of inverted topography, their morphologies are not as distinctive as that of the Lovejoy Basalt, which can often be seen from great distances.

The proposed vent area for the Lovejoy Basalt is located on a ridge which connects to Thompson Peak near the town of Janesville, Ca. From here the lava is believed to have traveled at least as far as Putnam Peak, a distance of approximately 240 km, reaching a maximum thickness of more than 700 feet at Stony Ridge. If all of the known Lovejoy Basalt was extruded from this singular vent area, it would be the longest basalt flow in California.

Perhaps due to high fluidity, individual flows reached greater thicknesses (up to 140 feet) than those of other local basalts, as indicated by huge, vertical, roughly hexagonal columns such as the ones which can be seen when driving near the southern edge of South Table Mountain. Because columns are a product of cooling, they rarely, if ever, have vertical continuity across flow boundaries.

The boundaries between individual flows remain somewhat controversial, however. Some have speculated that the horizontal fractures which appear to separate individual flows at certain locations are merely joints which are unrelated to individual flows (Doukas, 1983). Magnetic susceptibility measurements taken vertically across one of these horizontal fractures at Big Chico Creek support this idea by showing no variation (Tobia, 1997). In the Red Clover Creek/Thompson Peak region, however, more definite individual flows are distinguished by alternating sequences of vertical cliff faces and talus slopes, in which the boundaries between flows have been previously interpreted to be marked by the upper surface of the talus slopes (Garrison, 2004).

Other distinguishing features of the Lovejoy Basalt include prominent linear surface structures which can be seen with ease from aerial photos and spectacular waterfall areas created by persistent undermining (Fig. 2).

The array of remaining outcrops of Lovejoy Basalt is significantly more extensive in distribution than any other volcanic rock in the Sierra Nevada. The primary erosive mechanism of the Lovejoy Basalt is mechanical, in which large pieces of the edge of the flow fall down slope after the softer sedimentary rocks underneath are removed. Stream channels cutting across outcrops play a much smaller part in the erosion process although over time the basalt is slowly worn away in this fashion. The results of this process can be observed at a channel-cut depression called "The Hollow" on top of Oroville Table Mountain.

Comprehensive analyses of Lovejoy Basalt chemistry have classified it as a tholeiitic, Mid-Ocean Ridge Basalt, typical of lavas extruded from zones of extension in oceanic lithosphere. It has also been interpreted as a continental intra-plate basalt based on trace element composition (Garrison, 2004). It is well-established that there is a high degree of similarity in chemical composition between certain flows of the Columbia River Basalt (CRB), particularly, the Grande Ronde flows (Coe, 2000; Garrison, 2008) and the Lovejoy Basalt. However, the Lovejoy Basalt is enriched in barium relative to the CRB, possibly indicating the incorporation of some continental material into the lava as it was emplaced (Wagner, 2000). The trend of the Thompson Peak vent along the Honey Lake fault of the Walker Lane shear zone parallels the NW-SE oriented, coeval

Figure 2. Naturally undermined area behind Phantom Falls at Oroville Table Mountain. These areas provide rare opportunities to study the basal surface of the Lovejoy Basalt (overhang) as well as underlying sedimentary units. The trees in the foreground are approximately 30 feet tall.

feeder dikes of the CRB group, indicating a similar regional stress field (Busby, et al., 2004).

As a result of these observations, it has been hypothesized that the Lovejoy Basalt represents the southwestern-most extension of Yellowstone Hot Spot volcanism (Coe, 2000; Garrison, 2008). Basin-and-Range extension was initiated at approximately the same time as the extrusion of the Lovejoy Basalt. This extension could have been partly responsible for helping bring the magma to the surface (Kato, personal communication).

The sizes of Lovejoy Basalt outcrops range from large, extensive plateaus or mesas such as Oroville Table Mountain and Stony Ridge to very small exposures in the bottom of creek beds where only the tip of the flow is visible, such as at Rock Creek and Mud Creek.

The maximum extent of the regional distribution is currently not known with certainty, although in general, the Lovejoy Basalt is thought to have once occupied a broad triangular region between Thompson Peak, Orland Buttes, and Putnam Peak (Fig. 1). The Red Bluff Formation along the western edge of the Sierra Nevada contains abundant Lovejoy basalt clasts around the Chico area and may contain information as to the northernmost extent of its original distribution. Putnam Peak represents the southwesternmost known extent, although it is possible that the flow extended even further south and that evidence has been removed or covered. Similarly, the Thompson Peak vent may not necessarily represent the northeastern most extent. A cross section published in a 'Friends of the Pleistocene Pacific Cell field trip guide' shows a small outcrop of Lovejoy Basalt existing just off of Highway 395, in the Honey Lake Valley northeast of the Thompson Peak vent (Page and Sawyer, 1995).

Discussion of Sierra Nevada Basement Geology

After a series of often controversial ages reported over the years, it is now fairly accepted that the Lovejoy Basalt is approximately 16 million years old (Busby and Wagner, 2004). In order to more fully understand the paleo-geomorphology of the Lovejoy Basalt, it is necessary to more fully understand the regional topography that existed during its extrusion in the mid-Miocene. This requires an examination of the distribution of pre-Miocene rocks which currently exist in the northern Sierra Nevada, the Sacramento Valley, and the eastern Coast Range between Thompson Peak and Putnam Peak. It is also necessary to note the deformation and uplift which has occurred since the mid-Miocene.

The northern Sierra Nevada is composed of a series of mostly post-Eocene volcanic eruptions and volcaniclastic sedimentary deposits known as the Superjacent Series which stratigraphically overlie the plutonic and metamorphic basement rocks of what is known as the Subjacent Series (Creely, 1954; Durell, 1987). Because the basement rocks largely provided the mold into which the Lovejoy Basalt flowed as it traveled from the Honey Lake Valley area to the Sacramento Valley, it is the Subjacent Series that is most relevant to the Lovejoy Basalt distribution in the Sierra Nevada. In the Sierran foothills, the paleo-Sacramento Valley, and the Coast Range, however, the Cretaceous to Miocene age sedimentary rocks provided the upper crust of the substrate surface into which the Lovejoy Basalt poured.

The Subjacent Series of the northern Sierra Nevada can be roughly divided into several vertically-oriented geologic zones known as the Western Belt, the Central Belt, and the Eastern Belt, in which the Central and Eastern Belts are divided by the Melones Fault zone (Durrell, 1987).

The Western Belt is composed mostly of the Jurassic rocks of the Smartville Complex. The eastern margin of the Smartville Complex approximately marks the boundary of the “mother lode” of the gold zone in the western foothills of the northern Sierra Nevada. Although the western margin surficially ends at the Sacramento Valley, it extends to the west under younger deposits for some distance. These slightly metamorphosed volcanic, gabbroic, and ultramafic rocks are believed to be part of an ophiolitic arc collision. The collision occurred sometime during the Jurassic, causing the heat necessary to initiate the gold-bearing quartz veins which exist somewhat sporadically within the Western Belt (Durrell, 1987). Unlike the Eastern Belt, rocks of the Smartville Complex are not composed of a sequential series of rocks laid on top of each other, but rather they exist as a group of related ophiolitic type rocks. It is not, however, a complete ophiolitic sequence due to the lack of a chert layer (Durrell, 1987).

Rocks of the Central Belt lay adjacent to the Smartville Complex but are separated from the Eastern belt by the serpentinized ultramafic rocks of the New Melones Fault zone. Individual formations and their relative ages are difficult to determine within this belt due to the high degree of disruption experienced, particularly the chert, mud, and ash layers (Durrell, 1987). Large zones of mélange exist in which the more resistive rocks leave blocky remnants outcropping in an unpredictable fashion. Fossils in blocks of limestone found within this belt are Permian and Pennsylvanian in age, which does not necessarily indicate the age of the formation of the mélange. Some of the rocks in this belt are similar enough in lithology and age to rocks in the Western Belt that they could be part of the same massive ophiolite (Durrell, 1987).

The Melones fault zone, also referred to as the Feather River Peridotite belt, is a vertically oriented mass of ultramafic rocks with serpentinized zones about 3 miles thick which lies between the Central and Eastern Belts of the northern Sierra Nevada. Both sides of this zone are bounded by faults. The eastern side is bounded by the

Melones fault and the western side is bounded by the Rich Bar fault. Some of the rocks in this zone have been shown by radiometric age dating to be approximately 400 million years old (Durrell, 1987). This zone may represent a section of the mantle that was somehow transported to the surface with the help of the serpentinization process.

The oldest and most metamorphosed rocks in the northern Sierra Nevada can be found within the Eastern Belt (Durrell, 1987). A large section of this belt is covered with Mesozoic volcanic rocks of the Superjacent Series. Of the Subjacent Series rocks exposed, however, the primary component is the Shoo Fly Formation, a span of meta-sedimentary rocks which were likely deposited during the Silurian or possibly the Ordovician, as indicated by fossils found in blocks of limestone at Mt. Hough (Durrell, 1987). Large sections of slate and some sandstone along Highways 70 and 89 are exposed in the road-cuts showing prominent vertical foliation as well as secondary crenulations, indicating that the rocks have undergone a series of deformational events. Chert and limestone are also commonly found within the Shoo Fly Formation, although not often in road-cuts.

Mesozoic plutons, consisting mostly of granitic rocks, began to intrude the northern Sierra Nevada shortly after the initiation of the Nevadan Orogeny approximately 140 million years ago. They continued as a series of injections for at least 50 million years, well past the deformational period of the orogeny. As a result, most of the plutonic rocks are undeformed. The orientation of the foliation of the metamorphic rocks surrounding the plutons suggests a relationship between the injection of the plutons and the direction of cleavage, indicating that the intrusion occurred simultaneously to the deformation of the metamorphic rocks. In the northern Sierra Nevada, the Mesozoic plutonic rocks exist in all three belts, although there is a large gap where they seem to be missing in the eastern belt.

Regional Stratigraphy

It is apparent that much of the eastern portions of the remaining Lovejoy Basalt overlie either Cretaceous or Eocene age sedimentary rocks. Most of the Cretaceous deposits are marine and predate the uplift of the Coast Range, whereas most of the Eocene deposits are nonmarine (except for in the Putnam Peak area), originating either from the Coast Range or the Sierra Nevada.

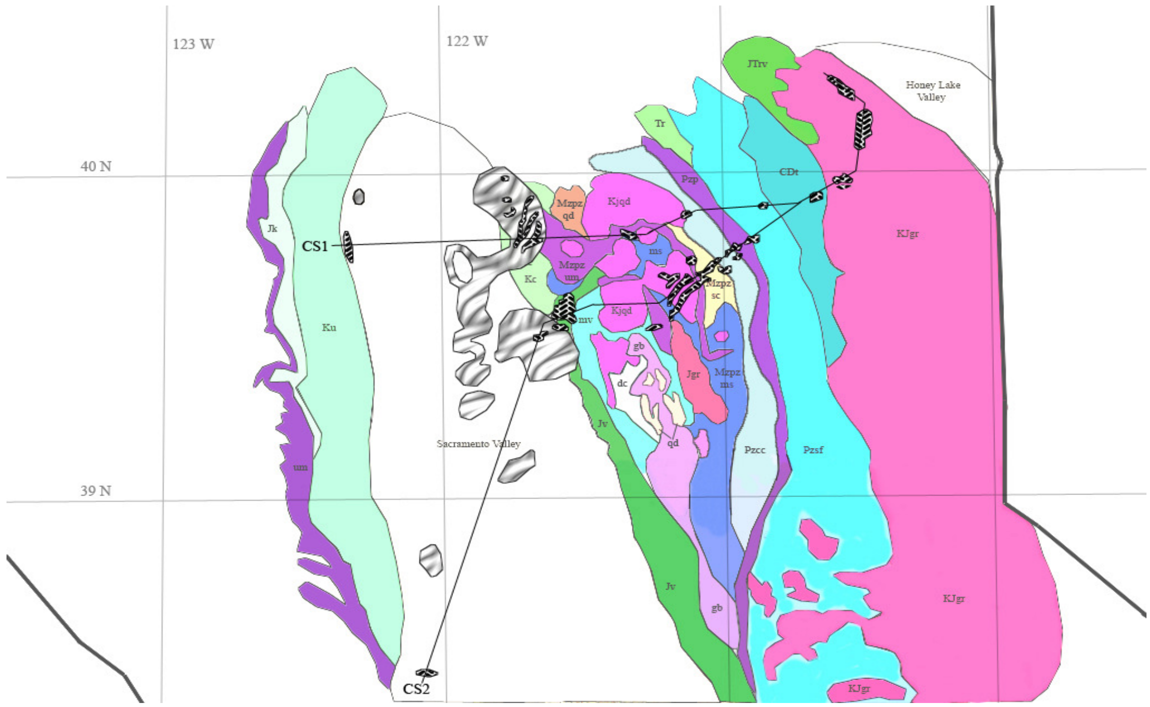
In the subsurface of the Sacramento Valley, the Lovejoy Basalt overlies the nonmarine Eocene deposits of the Nord and Domengine (correlative with the Ione Formation) Formations, which in turn overlie the Cretaceous Kione/Forbes marine sedimentary rocks. Directly overlying the Lovejoy Basalt is the Pliocene/Pleistocene Tuscan and Tehama Formations.

At Campbell Hills and Oroville Table Mountain, the Lovejoy Basalt is mapped as overlying Eocene nonmarine deposits and Jurassic pyroclastic rocks, but some of the nonmarine conglomerates directly underlying the Lovejoy Basalt at Oroville Table Mountain may be approximately mid-Miocene in age. X-Ray Fluorescence evidence presented in this paper supports the notion that some of the rounded basalt cobbles within these underlying conglomerates are Lovejoy Basalt clasts transported downstream. Considering that the Lovejoy Basalt was likely erupted in a short time interval (Gromme, 1963; Coe, 2000), the conglomerates containing the rounded Lovejoy Basalt cobbles are likely to be approximately the same age. Alternatively, it may be that the period of Lovejoy Basalt eruption was longer than expected.

From Oroville Table Mountain to the vent area at Thompson Peak, the Lovejoy Basalt directly overlies rocks of the Subjacent Series. In a few locations, however, such as along the edges of Mooreville and Lumpkin Ridges, thin layers of fine sandstone and mudstone can be observed to lie between the Lovejoy Basalt and the underlying plutonic rocks of the Subjacent Series. Such units could be remnants of paleo-channel deposits removed in areas not protected by the overlying erosion-resistant cap of the Lovejoy Basalt. At most places in the higher reaches of the Sierra Nevada, however, the Lovejoy Basalt could be seen to directly overlie rocks of the Subjacent Series, although in many places the actual contact is obscured by thick talus slopes. An exception is the outcrop at Big Grizzly Creek, west of Lake Davis, where the basalt overlies Tertiary auriferous gravels similar to those found beneath the Lovejoy Basalt in the foothills and subsurface Sacramento Valley. The original distribution of these Eocene gravels remains uncertain, as much have them have undoubtedly been eroded away.

Two hanging cross sections (hung on the Lovejoy Basalt) were created for this study in order to emphasize the types of rocks overlying and underlying the Lovejoy Basalt at each of the major localities (Figs. 3-7). The first cross section, CS1 (Figs. 4 and 5), shows the stratigraphy at the outcrops between Orland Buttes and Thompson Peak, signifying the approximate path of the northern branch of the lava flow. The second cross section, CS2 (Figs. 6 and 7), shows the stratigraphy at the outcrops between Putnam

Peak and Big Grizzly Ridge, leaving out the outcrops between Red Clover Creek and Thompson Peak which are the same as in the first cross section. The second cross section represents a crude approximation of the path of the southern branch of the lava flow (see Chapter V for a discussion on the channelization of the Lovejoy Basalt in the Sierra Nevada).



LEGEND

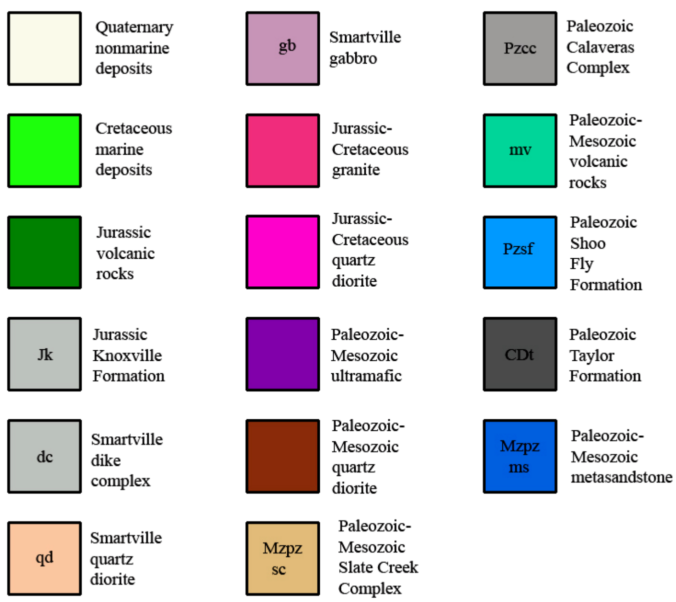


Figure 3. Geologic map of northern California showing the locations of the profiles used for the following cross sections. Data was compiled from Geologic Maps produced by the California Division of Mines and Geology.

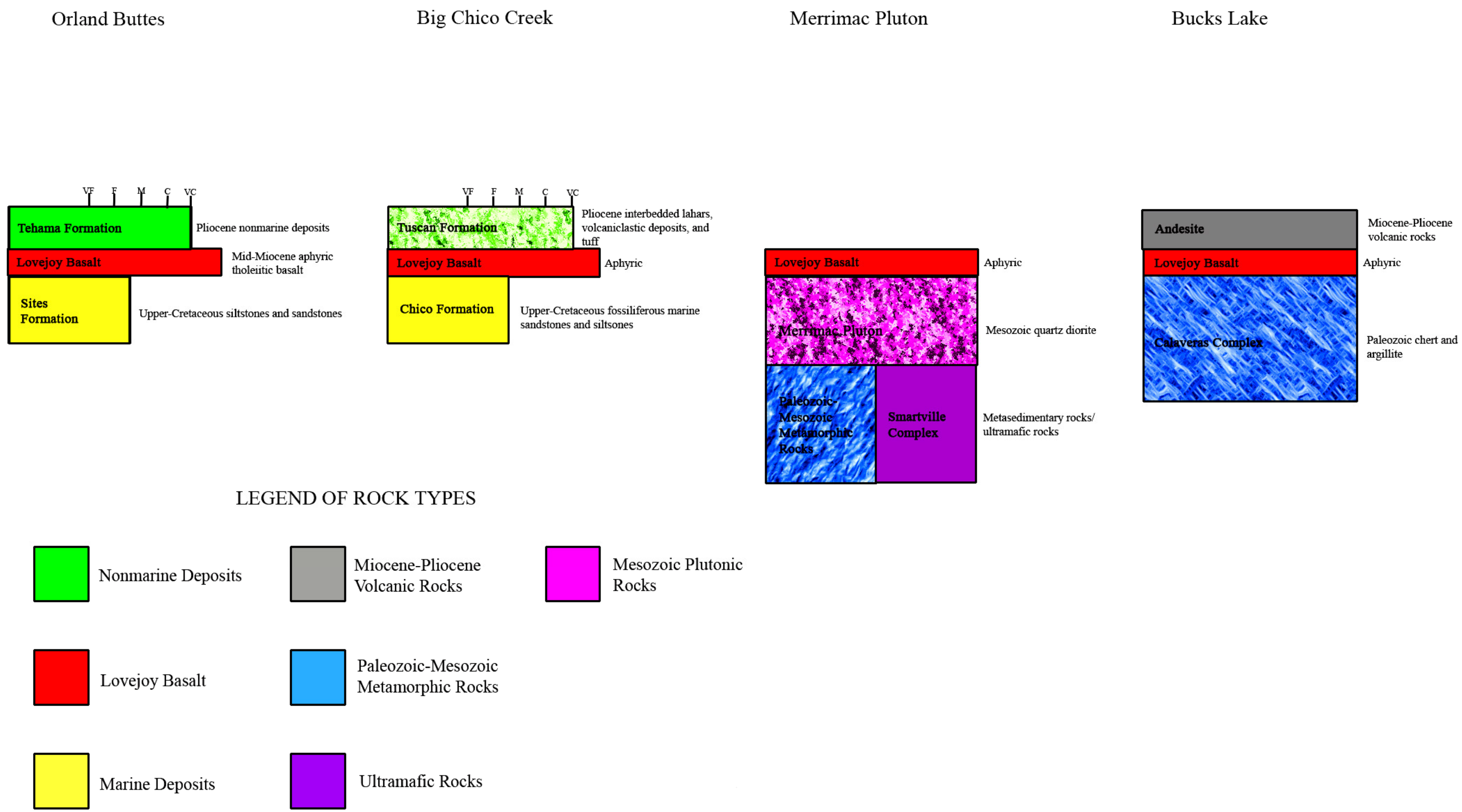


Figure 4. Hanging cross section (hung on the Lovejoy Basalt) showing stratigraphic relationships at each of the major Lovejoy Basalt localities between Orland Buttes and Bucks Lake. Note that thicknesses of rock units and distances between outcrops are not accurate. This diagram is meant only to show the rock formations which overlie and underlie the Lovejoy Basalt regionally, with emphasis on rock type.

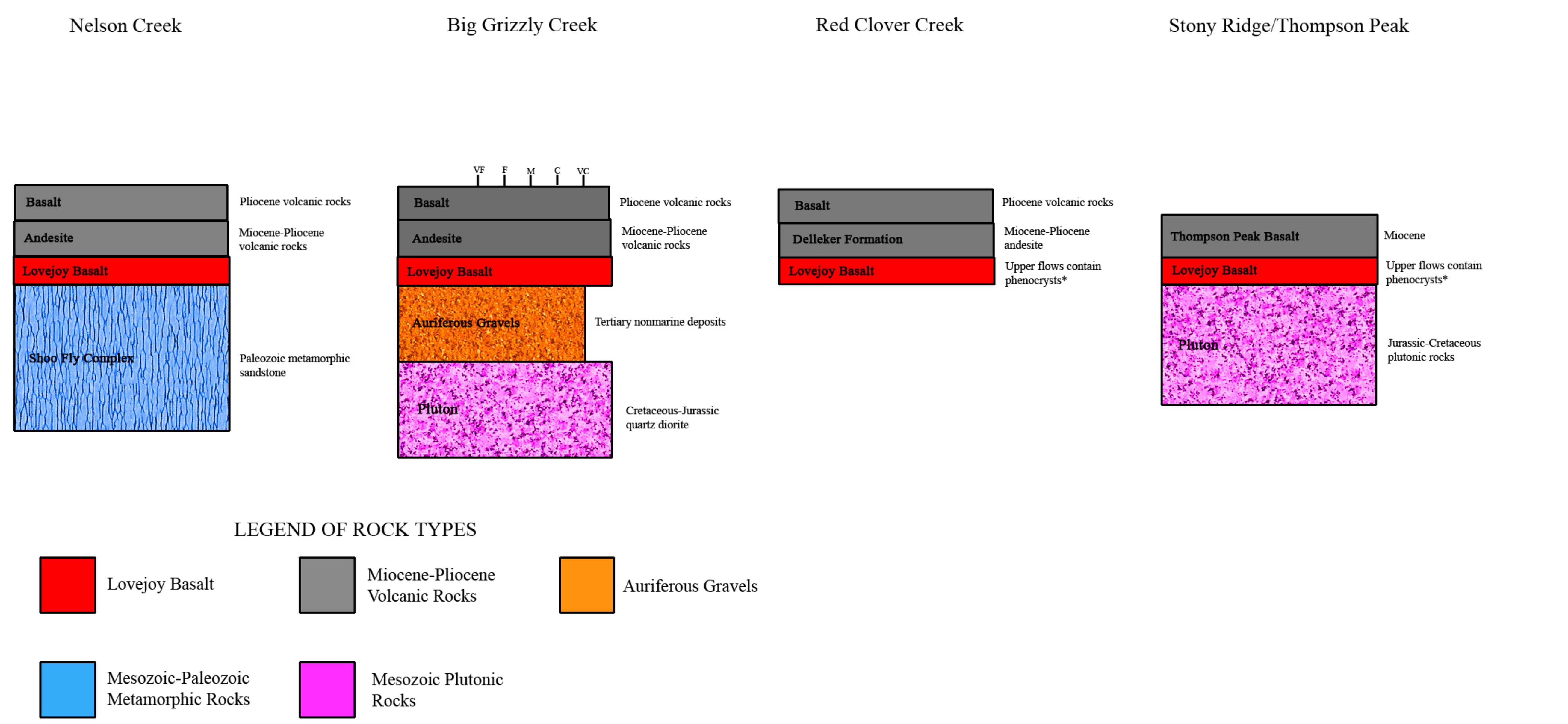


Figure 5. Continuation of the previous hanging cross section (hung on the Lovejoy Basalt) showing stratigraphic relationships at each of the major Lovejoy Basalt localities between Nelson Creek and Thompson Peak. Note that thicknesses of rock units and distances between outcrops are not accurate. This diagram is meant only to show the rock formations which overlie and underlie the Lovejoy Basalt regionally, with emphasis on rock type.

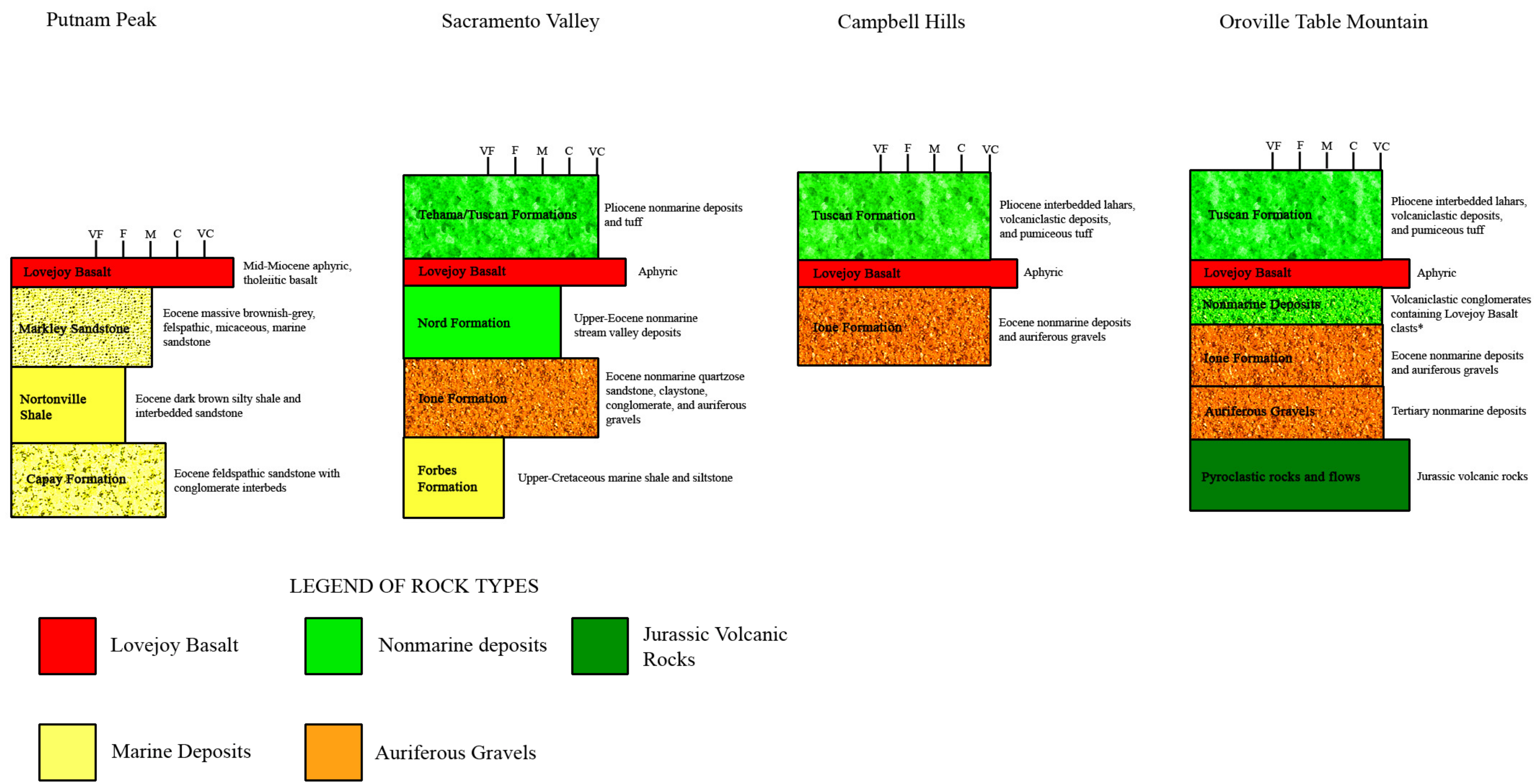


Figure 6. Hanging cross section (hung on the Lovejoy Basalt) showing stratigraphic relationships at each of the major Lovejoy Basalt localities between Putnam Peak and Oroville Table Mountain. Note that thicknesses of rock units and distances between outcrops are not accurate. This diagram is meant only to show the rock formations which overlie and underlie the Lovejoy Basalt regionally, with emphasis on rock type.

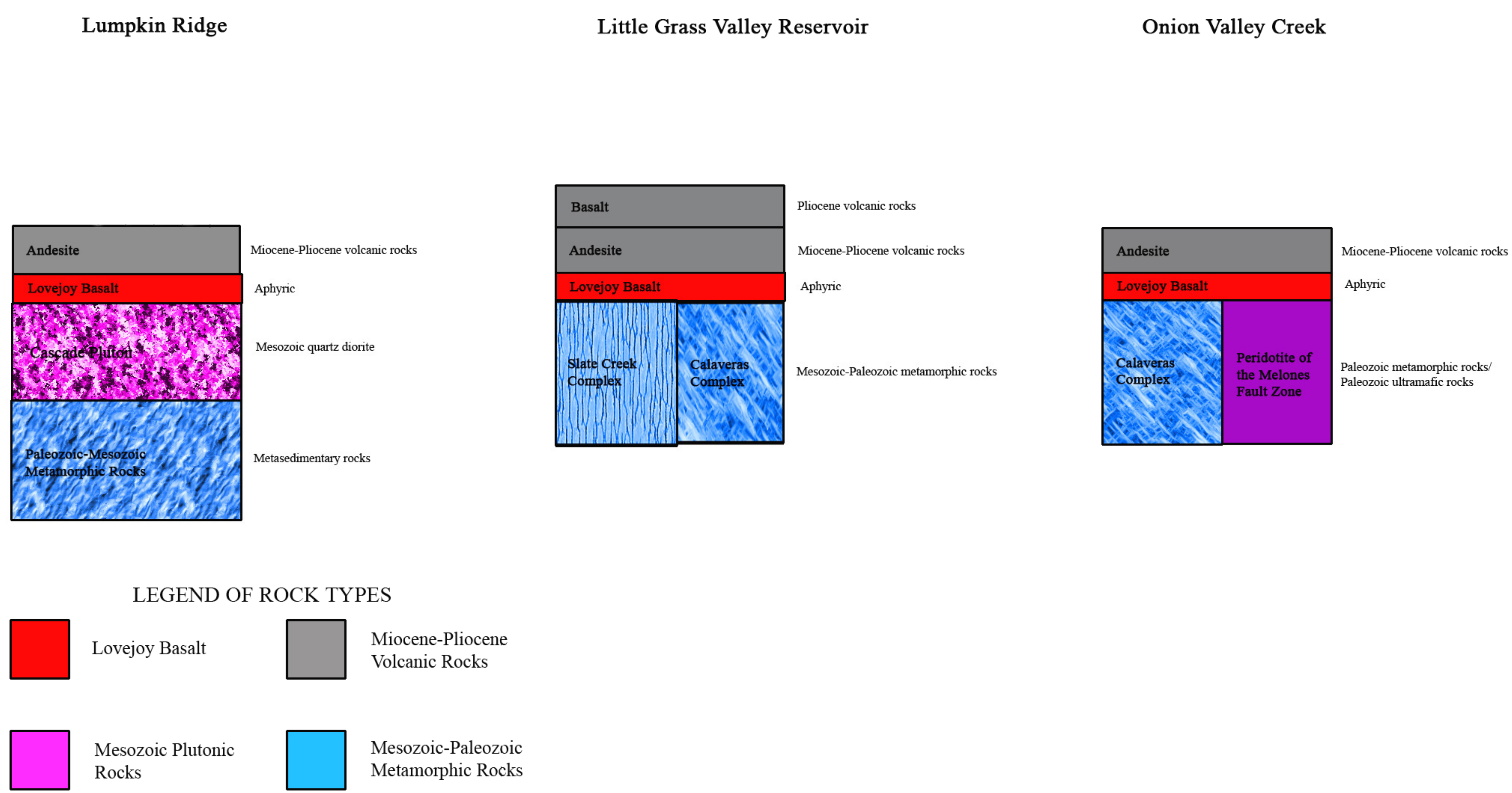


Figure 7. Continuation of the previous hanging cross section (hung on the Lovejoy Basalt) showing stratigraphic relationships at each of the major Lovejoy Basalt localities between Lumpkin Ridge and Onion Valley Creek. Note that thicknesses of rock units and distances between outcrops are not accurate. This diagram is meant only to show the rock formations which overlie and underlie the Lovejoy Basalt regionally, with emphasis on rock type.

CHAPTER III

METHODOLOGY

Field research was conducted with four primary goals in mind: physically locate the Lovejoy Basalt outcrops; measure their magnetic susceptibility; look for indications of flow direction; and attempt to find underlying rock units which have been preserved by the erosion-resistant cover of the Lovejoy Basalt. Although not every outcrop produced sufficient data to meet all of these goals, almost every outcrop provided some sort of information for this project.

Locating Outcrops

Even the seemingly trivial process of finding these sometimes small outcrops of basalt in the vast wilderness of the northern Sierra Nevada can be somewhat challenging. I began the task by examining current geologic maps of northern California, old folios, and a Master of Science Thesis by Maria Tobia (1997) showing approximate coordinates of known Lovejoy Basalt outcrops. From these, I determined which outcrops would likely be the most important to visit, based primarily on their spatial distribution. The goal was to obtain an encompassing perspective of the Lovejoy Basalt in hopes of seeing large-scale patterns, rather than focusing too much time on particular localities. However, because some localities have more information available at the surface than others, they are inevitably far more interesting and demanded a great deal more time.

To locate a particular outcrop, I used a combination of Terrain Navigator Pro (topographic map software produced by Maptech), Google Earth, and geologic maps to determine the best possible route. Many of the larger outcrops are covered with United States Forest Service (USFS) and California Forest Service (CFS) roads, making them relatively easy to access, but a great deal of the smaller outcrops (and some of the more significant parts of the larger ones) cannot be accessed by roads. For these I drove as closely as possible and then used a Garmin G.P.S. unit to hike directly to the outcrops, often through dense foliage and usually without any sign of a trail. Fortunately, due to its distinctive ridge-forming nature, it was rarely difficult to be certain I had found the outcrop I was seeking.

Magnetic Susceptibility

The magnetic susceptibility of a rock is a measurement of the intensity and/or direction of its induced magnetization when responding to an applied magnetic field. Ferromagnetic minerals, particularly magnetite, are known to be the primary cause of magnetic susceptibility in most volcanic and metamorphic rocks (Gromme, 1965; Lindsley, 1966; Godoy and Kato, 1990; Coe, 2005; Philpotts, 2007). It has been shown that less than 1% volumetric content of ferromagnetic minerals can be enough to dominate the bulk magnetic susceptibility of a rock (k_m) (Borradaile, 1988). The particular ferromagnetic minerals in the Lovejoy Basalt which are responsible for its high magnetic susceptibility are titanomagnetite and its oxidation product, titanomaghemite (Coe, 2005).

The Model MS2 Magnetic Susceptibility Meter produced by Bartington Instruments was used to measure the relative intensities of the magnetic susceptibility of widely distributed Lovejoy Basalt outcrops. The measurements were recorded in S.I. (International System of Units), which are, in this case, qualitative rather than quantitative values. These values are based on the equation $M=k_mH$, where k_m is the bulk magnetic susceptibility, M is the magnetization of the material (Amperes per meter), and H is the magnetic field strength (also Amperes per meter). Because these measurements are not calibrated to a standard, they represent only the relative intensities of magnetic susceptibility within the Lovejoy Basalt.

Variations in magnetic susceptibility, also known as the anisotropy of magnetic susceptibility (AMS), can be the result of several factors related to the orientation of minerals within the rock. In rocks in which k_m is dominated by ferromagnetic minerals, however, the orientation (although not necessarily the distribution) of the ferromagnetic minerals is mostly irrelevant due to crystals usually being isometric, resulting in a similar value regardless of the direction of measurement (Eduardo, 2005).

AMS studies are usually concerned with measuring the direction of the magnetic susceptibility in rocks to map patterns of petrologic texture, flow deformation, and flow direction, the latter of which has been and remains somewhat controversial due to multiple possible interpretations of the data (Eduardo, 2005).

Paleomagnetic studies involving remnant magnetism are concerned primarily with the magnetization of the rock while not under the influence of an externally applied magnetic field, so as to study the orientation of the regional magnetization of the earth during crystallization of the minerals composing the rock.

This study is concerned only with the variation of intensity of relative magnetic susceptibility due to variations in titanomagnetite, leaving out its directional aspect. Furthermore, the intent was not to obtain a quantitative analysis of the titanomagnetite content in the Lovejoy Basalt, but rather to assess patterns of depletion and/or variation within and between flows.

Following in the manner of Maria Tobia's preliminary magnetic susceptibility study of the Lovejoy Basalt (M.S. Thesis, 1997), the measurements suggest changes in the intensity of the bulk magnetic susceptibility of Lovejoy Basalt outcrops over relatively long distances throughout the Sierra Nevada. Heavy minerals, such as titanomagnetite, can settle out of suspension during the course of a lava flow (Best, 1982). Based on this fact and on the general assumption that the Lovejoy Basalt is thought to have been extruded from a single localized source area, it is possible that some of the titanomagnetite may have settled out along the course of its exceptionally long flow path. A systematic decrease in titanomagnetite content, and hence, magnetic susceptibility, with respect to distance from the vent area at Thompson Peak might be a further indicator of the likelihood that the Lovejoy Basalt was extruded from a single source in a relatively short period of time.

If, on the other hand, it turns out that there is no systematic decrease in titanomagnetite content with respect to distance from the vent area, variations in magnetic susceptibility might be explained in other ways. Variations in these values over significant distances may be the result of the stratigraphic nature of the Lovejoy Basalt in which individual lava flows contain varying concentrations and/or distributions of titanomagnetite, and hence, varying magnetic susceptibility.

At each location where I measured the magnetic susceptibility of a Lovejoy Basalt outcrop, I first attempted to find a flat surface in order to take the most accurate measurement. The device was first cleared of static magnetism by engaging it while holding it in the air. I recorded several measurements at each location, usually taken several feet apart. Table 1 shows all of the magnetic susceptibility measurements as well as control measurements of individual flows, generally taken at a single coordinate position. The three locations where I was able to isolate multiple separate flows for measurement were Red Clover Creek (the type locality), Stony Ridge, and Thompson Peak. Elsewhere it was difficult to visually distinguish multiple flows with certainty. Possible interpretations of this data will be presented later.

Indications of Flow Direction

It is generally assumed that the Lovejoy Basalt flowed toward the southwest from the vent at Thompson Peak approximately 140 miles to Putnam Peak near Lake Berryessa, behaving primarily as flood basalt. This could be due to the present slope and drainage of the western Sierra Nevada. After examining its entire span in greater detail, however, it is likely that significant deviations from this general flow direction may exist. Its flow path may have been more complex than previously imagined, and could have been diverted into multiple channels.

Data was collected during the course of this study that may be significant in determining the direction of flow of the Lovejoy Basalt at various locations throughout

Table 1. Table of Magnetic Susceptibility data taken from a wide distribution of Lovejoy Basalt outcrops in northern California.

G.P.S. coordinates of outcrop	Magnetic susceptibility (S.I.)	Average S.I.
N 38 30’ 47” W 122 02’ 58”	299, 293, 283, 129, 137	228
N 39 45’ 48.6” W 122 20’ 5.9”	74, 44, 78, 70, 100, 40	68
N 39 48’ 39.3” W 122 20’ 15.9”	104, 88, 92, 98	96
N 39 31’ 23.3” W 121 38’ 22.3”	156, 179, 182, 193, 203	183
N 39 35’ 38.7” W 121 33’ 9.3”	340, 320, 314, 270, 304, 270, 255,	294
N 39 50’ 16.4” W 121 46’ 19.2”	84, 85, 75, 104, 103	90
N 39 46’ 38.4” W 121 45’ 3.7”	138, 120, 113, 115, 132	124
N 39 48’ 21.7” W 121 43’ 42.4”	113, 120, 116, 111, 119, 115	116
N 39 50’ 20.4” W 121 42’ 14.6”	79, 84, 104, 92, 76, 128, 132, 103	100
N 39 40’ 48.91” W 121 29’ 14.64”	145, 168, 172, 350, 480, 363, 297,	N/A
	410, 210, 134, 177, 147, 121, 130,	
	130, 210, 224, 230, 134, 230, 175,	
	206, 130, 130, 469, 550, 383, 190	
N 39 35’ 17.8” W 121 09’ 20”	304, 310, 312, 292, 286, 307	302
N 39 36’ 08” W 121 08’ 50”	191, 167, 170, 205, 186	184
N 39 37’ 36.7” W 121 09’ 12”	258, 266, 263, 304, 304	279
N 39 44’ 20.7” W 121 01’ 20.78”	251, 317, 213, 301, 304	277
N 39 43’ 19.6” W 120 59’ 4”	181, 185, 192, 212	193
N 39 46’ 00” W 120 56’ 02”	514, 421, 489, 423 (plagioclase)	462
N 40 00’ 51.9” W 120 34’ 20.7”	1.) 640, 683, 635, 632, 644 (plagioclase)	647
	2.) 158, 132, 130, 161, 160 (olivine)	148
	3.) 128, 130, 119, 123, 137 (garnet)	127
	4.) 163, 190, 158, 182, 187 (olivine)	176
	5.) 115, 119, 122, 125, 129	122
	6.) 314, 323, 304, 319, 297	311
N 40 06’ 34.3” W 120 28’ 44”	104, 105, 119, 156	121
N 40 07’ 23” W 120 29’ 18.1”	335, 404, 289, 219 (plagioclase)	312
N 40 09’ 18.5” W 120 29’ 3.2”	1.) 122, 138, 135, 118 (plagioclase)	128
	2.) 220, 228, 235, 219 (garnet and olivine)	226
	3.) 128, 111, 113, 135 (garnet)	122
	4.) 112, 117, 125, 114, 123 (olivine)	118
	5.) 298, 310, 315, 287, 323	307
	6.) 176, 189, 154, 163	171
N 40 16’ 20.1” W 120 34’ 16.2”	138, 177, 146, 141	151
	409, 389, 423, 390 (scoria)	403
	177, 174, 209, 186 (vesicular)	187
N 40 16’ 17.3” W 120 34’ 17.2”	200, 228, 214	214
N 40 16’ 2.1” W 120 34’ 6.4”	206, 225, 231	221
N 40 15’ 57.3” W 120 33’ 59.3”	195, 171, 183	183
N 40 15’ 53.2” W 120 33’ 52.4”	251, 228, 232, 209 (plagioclase)	230
	519, 471, 508 (scoria)	499
N 40 10’ 9” W 120 22’ 20”	210, 194	202

Distinguishing physical characteristics of individual flows, described in more detail in chapter IV, are listed in parentheses.

the Sierra Nevada. It has long been noted (Creely, 1954; Durrell, 1959) that there are a series of linear ridges and swales on the surface of Table Mountain just north of Oroville, Ca. In the field, these ridges appear several meters wide by several meters tall and can extend hundreds of meters in length, almost always paralleled by an associated swale. In places where these topographic features are less pronounced, one can still see foliage patterns paralleling these structures, in which the plant life has taken root in the linear depressions, leaving the linear ridges bare.

These linear features could be the remnants of large-scale pressure ridges (Garrison, 2008). They might also represent joints or inflation fractures formed by pressure within the lava while it was in motion (Creely, 1965; Schaefer, 2001). Whatever caused them, they appear not to be merely superficial features, but associated with deep fractures that extend through large sections of the basalt. This has been observed previously (Creely, 1965) and can be confirmed both by observation of Google Earth images as well as directly in the field at Oroville Table Mountain and Black Butte Reservoir by following the depressions to the edge of the cliff where they connect to steep gullies resembling inflation fractures (Schaefer, 2001). Large blocks at Table Mountain are detached along these fractures and often rest as mega-landslide blocks on the erosional surface (Fig. 8).

This alone would not necessarily be enough evidence to associate the fractures with the direction of flow, but pipe vesicles, tube vesicles, stretched vesicles, and linear flow grooves on the basal surface of the Lovejoy Basalt at Oroville Table Mountain were located during this study. The orientations of these linear features are approximately perpendicular to the orientations of the linear ridges, swales, and vertical joints found directly above. The assumption that this relationship could be true elsewhere is what prompted me to collect the flow direction data presented in the following chapters.

Figure 8. Mega-landslide blocks on the erosional surface below steep Lovejoy Basalt cliffs at Oroville Table Mountain. These blocks stand testament to the extreme mechanical erosion which is likely responsible for removing much of the basalt since its emplacement. The large columnar basalt block in the foreground is approximately 25 feet long.

On aerial photos of the area, the lineated surface is particularly visible and easy to measure. Google Earth images were used to measure the orientations of these features on Oroville Table Mountain, Campbell Hills to the southwest, and Black Butte Reservoir across the valley to the west. There is no apparent correlation between the orientations of these features and orientations of faults and/or flexure associated with the Chico Monocline.

Most of the remaining Lovejoy Basalt outcrops are covered with dense foliage, rendering the ability to discern these linear patterns with aerial photos ineffective. However, very similar ridges, swales, and/or preferential vertical fractures were measured in the field, showing orientations that approximately correspond with the predicted flow direction. Occasionally stretched vesicles were found. Because stretched vesicles are known to be an indication of flow direction in which the direction of elongation of the vesicles parallels the direction of flow of the lava, finding these present a direct check on the local flow direction (Bagdassarov and Pinkerton, 2004).

It should be noted that the flow directions measured do not necessarily represent the exact original flow directions when it was erupted during the mid-Miocene. Since that time, the Lovejoy Basalt has undergone some minor tectonic deformation (Page, 1995; Wakabayashi, 2000), which may have locally offset the true orientations of the original flow directions.

Mid-Miocene Paleo-topography

Oroville Table Mountain is well-known for its inverted topography, wherein the Lovejoy Basalt capping the ridge, now the highest topography in the area, once represented the lowest topography in the area during its flow emplacement. After millions of years of erosion, outcrops of Lovejoy Basalt, such as Table Mountain, remain as isolated topographic highs where the surrounding rock units have been removed, resulting in characteristic inverted topography.

Directly underlying the Lovejoy Basalt at Oroville Table Mountain are the rounded, auriferous gravels of the Eocene Ione Formation. Locally, this formation remains only directly underneath the protective cap of Lovejoy Basalt where it is preserved by its resistance to erosion. I attempted to examine places where I could study the rock units directly underlying the Lovejoy Basalt in an attempt to better understand the isochronous surface which existed during the mid-Miocene. The hope was that documenting the rock units directly underlying the Lovejoy Basalt (rock units which often do not have enough surface expression to be mappable on geologic maps) might result in a further understanding not only of the nature of the geology and topography that existed at the time of its emplacement, but also of the morphology of the extrusion, particularly, the extent and distribution of channelization.

Unfortunately, in most places, the basal contact of the Lovejoy Basalt is covered with thick talus slopes from the blocks and debris mechanically eroded from steep cliffs, making it very difficult to study the underlying rock units. Because of this, the extent of Eocene sedimentary deposits will likely remain uncertain. Similarly, paleosols were never observed to underlie the Lovejoy Basalt, though they likely exist and have since been covered by talus. There are some places, however, particularly waterfall areas, where the eroded material is removed by the water such that the basal contact is well-exposed. At these locations I was able to closely examine the underlying unit which had been effectively undermined.

CHAPTER IV

FIELD SITE INVESTIGATIONS

Due to the extensive distribution of the Lovejoy Basalt, field work took me across four major geologic provinces: the California Coast Range, the Great Valley, the Sierra Nevada, and the Basin and Range. While the basalt changes only slightly across this great expanse, the terrain and foliage vary dramatically from oak-covered grassy foothills to steep canyons in evergreen forests. At times, finding a particular outcrop of the basalt was as simple as following a public road directly to it, while at other times I followed no path at all through thick growths of trees and bushes that obviously had not been touched by humans for many years. What follows is a compilation of the geologic observations I made during these journeys, excluding magnetic susceptibility measurements (Table 1).

Lake Berryessa

It is difficult to obtain permission to observe the Lovejoy Basalt that crops out on the privately owned Putnam Peak, but the alternative is to examine the edge of a small outcrop a few miles to the northwest along the road leading into Lake Berryessa. Shortly before the dam, large displaced blocks of Lovejoy Basalt can be seen lying on the sides of the road. In all ways it appears similar to aphyric, columnar, Lovejoy Basalt found elsewhere. The basalt does appear to crop out further up the hill but it is on private property. Samples were collected for X-Ray Fluorescence analysis and magnetic susceptibility measurements.

Orland Buttes

The Orland Buttes are prominent ridges composed of Lovejoy Basalt which flank the eastern side of Black Butte Reservoir approximately 30 miles due west of Chico. The ridges were once connected along a strike of approximately 170^o but are now separated into three segments, the longest of which is approximately 2 miles in length.

Underlying the Lovejoy Basalt at this locality are upper Cretaceous marine deposits of the Sites Formation (Haggart, 1984) which have an approximate strike/dip of 355^o, 21^o (Fig. 9). The rocks are arranged in distinctive, thin-bedded shale and siltstone layers, each usually a few inches thick. Some layers contain abundant concretions ranging in size from a few centimeters to several inches in diameter, and other zones were composed of alternating layers of oxidized and non-oxidized layers. These sedimentary rocks are correlative with the Cretaceous marine sedimentary rocks of the Chico Formation which directly underlie the Lovejoy Basalt in the Big Chico Creek area.

Unlike many Lovejoy Basalt outcrops, the surfaces of the ridges here have been eroded into a somewhat undulating topography, making it difficult to determine the dip direction of the basalt. There were a few steep, wedge-shaped gullies along the edges of the northernmost outcrop which connected to linear protrusions and depressions with an average approximate orientation of NE-SW.

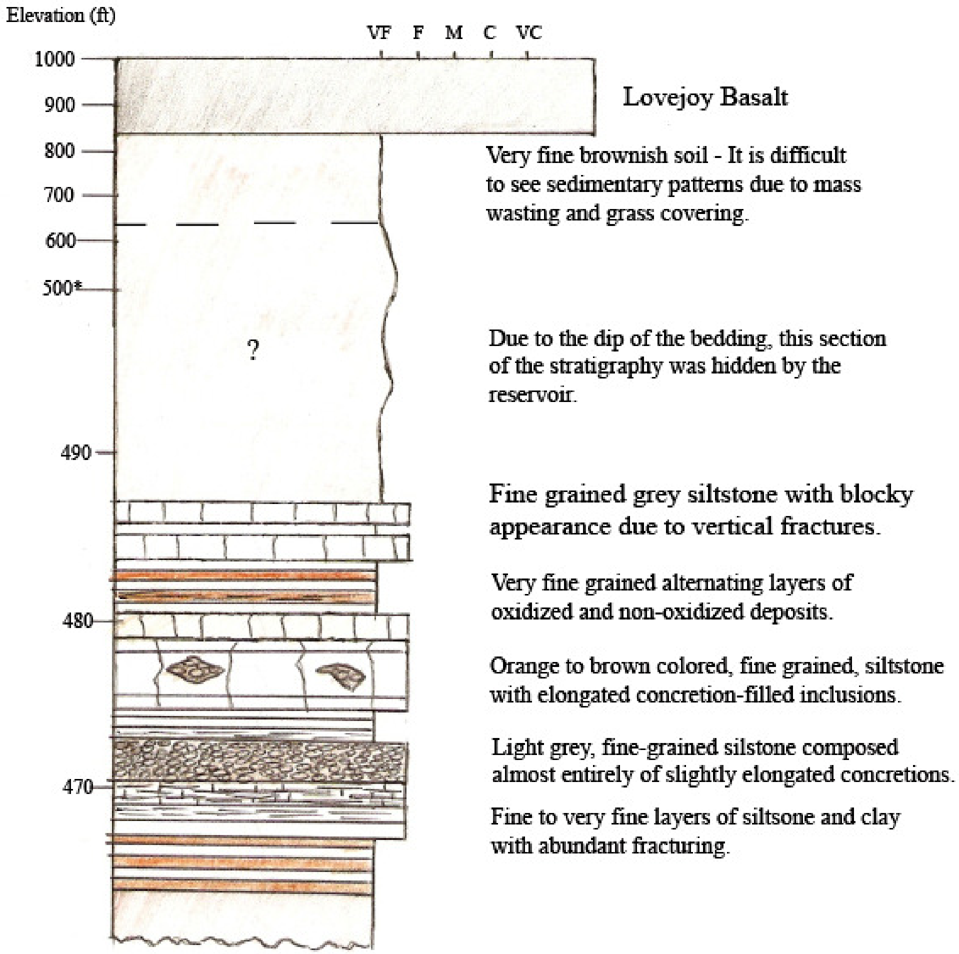


Figure 9. Columnar section showing Cretaceous rocks of the Sites Formation underlying Lovejoy Basalt at the Orland Buttes. *Note the vertical scale change at 500 feet in elevation.

Campbell Hills

Approximately 3 miles southwest of south Oroville Table Mountain are a series of small outcrops of Lovejoy Basalt known as the Campbell Hills which appear to have once been continuous with the Oroville Table Mountain flows. Unfortunately, the *in situ* basalt is all on private property, but about 30 meters below one of the outcrops is a small pit dug into the side of the hill, revealing a conglomerate unit (Fig. 10).

Figure 10. Small pit of unknown purpose exposing volcaniclastic conglomerates at Campbell Hills. Though the conglomerates appear to underlie the Lovejoy Basalt (seen on the horizon line), closer inspection shows that a buttress unconformity in which the conglomerates stratigraphically overlie the Lovejoy Basalt is more likely. The pit is approximately 10 feet wide.

Approaching the pit, there are numerous Lovejoy Basalt clasts on the surface, some of which are fresh and angular and some of which are sub-rounded and heavily oxidized. The pit provided an excellent look at the sedimentary units which, at first glance, appeared to underlie the outcrop of Lovejoy Basalt on the top of the hill (Fig. 11).

The bulk of the outcrop in the pit is composed of a semi-consolidated volcaniclastic conglomerate containing what appear to be exclusively rounded to sub-rounded, heavily oxidized Lovejoy Basalt clasts ranging in size from a few centimeters to several inches across. They are supported by a buff-colored matrix of fine-grained,

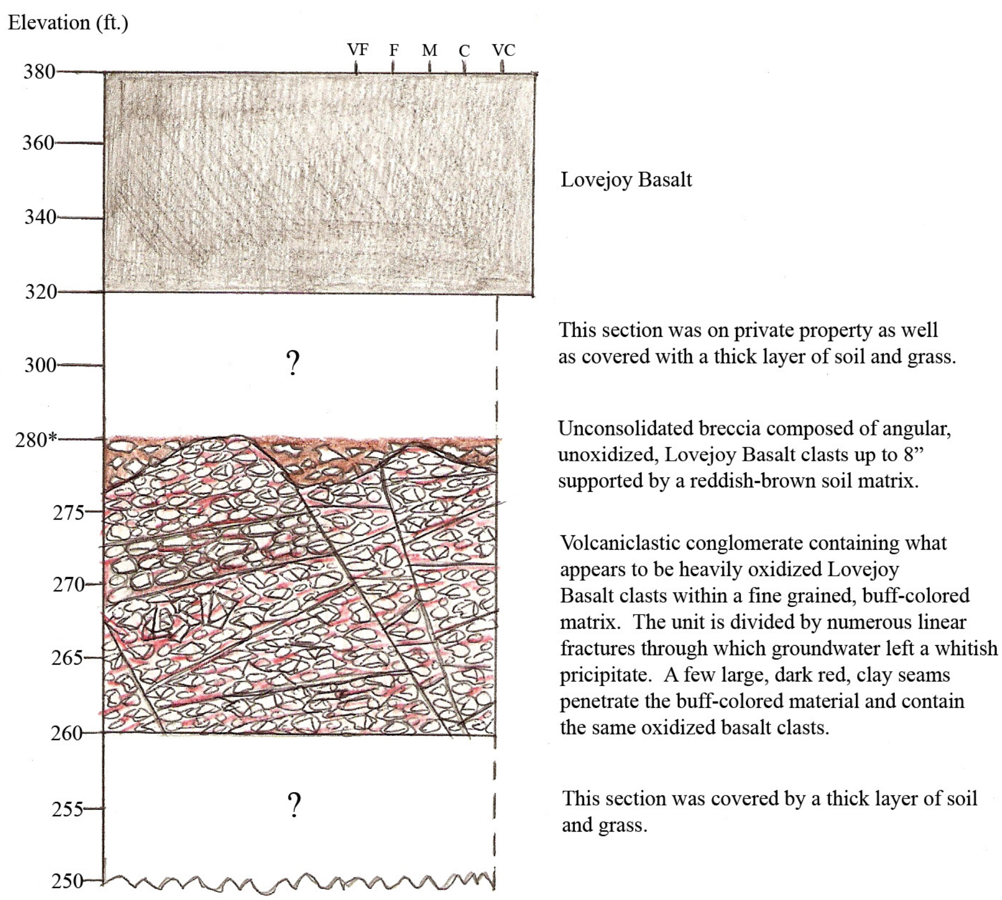


Figure 11. Columnar section showing the elevations of the rock units found at Campbell Hills. Although the conglomerates appear to underlie the Lovejoy Basalt, closer inspection reveals that a buttress unconformity, in which the conglomerates stratigraphically overlie the Lovejoy Basalt, is more likely. *Note the vertical scale change at 280 feet in elevation.

whitish sand and clay. The unit is divided into multiple sections by numerous, irregular fractures, most of which seem to be horizontal, but a few of which are sub-vertical. The fractures are marked by a very fine-grained white mineral which might be a precipitate from groundwater circulating through the fractures. There a few thin, red, clay veins penetrating the unit, some of which are a few feet in width and all of which contain the same oxidized basalt clasts.

The basalt clasts, which appear brown and rounded on the outside, show fresh, dark, sub-angular, aphyric basalt when cracked open (Fig. 12). Most of the oxidation layers around the clasts are a few centimeters thick but a few of the smaller clasts have been oxidized to the point where no fresh basalt remains within. This is a testament to the Lovejoy Basalt having been significantly weathered by chemical alteration due to circulation of groundwater. Chemical alteration undoubtedly assists the mechanical processes which are thought to be largely responsible for removing large pieces of the basalt along fractures near the flow's edge.

Figure 12. Decomposed, sub-angular basalt clasts in the conglomerate at Campbell Hills.

The semi-consolidated conglomerate is overlain unconformably by another volcaniclastic conglomerate unit which is completely unconsolidated. The contact between them is somewhat disorderly, perhaps indicating an erosional surface. Its fine-grained, dark red to brown matrix contains sub-angular basalt clasts of a similar size range which have the same general appearance as the ones found below except for a complete lack of concentric oxidation bands. The primary difference between the two is that the lower unit seems to have been subjected to groundwater circulation for considerably longer.

Keeping in mind that it is usually the softer, underlying sedimentary units which are eroded first, it is unlikely that these volcaniclastic conglomerates are truly underlying the Lovejoy Basalt stratigraphically at this locality. Rather, they are ancient talus slopes shed from local Lovejoy Basalt outcrops and buttressed against the side of a typical, steep Lovejoy Basalt cliff face (Fig. 13). Evidence to support this is the fact that the fresh parts of the clasts are sub-angular to angular, the externally sub-rounded appearance having been caused by chemical weathering. If the clasts did not come from the immediately adjacent cliff, then this area could represent an ancient channel edge where coarse sediments accumulated.

Oroville Table Mountain

Perhaps the most conspicuous Lovejoy Basalt outcrop is Oroville Table Mountain, located approximately 5 miles north of the town of Oroville, Ca. The somewhat irregular shaped mesa is divided into two main sections known as North Table Mountain and South Table Mountain.

The northern outcrop is by far the larger, spanning approximately 5 miles in a N-S direction and 3 miles in an E-W direction. South Table Mountain is only about one mile by one and a half miles in dimension but displays striking columnar jointing.

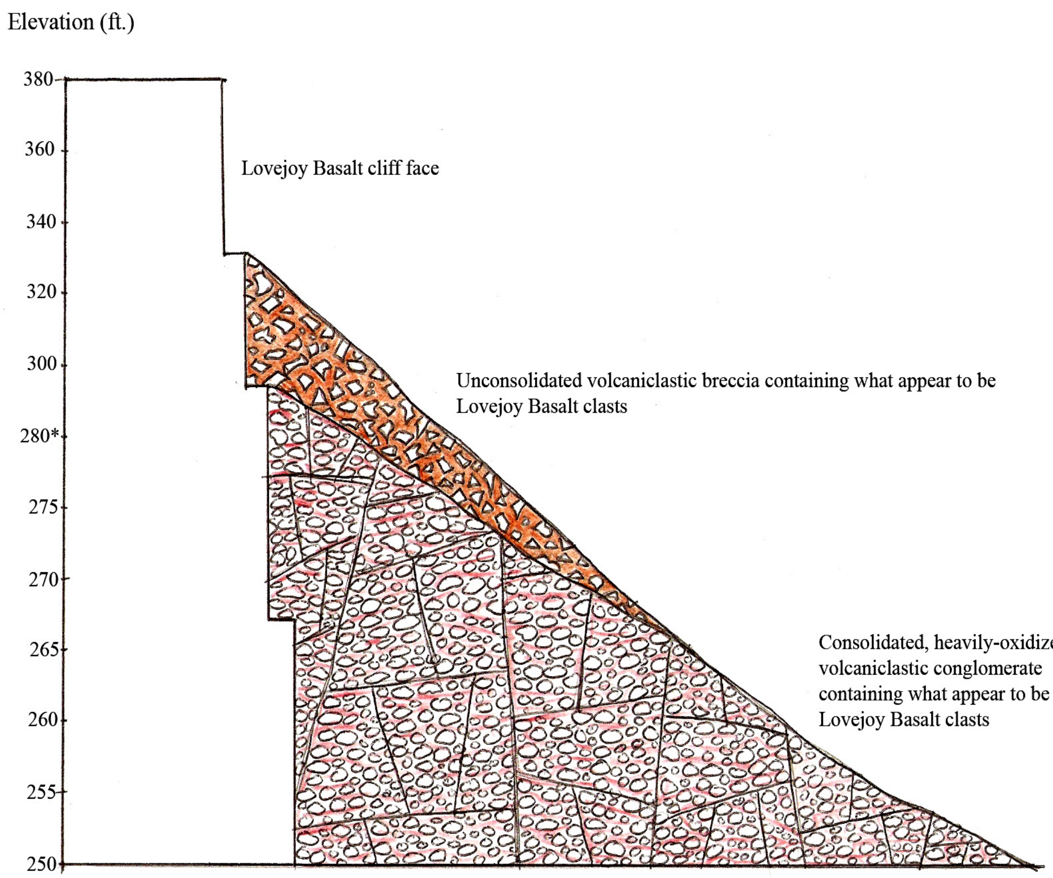


Figure 13. Diagram showing the buttress unconformity between the Lovejoy Basalt and the stratigraphically overlying volcaniclastic conglomerates at Campbell Hills. *Note the vertical scale change at 280 feet in elevation.

Individual columns and hence, individual flows, reach heights of over 220 feet at this location, possibly because this is where the lava was ponded as it poured into the ancestral Sacramento Valley (Garrison, 2004).

The surface of Oroville Table Mountain is covered with a series of linear protrusions and depressions a few meters high and sometimes up to 4 miles long. It has been said that these linear features have no correlation to visible jointing or fracture patterns (Garrison, 2004), but after following a few of them to the edge of the outcrop it appears that they are connected to vertical fractures that extend all the way through the flow. This relationship can also be observed using Google Earth, as will be discussed later.

Oroville Table Mountain is probably the best locality to examine the erosive mechanisms which have been removing the basalt over the last 14 million years. When walking in the canyons and gullies below the flow it is not uncommon to see huge displaced sections of columnar basalt which have fallen from the outcrop above (Fig. 8). These large blocks, which sometimes look like the ruins of an ancient city, are testaments to the extreme manner in which the Lovejoy Basalt is eroded.

What makes this type of erosion possible is the undercutting of much softer sedimentary rocks which underlie the Lovejoy Basalt. This undercutting is most prominent at waterfall areas along the western side of Oroville Table Mountain in which the water readily transports the sedimentary rocks and chemically decomposed Lovejoy Basalt downstream away from the outcrop (Fig. 2). Consequently, these areas are the best to examine the underlying sedimentary rocks as well as the nature of the contact and basal surface of the Lovejoy Basalt.

Shallow Overhang South of Phantom Falls

Phantom Falls, the largest of the undermined areas on Oroville Table Mountain, is located at the end of Coal Canyon. South of the main falls in a small stream gully approximately 60 feet below the basal contact of the Lovejoy Basalt is an exposed section of sedimentary rocks (Fig. 14). Among these units is a distinctive light brown, well-sorted, medium-grained, cross-bedded sandstone, likely derived from a granitic source (Fig. 15). Strike and dips of the unit were taken on dip slopes, yielding measurements of 193^{o}, 05^{o} and 206^{o}, 05^{o}. Along the same gully, twenty feet higher in the section, is another exposure of what appears to be the same sandstone unit unconformably contacting an unconsolidated conglomerate (Fig. 16).

The conglomerate appears to be composed of two different units which may have been mixed together by slumping and small landslides. The older, more consolidated unit which stratigraphically underlies the Lovejoy Basalt is generally clast-supported and is made up of volcanic, metamorphic, and quartz pebbles up to a foot in diameter. The unconformably overlying unit, composed of angular fragments of columnar Lovejoy Basalt up to several feet long in a dark brown soil matrix, is actually the relatively fresh talus pile which has recently accumulated below the main outcrop.

At the base of the Lovejoy Basalt is a shallow overhang extending underneath the basalt at least 30 or 40 feet (Fig. 17). At the back of the cave is a visible contact between the basalt and the underlying sandstone (Fig. 18). The basalt dips 2-3 degrees in an approximately westward direction. Fragments of what appears to be Lovejoy Basalt are incorporated into the fine to medium-grained reddish-brown sandstone.

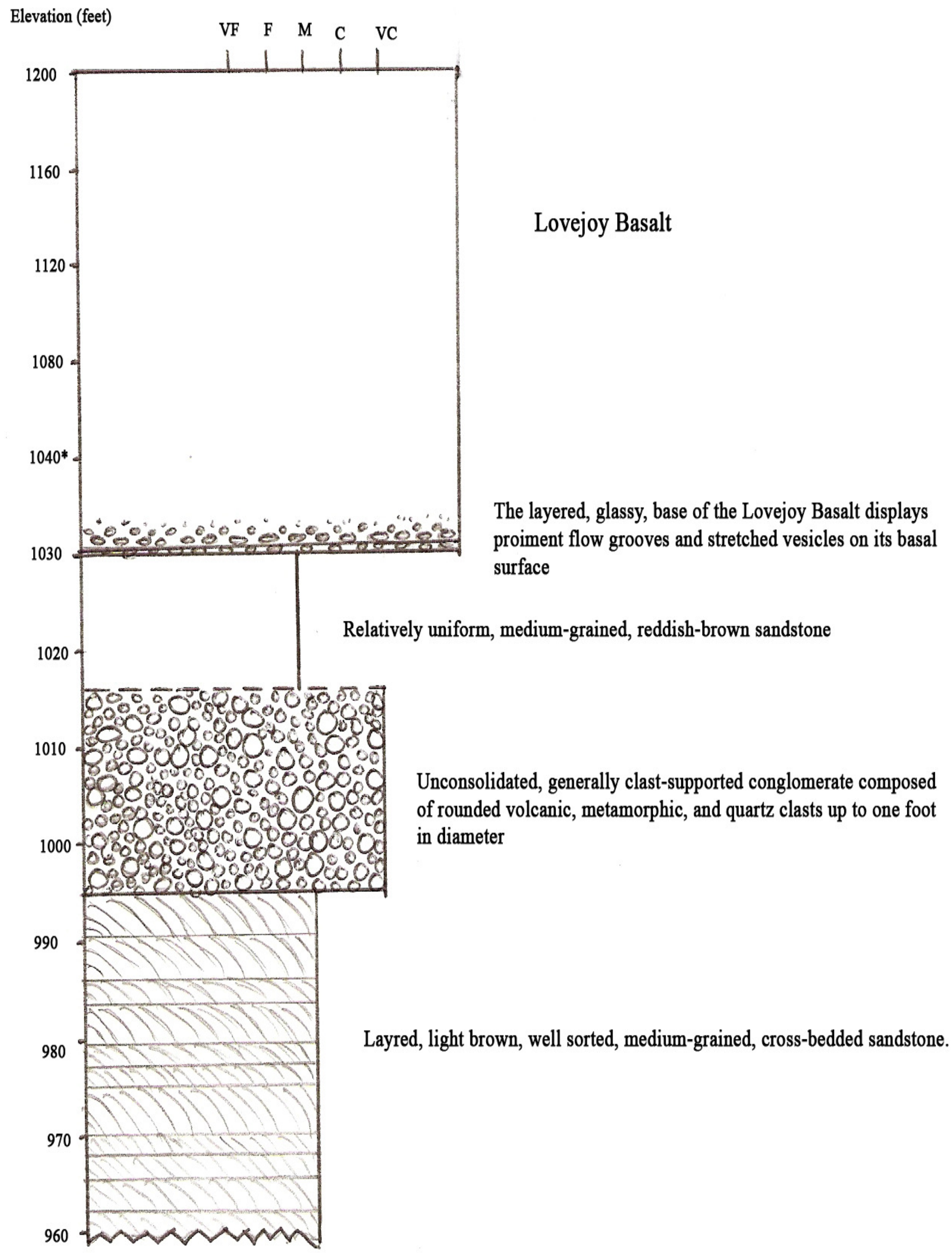


Figure 14. Columnar section showing the Lovejoy Basalt and underlying rock units south of Phantom Falls at Oroville Table Mountain. *Note the vertical scale change at 1040 feet in elevation.

Figure 15. Cross-bedded sandstone underlying the Lovejoy Basalt near Phantom Falls at Oroville Table Mountain.

The sandstone appears mostly uniform, displaying none of the cross-bedding found below, but there are a few horizontal lines which may be surficial oxidation lines left by high water levels. The Lovejoy Basalt is glassier than usual near the contact and is also stratified into multiple flow layers with abundant vesicles, but only for a few inches upwards from the contact.

The contact surface of the Lovejoy Basalt hangs many feet outward from the contact, allowing a rare and valuable look at the base of the flow. The basal surface is covered with linear grooves and large stretched vesicles up to 8 inches long, all of which are oriented in a similar NW direction (Fig. 19), approximately perpendicular to the orientation of the linear features found on the upper surface of the basalt. While most of

Figure 16. Contact between mixed conglomerate and cross-bedded sandstone near Phantom Falls. The largest clast in the photograph is approximately 4 inches in diameter.

the vesicles have been filled in by a fine, reddish-orange iron oxide material, a few have been filled by calcite, probably from circulating groundwater. Also present are large botryoidal calcite clusters up to several inches in diameter clinging to the basalt along small fractures.

Large Overhang at Phantom Falls

A few hundred feet north, at the main cave below Phantom Falls, is an even larger exposure of the basal surface of the basalt as well as the underlying sedimentary units. A section of sedimentary rocks approximately 80 feet thick is visible, including the section inside a hand-dug pit of unknown purpose near the bottom which, if the engravings on the wall are accurate, date back to at least 1930 (Figs. 20 and 21).

Figure 17. Shallow overhang exposing the basal surface of the Lovejoy Basalt south of Phantom Falls at Oroville Table Mountain. The direct contact between the basalt and underlying mudstone can be observed. The entrance to the cave is approximately 4 feet high.

The lowest unit in the section, visible only from the inside of the pit, is a light-brown, fine-grained, muddy sandstone with orange-yellow, lens-shaped masses of oxidized sandstone lined with a thin layer of dark brown mud. The thickness of this unit was undeterminable because the base is not exposed.

Overlying the muddy sandstone is a 35 foot section of poorly-sorted, upward-fining, matrix-supported, conglomerate composed of approximately 90% basalt clasts and 10% metamorphic and quartz clasts. At the base of the flow is what appears to be an ancient channel-fill where a U-shaped area was filled in with similar conglomerate

Figure 18. Contact between the Lovejoy Basalt and underlying sedimentary rocks near Phantom Falls.

material that fines upwards more dramatically than the surrounding material. Towards the top of the unit are multiple medium to coarse-grained sandstone lenses up to several feet in length.

Overlying this conglomerate unit is a 10 foot thick section of medium-grained, whitish sandstone containing a small percentage of biotite. Within this unit is a layer about three feet thick composed of darker, finer grained sandstone containing abundant shell-shaped inclusions which may be fossil remnants (Fig. 22).

Figure 19. Westward oriented stretched vesicles on the basal surface of the Lovejoy Basalt at Oroville Table Mountain. The largest stretched vesicle in the photograph is approximately 4 inches long.

The highest unit in the section, which contacts the basal surface of the Lovejoy Basalt, is a light-grey, layered, mudstone with vertical cracks. There is some evidence of baking near the top where the unit takes on a slightly reddish color.

The contact between this unit and the overlying basalt is fairly uniform, although it is undulatory in places where what appear to be either small pahoehoe ropes or flow grooves line the basal surface (Fig. 23). They might also be remnants of pipe vesicles.

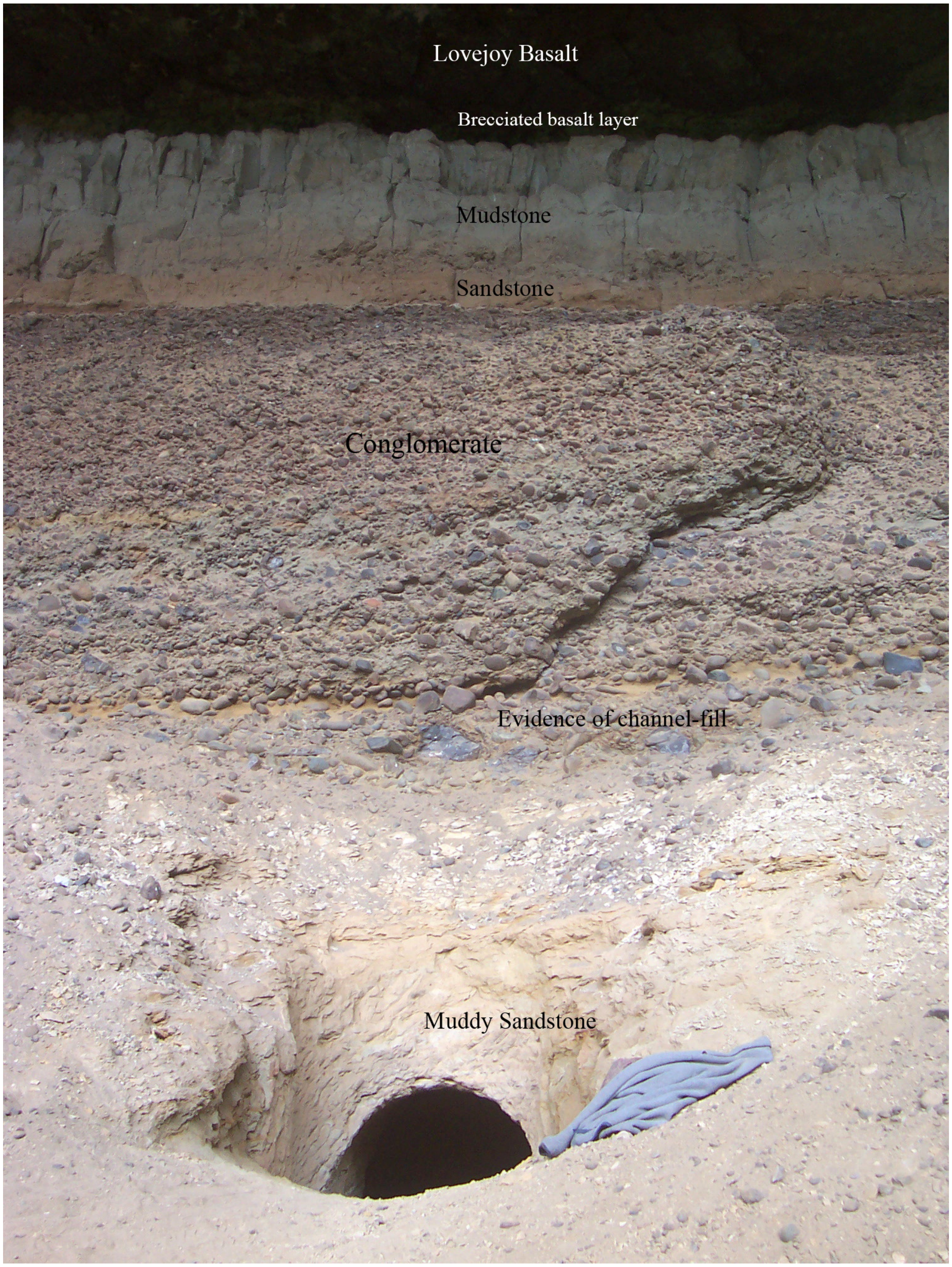


Figure 20. Large section of sedimentary rocks exposed under a Lovejoy Basalt overhang at Oroville Table Mountain. The pit provides a look at reddish sandstone beds beneath the conglomerate that normally would not be visible.

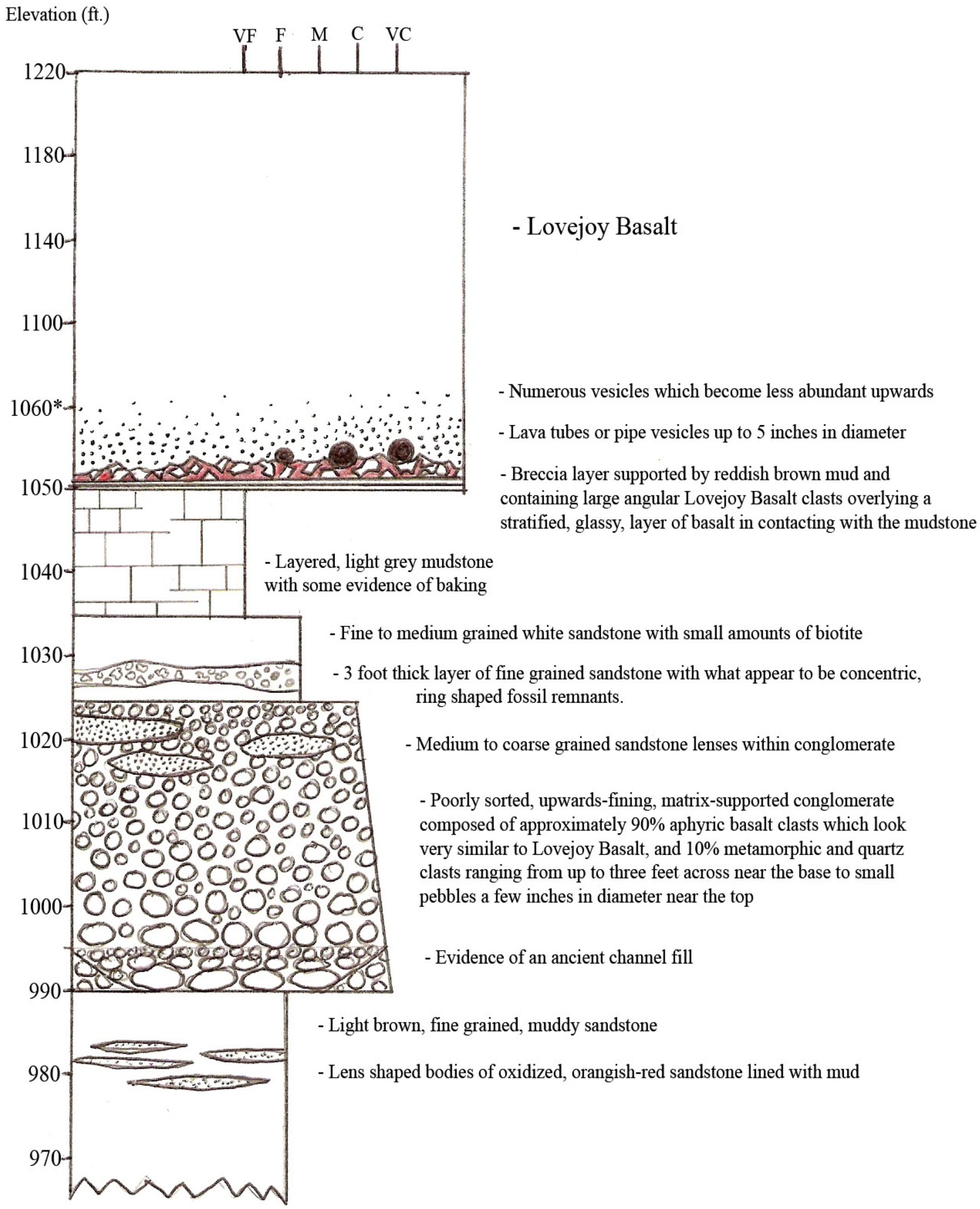


Figure 21. Columnar section showing the sedimentary units which underlie the Lovejoy Basalt at Phantom Falls. *Note the vertical scale change at 1060 feet in elevation.

Figure 22. Possible fossil remnants in a sandstone layer underlying the Lovejoy Basalt at Phantom Falls.

Immediately above this contact is a stratified layer of basalt a few inches thick which appears unusually glassy in texture. Directly above this layer is a breccia layer which varies in thickness between a few inches and about 3 feet. The breccia contains exclusively angular Lovejoy Basalt clasts supported in a very fine-grained reddish brown matrix. Above the breccia is a typical, thick section of Lovejoy Basalt. All three units, the stratified glassy layer, the breccia layer, and the typical Lovejoy Basalt, appear continuous.

A thin layer of glassy basalt with might be pahoehoe ropes was deposited first, followed by a mud flow, and capped with a thick flow of basalt. At certain locations along the contact, both the stratified layer and the brecciated layer do not appear in the sequence.

Figure 23. Undulatory flow grooves or pipe vesicle remnants along the basal surface of Lovejoy Basalt at Phantom Falls. This large block which fell from the ceiling measures over 5 feet along the indentation.

Numerous flow indicators are visible on the basal surface and in the contact zone at this location, including stretched vesicles, tube vesicles, linear grooves, and most strikingly, large pipe vesicles up to 5 inches in diameter (Fig. 24). Most of these pipe vesicles are located directly above the brecciated layer but at least a few of them appear to actually reside within the brecciated layer. They resemble small lava tubes except they terminate internally after several feet. Their orientations indicate flow directions ranging from due westward to slightly south of west and all of the other flow indicators had orientations which ranged from due westward to slightly north of west, making west the

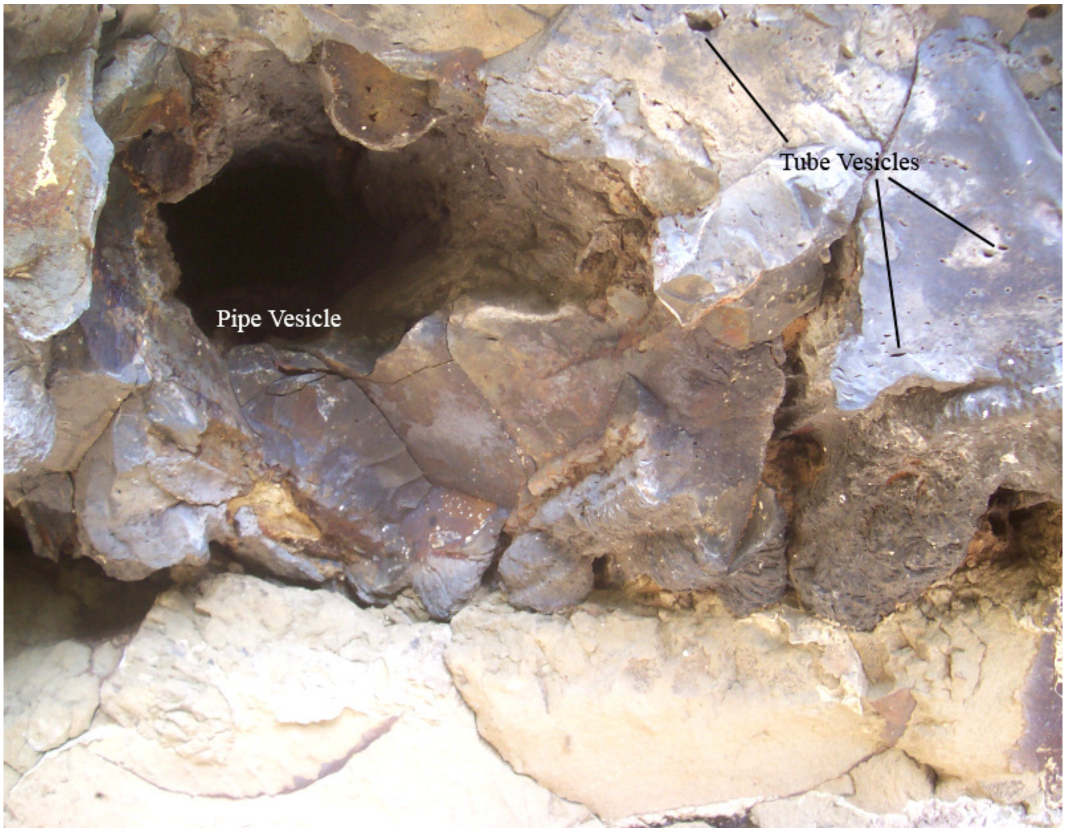


Figure 24. Large pipe vesicle approximately 4 inches in diameter.

average orientation of all the flow indicators. A detailed discussion of this is presented in Chapter IV.

Beatson Falls

About a mile west of what is known as 'the hollow' on top of Oroville Table Mountain is another large waterfall area called Beatson Falls. Due to the accumulation of piles of basalt clasts mechanically eroded from the cliff above, the underlying sedimentary units, and hence, the basal surface of the Lovejoy Basalt, are concealed here. A small opening at the base of one of the piles, however, reveals the collapsed entrance to a cave not unlike the one found south of Phantom Falls, though significantly smaller. At the back of the cave is a section of sedimentary rocks which directly underlie the Lovejoy Basalt (Fig. 25).

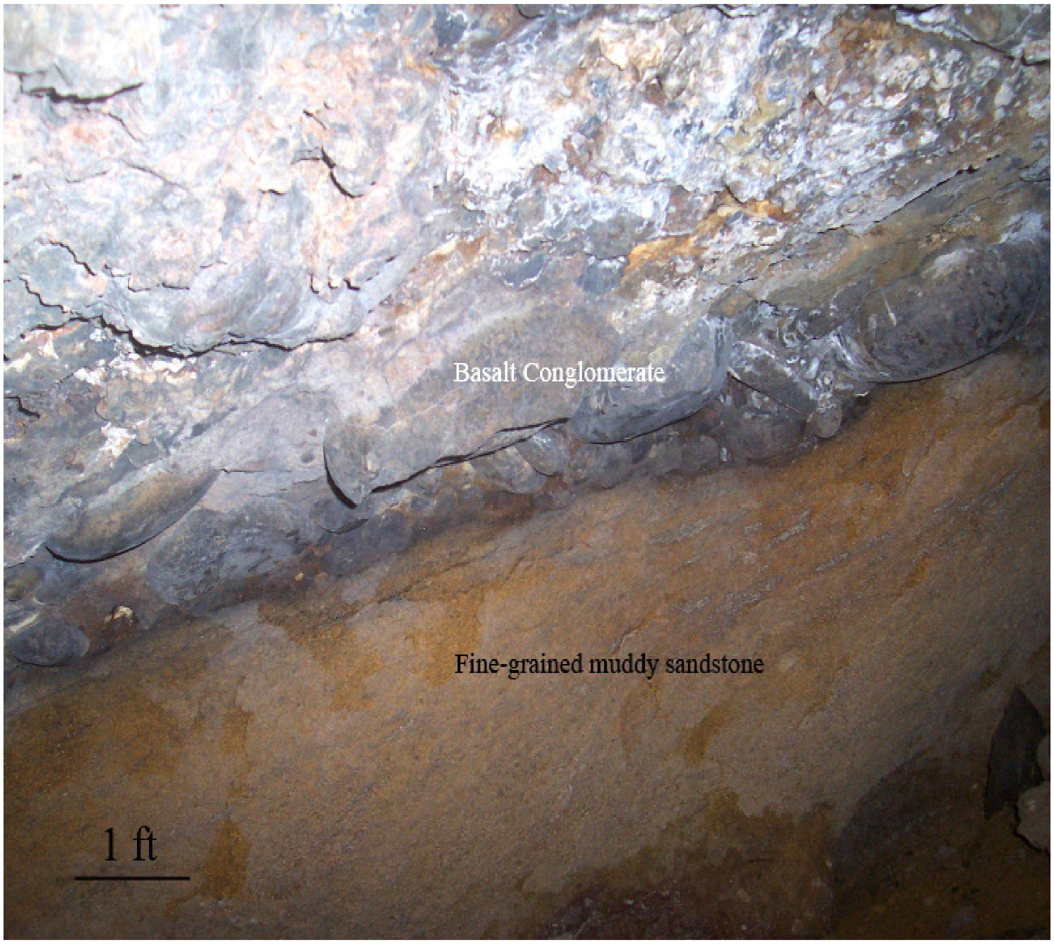


Figure 25. Sedimentary rocks containing what appear to be Lovejoy Basalt clasts directly underling the Lovejoy Basalt at Beatson Falls.

The wall is composed of fine-grained, reddish-brown muddy sandstone with biotite, directly underlying a matrix-supported conglomerate composed of large, rounded, basalt clasts up to a foot in diameter which appear very similar to Lovejoy Basalt. The conglomerate comprises the ceiling of the cave, concealing the basal surface of the Lovejoy Basalt, but when standing outside the cave it is apparent that the contact is only a few feet above the contact between the muddy sandstone and the conglomerate (Fig. 26).

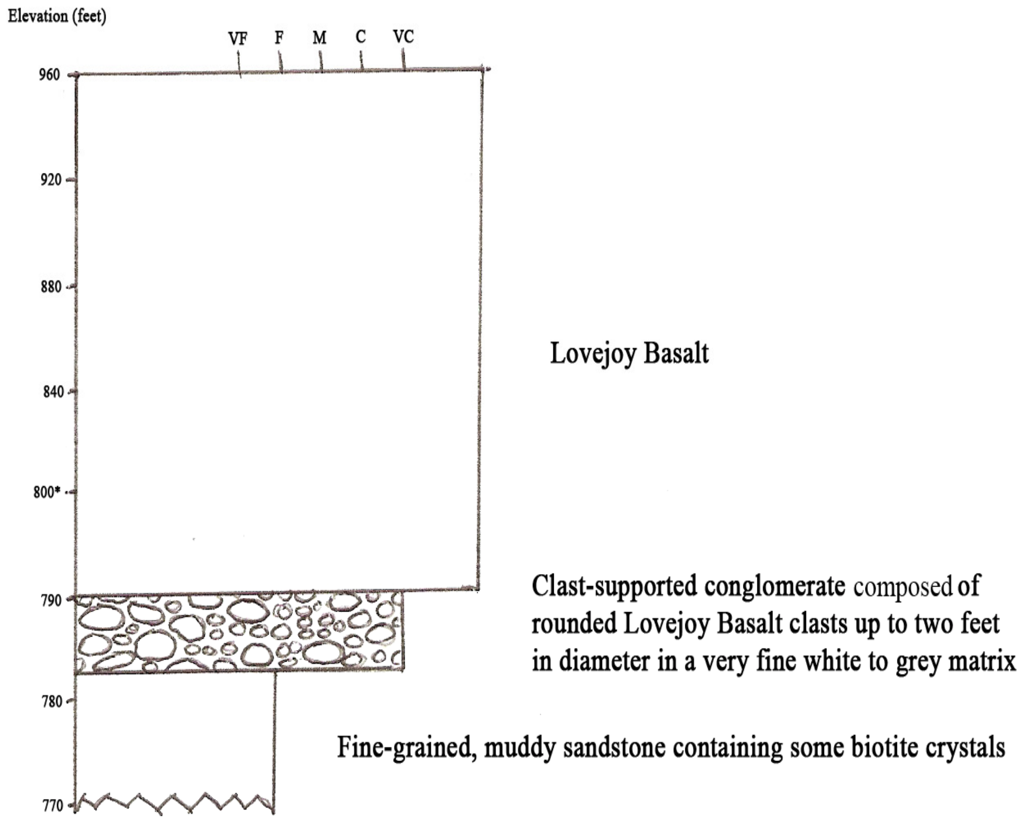


Figure 26. Columnar section showing rock units near Beatson Falls at Oroville Table Mountain. *Note the vertical scale change at 800 feet in elevation.

Richardson Springs

Just south of the town of Cohasset is a small, private community known as Richardson Springs. The waterfall area of their establishment is composed of the upper section of a buried Lovejoy Basalt outcrop. Another similar outcrop exists a few miles north in Iron Canyon.

The Waterfall at Richardson Springs

The upper surface of the Lovejoy Basalt here displays somewhat vague linear protrusions and depressions similar to those found on the surface of Oroville Table Mountain, although considerably more eroded. Erosion has shaped the surface of the Lovejoy Basalt to appear undulating, creating uncertainty in strike-dip measurements previously recorded for the surface here. Measurements of the strike of the linear features yield an approximate NE-SW orientation. It is difficult to be certain, but it appears that these linear features parallel the preferential fracturing and columnar jointing found at the edges of the flow.

At this location, the majority of the Lovejoy Basalt is buried by the Pliocene age volcaniclastic sedimentary rocks of the Tuscan Formation. The contact between these two units, however, is not visible here, as it is covered by a layer of fine, grass-covered, debris, apparently derived from an overlying, less resistant layer of the Tuscan Formation. The lowest visible unit of the Tuscan Formation above the Lovejoy Basalt here contains rounded, andesite boulders up to several feet in diameter. The extreme forces involved in transporting these boulders may have been in direct contact with the surface of the Lovejoy Basalt and thus, may have been responsible for eroding significant amounts of it locally.

Iron Canyon

North of Richardson Springs in Iron Canyon, there is another, even smaller outcrop of Lovejoy Basalt with even less exposure. Toward the top of the flow, near the contact with the Tuscan Formation, the basalt appears to have been chemically weathered, giving the appearance of a volcaniclastic conglomerate with rounded basalt clasts in a fine, white, muddy matrix. However, closer inspection shows that only the surface appears this way, and that it is in fact part of a large outcrop which becomes more typical-looking basalt as it extends downwards away from the surface.

The contact between the basalt and the overlying Tuscan Formation is clearly defined here at a naturally undermined waterfall area. The overhang here is somewhat similar to those found at Oroville Table Mountain, except the Lovejoy Basalt is the undermined unit (Fig. 27).

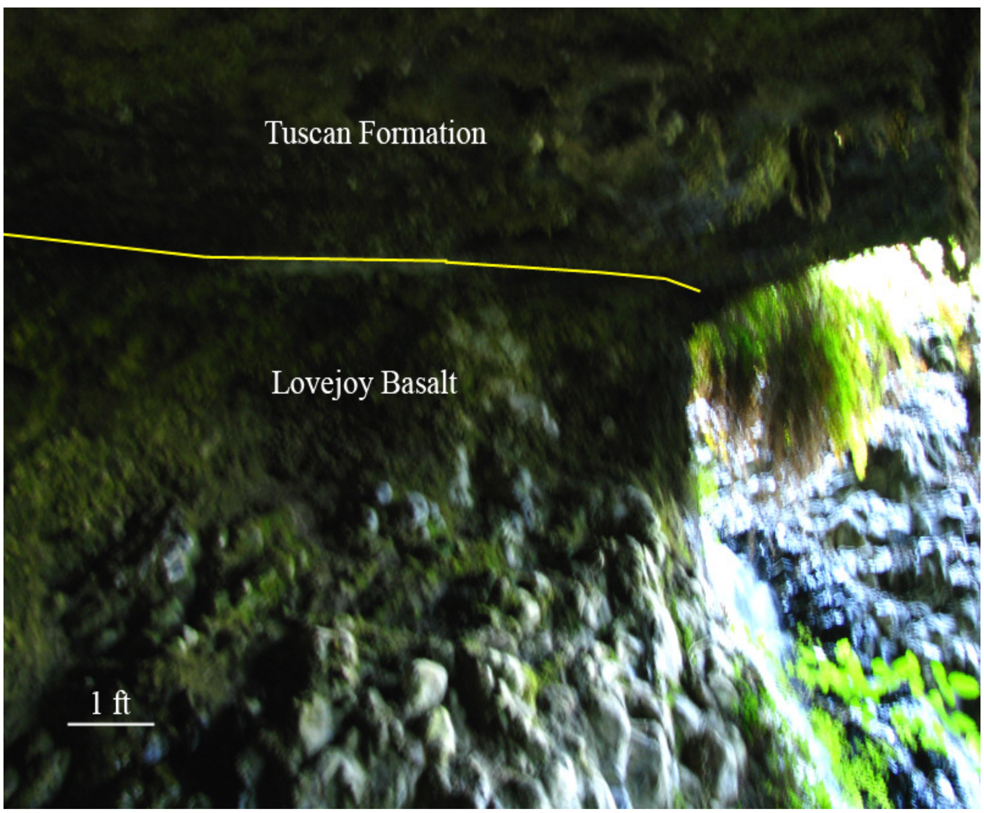


Figure 27. Contact between Lovejoy Basalt and overlying Tuscan Formation in Iron Canyon near Richardson Springs.

Rock Creek

On the northwestern side of Cohasset Ridge, along Rock Creek, is another small outcrop of Lovejoy Basalt. The only observable features here are found on the surface of the basalt. Eroded, linear undulations about 10 meters long were measured to have an orientation of approximately 060°. Large, angular, blocks of Lovejoy Basalt which are connected to the outcrop extend out from the hillside above and are continuous for about 40 meters at an orientation of approximately 027°.

A thin layer of basalt is exposed and all contacts with the unconformably overlying Tuscan Formation are covered with fine, grass-covered, sediments, shed from above. Approximately 60 feet above the top of the basalt, the volcaniclastic sandstones and conglomerates of the Tuscan Formation begin to be exposed.

Dark Canyon

Dark Canyon, on the northern edge of Lake Oroville, contains a barely mappable and somewhat anomalous outcrop of Lovejoy Basalt along its rim. Magnetic susceptibility measurements varied more than at other localities (see magnetic susceptibility discussion in Chapter V).

Assuming it is part of the same flow, the outcrop appears approximately 800 feet lower, topographically, than it should if it were to line up with adjacent outcrops (Fig. 28).

Another obvious difference between this outcrop of Lovejoy Basalt and most others is the appearance of a talus pile. The entire outcrop is composed of eroded angular boulders of Lovejoy Basalt, none of which connect to *in situ* Lovejoy Basalt outcrop.

Approximately 150 feet below the base of the Lovejoy Basalt is the top of a thick section of the highly foliated metasedimentary rocks mapped on the Geologic Map of the Chico Quadrangle as being Paleozoic-Mesozoic in age. These metamorphic rocks extend all the way down into the lake and below to an unknown depth.

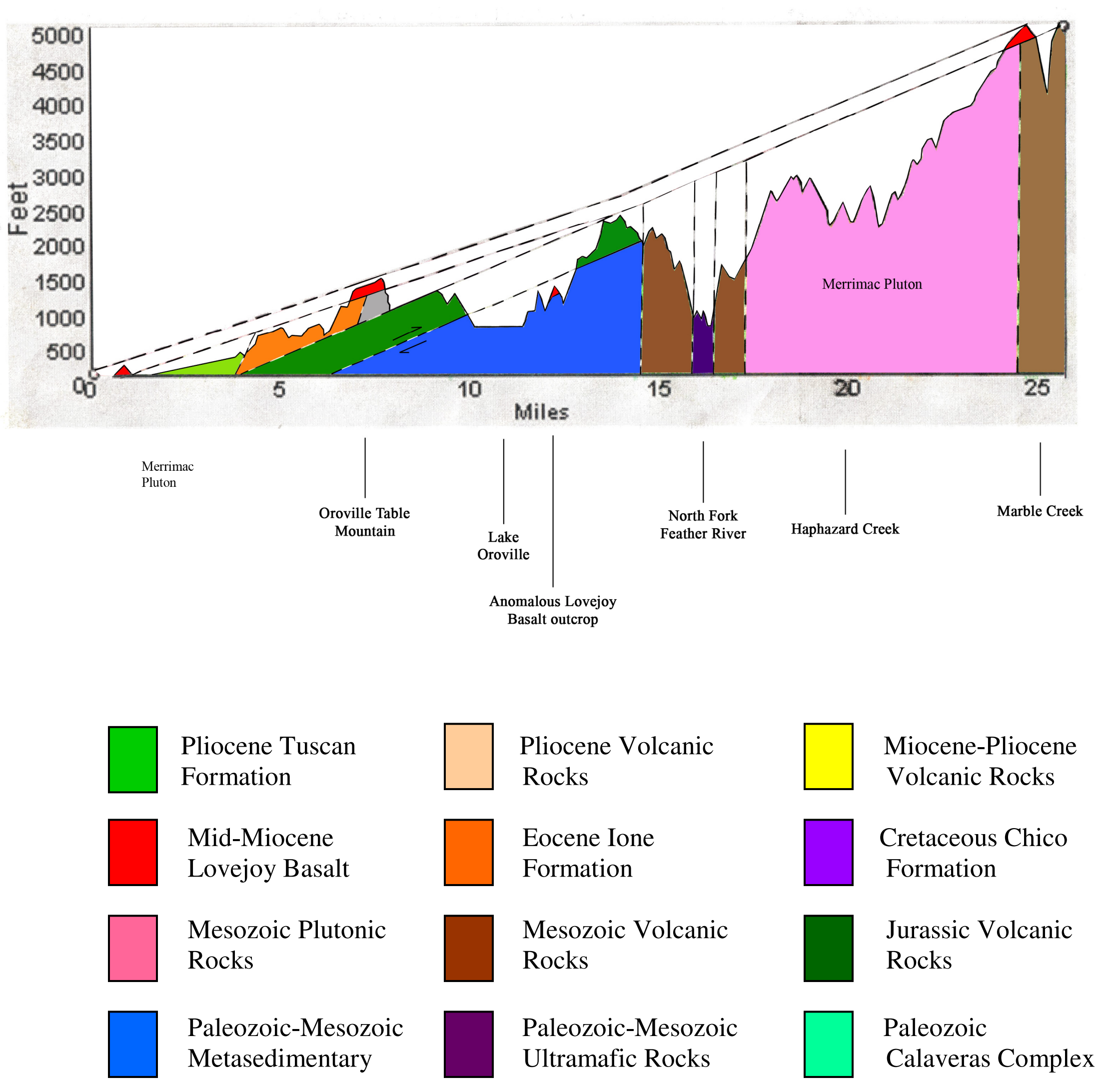


Figure 28. Cross Section between Wicks Corner and Merrimac Pluton showing the location of the anomalous Lovejoy Basalt outcrop near Lake Oroville. This legend of rock units is applicable to the cross sections in Chapter V.

Above the highest locatable outcrop of metamorphic rock is a grassy hillside which conceals the underlying bedrock for most of the section until approximately 10 feet below the base of the basalt.

The basal surface of the Lovejoy Basalt here is marked by a very irregular contact with an unconformably underlying, unconsolidated, clast-supported, conglomerate composed of sub-rounded to sub-angular quartz, serpentinite, chert, greenstone, phyllite, and other metamorphic clasts between 1 and 6 inches in diameter (Fig. 29). Due to very little surface exposure, this unit is not mapped on the geologic map of the Chico quadrangle. Instead, the map shows the Lovejoy Basalt overlying Paleozoic and Mesozoic metasedimentary rocks. It is doubtful, however, that this visible contact represents the lower surface of a Lovejoy Basalt flow.

Figure 29. Unconsolidated conglomerate underlying the Lovejoy Basalt in Dark Canyon near Lake Oroville.

Big Chico Creek

Upper Bidwell Park is characterized by steep cliffs formed by Big Chico Creek as it created deep channels into the Tuscan Formation, Lovejoy Basalt, and Chico Formation. Thus, the basalt outcrops in an elongated V-shaped narrow valley approximately 8 miles long along Big Chico Creek. In places along the creek, the Tuscan Formation directly overlies the Chico Formation, whereas in others, the Lovejoy Basalt is the overlying unit, indicating that the Lovejoy Basalt is somewhat discontinuous in this area.

To the northeast, along the creek, white-to-yellow muddy sandstones of the Cretaceous Chico Formation outcrop and can be seen to unconformably underlie the matrix-supported, sub-angular breccia unit associated with the basal flow of the Lovejoy Basalt. This sedimentary unit is similar to the one found at Oroville Table Mountain, containing almost entirely what appear to be Lovejoy Basalt clasts. The dip direction of this contact is east, which is likely a local topographic anomaly. A few meters above this conglomerate are in-place outcrops of Lovejoy Basalt. Elsewhere along the creek, this contact is concealed by a talus slope containing large boulders of columnar basalt.

Further to the northeast, in the Big Chico Creek Ecological Reserve, the basal contact of the Lovejoy Basalt appears to be mostly concealed by talus slope and fine-grained, grass-covered, debris. In a few locations, several meters below the basalt outcrop, a fine-grained, dark reddish-brown mudstone not unlike those found beneath the Lovejoy Basalt at Table Mountain and Orland Buttes is present. It is possible that this unit is part of the Chico Formation.

Although no definite linear undulations on the surface of the flow were located, there are a few extensive vertical fractures that appear to extend all the way through the exposed section of Lovejoy Basalt. The shorter of the two fractures is several feet wide whereas the longer one is less than a foot wide at its narrowest point. The shorter system runs for hundreds of yards laterally through the outcrop (Fig. 30). The orientations of both fractures are approximately northeast-southwest.

Figure 30. Extensive NE-SW oriented vertical fracture in the Lovejoy Basalt in the Big Chico Creek Ecological Reserve. This fracture extends towards the southwest for over 80 feet. The entrance is approximately 2 feet wide.

Mooreville Ridge

Mooreville Ridge is an elongated, ten mile long, northeast-southwest trending ridge of Lovejoy Basalt which flowed over the Cascade Pluton just southwest of Little Grass Valley Reservoir in the northern Sierra Nevada. Due to an abundance of dense evergreen forests in this area, the topsoil has become very thick making it difficult to locate large cliffs of the basalt such as those exposed elsewhere in the foothills of the Sierra Nevada.

Along the road-cut between Mooreville Ridge and the adjacent Lumpkin Ridge are a few heavily fractured Lovejoy Basalt outcrops overlying a section of sedimentary rocks. Approximately 80 feet below the base of the Lovejoy Basalt is the top of the highest visible outcrop of granitic rock of the Cascade Pluton.

The nonconformable contact between the pluton and an overlying fine-grained, unconsolidated, white-to-brown mudstone is visible in the road cut (Fig. 31). Stratigraphically above this relatively featureless mudstone is a clast-supported conglomerate containing sub-rounded to sub-angular Lovejoy Basalt clasts up to 3 feet in diameter which grades into matrix-supported zones.

Most of the section between the top of the pluton and the basalt is covered by unconsolidated landslide material containing relatively fresh Lovejoy Basalt clasts, concealing the contact between the pluton and the overlying sedimentary rocks (Fig. 32).

Lumpkin Ridge

Separated by a deep channel cut by the South Fork Feather River, Lumpkin Ridge parallels Mooreville Ridge and is of similar scale. The two units were undoubtedly once connected as a single flow and have since been separated by the erosive forces of the ancient Feather River.

Like Mooreville Ridge, extensive cliff faces are difficult to find here, but the surface of the ridge is composed of *in situ* Lovejoy Basalt. The basalt appears more fractured here than it does at lower elevations in the Sierra Nevada, possibly making it easier for the local quarry to process it into gravel.

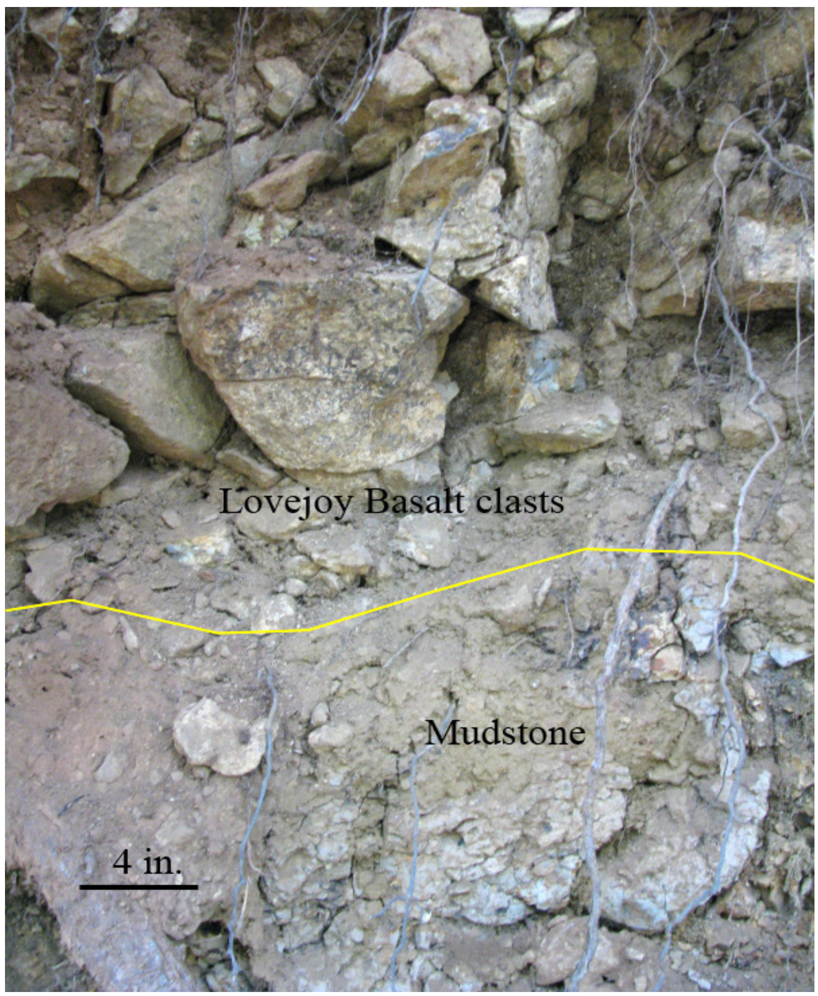


Figure 31. Contact between decomposed mudstone and overlying conglomerate composed of oxidized Lovejoy Basalt clasts. Photograph was taken in road cut along Mooreville Ridge.

Little Grass Valley Reservoir

Northeast of Lumpkin Ridge, Lovejoy Basalt crops out along the southern and western shores of Little Grass Valley Reservoir, most vividly near the dam at the western side of the lake. A few miles to the northeast are some smaller outcrops, one of which is anomalously tilted.

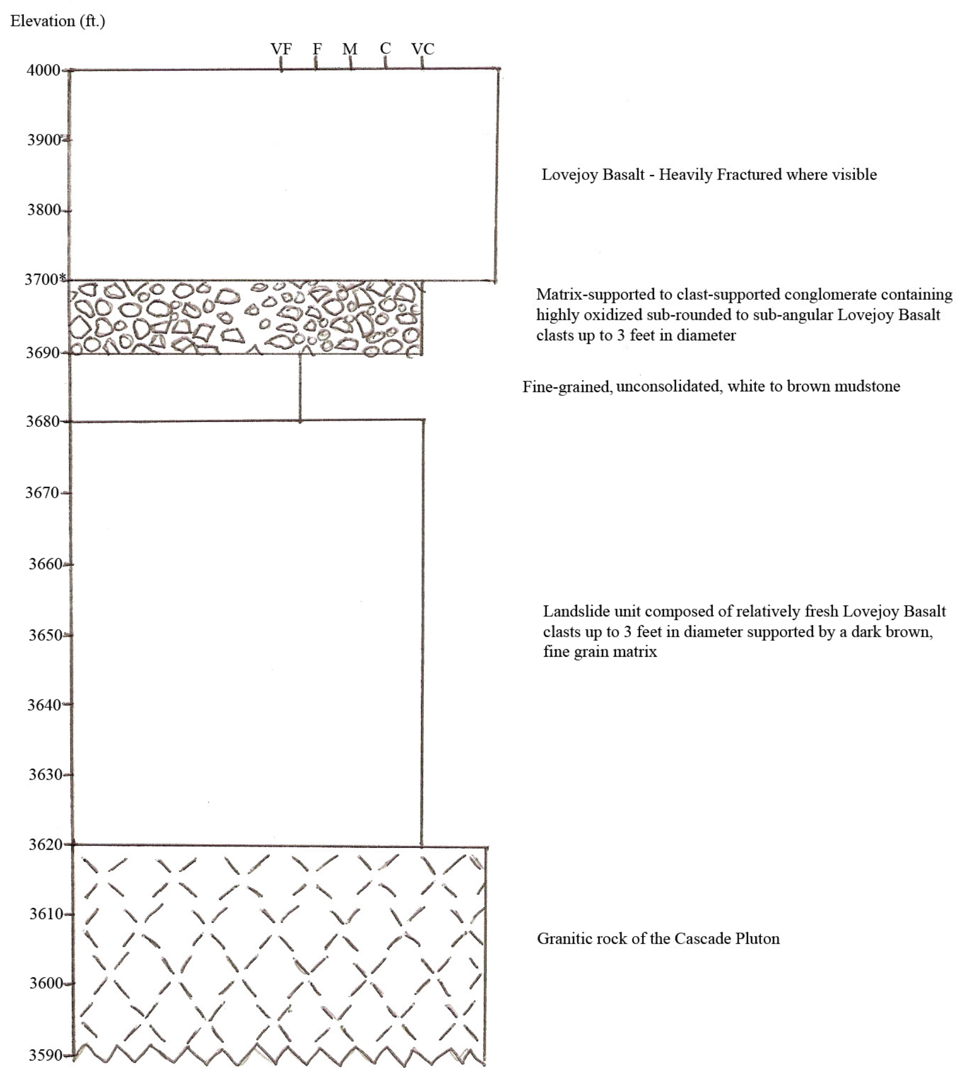


Figure 32. Columnar section showing the rock units which underlie the Lovejoy Basalt at Mooreville Ridge. *Note the vertical scale change at 3700 feet in elevation.

<u>The Dam at Little Grass Valley Reservoir</u>

Near the parking lot at the dam at Little Grass Valley Reservoir, the direct contact between the Lovejoy Basalt and the underlying Mesozoic/Paleozoic metavolcanic and metavolcaniclastic rocks can be observed (Fig. 33). Overlying the basalt is a section of younger andesite flows which can be seen along the road-cuts leading to the reservoir, though the contact between the Lovejoy Basalt and the andesite is concealed in the vicinity of the dam.

Figure 33. Contact between Paleozoic/Mesozoic metamorphic rocks and the overlying Lovejoy Basalt at the dam at Little Grass Valley Reservoir.

Although there is no undeformed layer underlying the Lovejoy Basalt at this location, it is possible that the basalt was displaced by thrust faulting. It is mapped here

(Geologic Map of the Chico Quadrangle) as unconformably overlying a thrust fault zone. When viewed from a distance, it appears as if it is either part of a thrust sheet or else flowed down a particularly steep section of the paleo-topography (Fig. 34). If this is a fault contact, it is uncommon, as most of the Lovejoy Basalt seems to rest where it flowed.

Figure 34. Possible thrust fault contact between the Lovejoy Basalt and underlying metamorphic rocks at the dam at Little Grass Valley Reservoir.

The south side of the reservoir, where most of the Lovejoy Basalt is exposed, is a privately owned subdivision, making access difficult. Large, loose, boulders of the basalt down on the shore were available for magnetic susceptibility measurements. No distinctive structural features of the basalt were apparent at either of these locations.

Anomalous Outcrop Northeast of the Reservoir

Approximately four miles northeast of the reservoir, along the road leading towards the town of Quincy, is a somewhat anomalous outcrop of Lovejoy Basalt, the base of which is concealed. The outcrop appears as a series of well-formed columns up to a foot in diameter. Besides the fact that most of the outcrops at this altitude do not display well-formed columns, it is apparent that these columns have been tilted at least 45 degrees toward the west from their originally vertical position (Fig. 35). Furthermore, magnetic susceptibility measurements of this outcrop gave exceptionally high values relative to surrounding outcrops.

Figure 35. Anomalously tilted Lovejoy Basalt outcrop northeast of Little Grass Valley Reservoir. This outcrop also has an anomalously high magnetic susceptibility measurements. The average diameter of the columns is approximately 8 inches.

Stony Ridge

Stony Ridge is a south-trending ridge about 6 miles long and 2 miles wide in the northern Sierra Nevada located just to the southwest of the Honey Lake Fault, not far from the proposed vent for Lovejoy Basalt at Thompson Peak. Up to 13 individual flows of varying thickness are exposed here (Garrison, 2004), each of which is marked by a steep cliff face and corresponding talus slope, in which the lower surface of the talus slope marks the boundary between flows (Fig. 36). This is also the location where the Lovejoy Basalt reaches its maximum thickness of over 700 feet. In most places, except on the northern end of the ridge, the base of the basalt is buried.

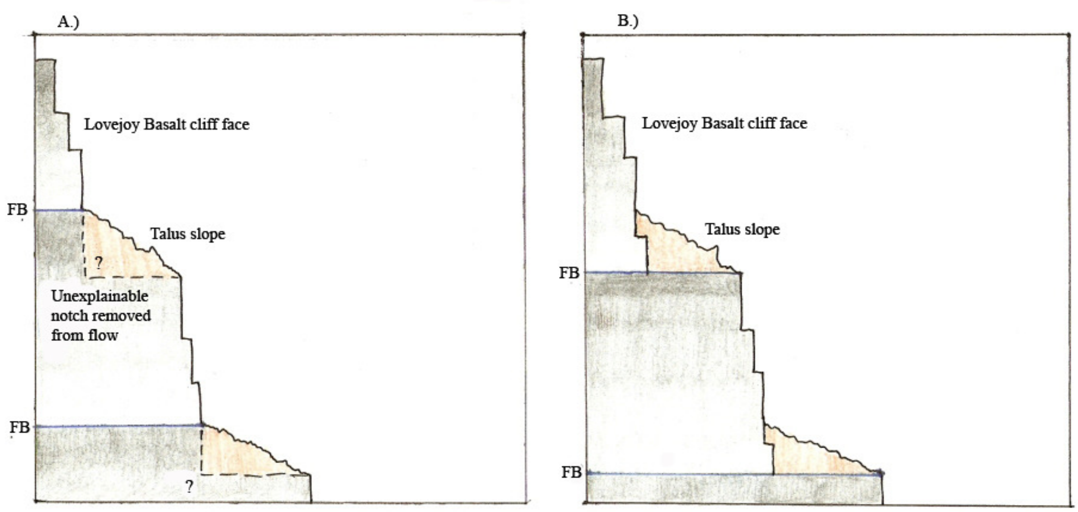


Figure 36. Diagram showing two possible interpretations of the boundaries between individual flows of Lovejoy Basalt at Stony Ridge and Red Clover Creek. (A) The interpretation showing the boundaries between flows as being marked by the upper surface of the talus slope presents problems, such as the unexplainable missing 'notch' of basalt. (B) The interpretation in which the boundaries between flows are marked by the lower surface of the talus slope eliminates problems associated with the first interpretation.

Many of the lower flows here look like typical aphyric Lovejoy Basalt, although significantly fractured. The top three or four flows, however, contain phenocrysts which distinguish them from the underlying flows. Part of the ridge has been incised by Stony Creek.

The top flow, which makes up the flat, extensive, surface of Stony Ridge, is composed of porphyritic Lovejoy Basalt containing distinctive phenocrysts of plagioclase feldspar. The three flows below it contain either garnet or olivine phenocrysts (sometimes both), depending on the particular location. Magnetic susceptibility measurements were taken of as many flows as possible to help serve as a control for understanding other flows in the area.

Abundant vesicles up to several centimeters in length, many of which have been stretched in a roughly north-south direction, were observed in some of the upper flows (Fig. 37).

Figure 37. North-south oriented stretched vesicles in one of the upper flows of Lovejoy Basalt at Stony Ridge.

Along the surface of some of the flows on the ridge are subtle linear features, all of which are oriented in a roughly east-west direction, parallel to that of the local flow direction (Fig. 38). Paralleling these linear features is a series of east-west oriented fractures along the edge of the flow which connect to steep gullies on the cliff face. They can sometimes be seen more easily from a distance.

Figure 38. Subtle E-W oriented linear features along the surface of a flow of Lovejoy Basalt on Stony Ridge. The large boulder in the center of the foreground is approximately 6 feet in diameter.

Red Clover Creek

A few miles north of Lake Davis, Lovejoy Basalt is exposed in an area approximately 2 square miles along Red Clover Creek. The individual flows here are distinctive, which could be why it was designated as the type locality (Fig. 39).

Like Stony Ridge, the uppermost flow comprises the ridge top and contains plagioclase feldspar phenocrysts. The three flows below it contain garnet and olivine phenocrysts, although not necessarily in the same proportions as those found at Stony Ridge. Once again, the basal contact of the Lovejoy Basalt is either covered with talus or buried.

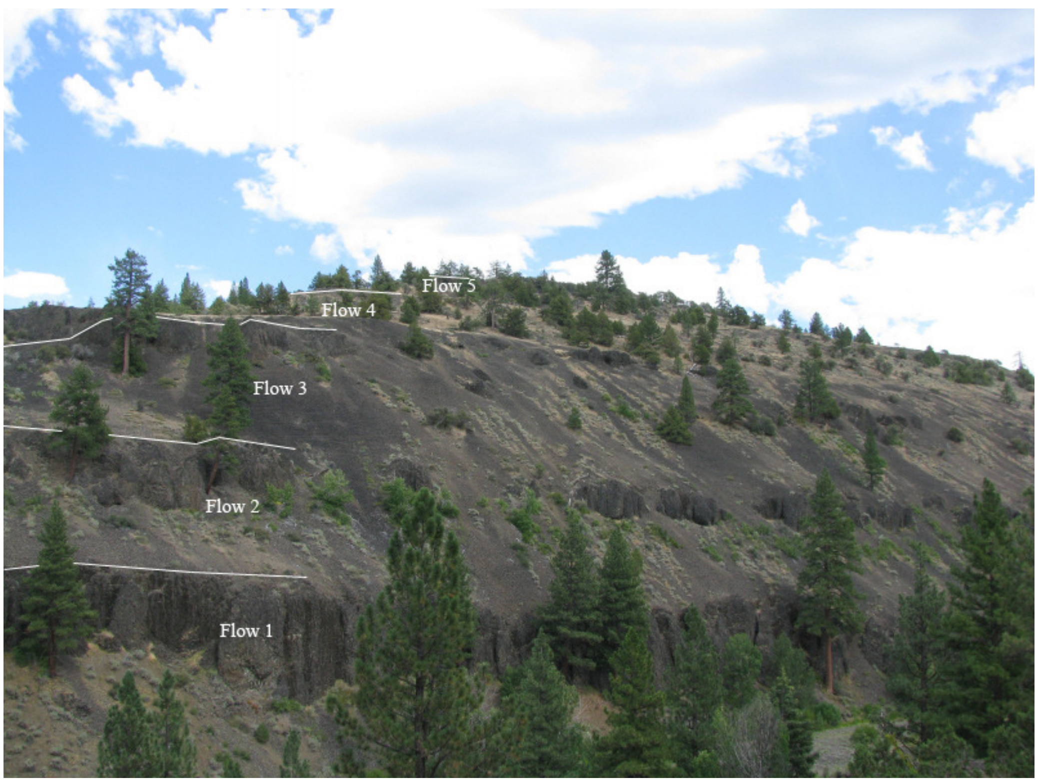


Figure 39. Prominent individual flows of Lovejoy Basalt at Red Clover Creek. Flows boundaries are shown and listed from bottom up in order of relative age. The tallest trees in the foreground are approximately 35 feet tall.

Also similar to Stony Ridge are the abundant vesicles in the upper flows as well as the subtle linear features and preferential fractures along the edge of the flow. Stretching of the vesicles also trends roughly north-south, and the linear fractures at the edge of the flow are oriented approximately east-west (Fig. 40).

At the top of the uppermost basalt flow, one significant linear undulation was found which appears very similar to those on top of Oroville Table Mountain and elsewhere except for the fact that it is curved (Fig. 41). The main limb is oriented approximately east-west but the eastern side of it curves dramatically towards the southeast.

Figure 40. E-W oriented preferential fractures of Lovejoy Basalt at Stony Ridge. The two outcrops are separated by approximately 20 feet.

At the top of the ridge, the Lovejoy Basalt can be observed to directly underlie the Delleker Formation, although the contact is covered by talus. Toward the western side of the basalt outcrop, it is apparent that the andesitic mudflows of the Delleker Formation were deposited in previously incised channels within the Lovejoy Basalt, a somewhat controversial issue which was clarified recently (Garrison, 2004).

Thompson Peak

Thompson Peak, the proposed vent area for the Lovejoy Basalt, is located at the northeastern edge of the Sierra Nevada, overlooking the town of Janesville, Ca and the Honey Lake Valley. This location resides in the general transition zone between three major geologic provinces of northern California; the Basin-and Range, the Sierra Nevada, and the Modoc Plateau.

A few miles down the ridge from the lookout tower on the peak, the top of the Cretaceous granite of the Sierra Nevada Subjacent Series is exposed. The contact between the granite and the overlying basalt is concealed in most places, so the direct contact was only located in one place (Fig. 42), making it difficult to determine the nature of the contact.

Along this contact, the Lovejoy Basalt is mostly a dark grey, brecciated, scoria material found only at this general locality. It contacts the underlying granite at a relatively steep angle, dipping the opposite direction of the generally accepted southwestward flow direction of the basalt. If the lava was traveling in a relatively vertical motion here, it may have traveled up the slope of the granite and poured down

Figure 41. Curved, linear ridge on the highest Lovejoy Basalt flow at Red Clover Creek. The ridge is similarto those found on the surface of Oroville Table Mountain.

the other side towards the southwest. A less likely possibility is that the lava was traveling down slope towards the northeast.

This scoria material is part of a NW-SE trending, 3 mile long ridge of Lovejoy Basalt which directly underlies the younger Thompson Peak Basalt. This trend is approximately parallel to the feeder dikes associated with much of the Columbia River

Figure 42. Direct contact between Mesozoic plutonic basement rock and overlying Lovejoy Basalt along the vent ridge at Thompson Peak. The section of granite exposed in the photograph is approximately 3 feet wide.

Basalt group (Garrison, 2004). This ridge is thought to represent the primary vent for the Lovejoy Basalt (Garrison et al, 2008) (Fig. 43).

Figure 43. The proposed vent at Thompson Peak. Note the extensive contact between the basalt along the ridge and the underlying pluton (covered in evergreen trees).

Abundant vent indicators such as scoria and zones of clastogenic texture are present along the ridge (Fig. 44). Small topographically high spots along the top of the ridge expose what appears to be the uppermost, plagioclase-rich flow of the Lovejoy

Basalt, directly overlying chaotic zones of brecciated, clastogenic, scoria and vesicular basalt (Fig. 45).

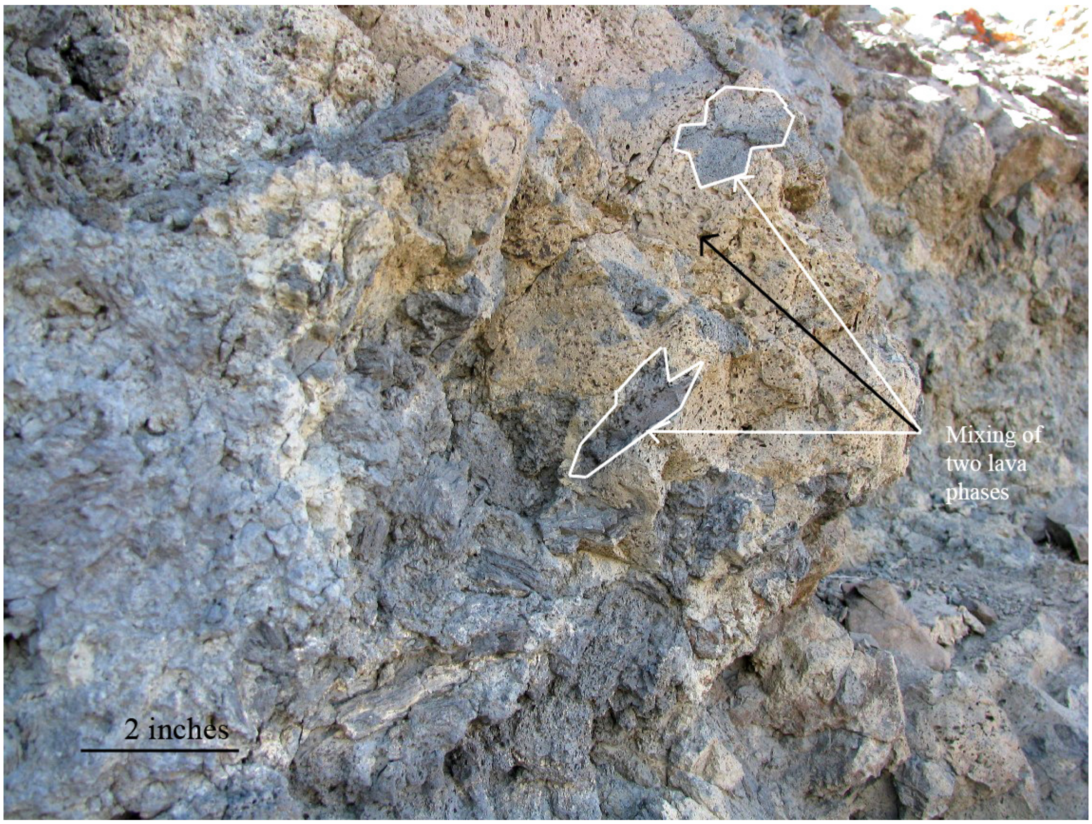


Figure 44. Zone of clastogenic texture along the proposed vent ridge at Thompson Peak. This chaotic material, composed of at least two distinctly different phases of Lovejoy Basalt, comprises the majority of the vent ridge. Each phase of basalt has a distinctly different magnetic susceptibility.

These chaotic zones are composed primarily of dark grey to black, fragmented, basalt with randomly oriented layering, grading into areas which display dark grey, highly vesicular scoria ‘clasts’ embedded in a somewhat less vesicular, light-brown, basalt matrix. In some areas, however, it is the light-brown basalt which composes the clasts embedded in a matrix of the layered, dark grey, scoria material. The fact that both types of basalt contain each other's clasts within close proximity to each other indicates the likelihood that they were both in a liquid or semi-fluid state upon eruption.

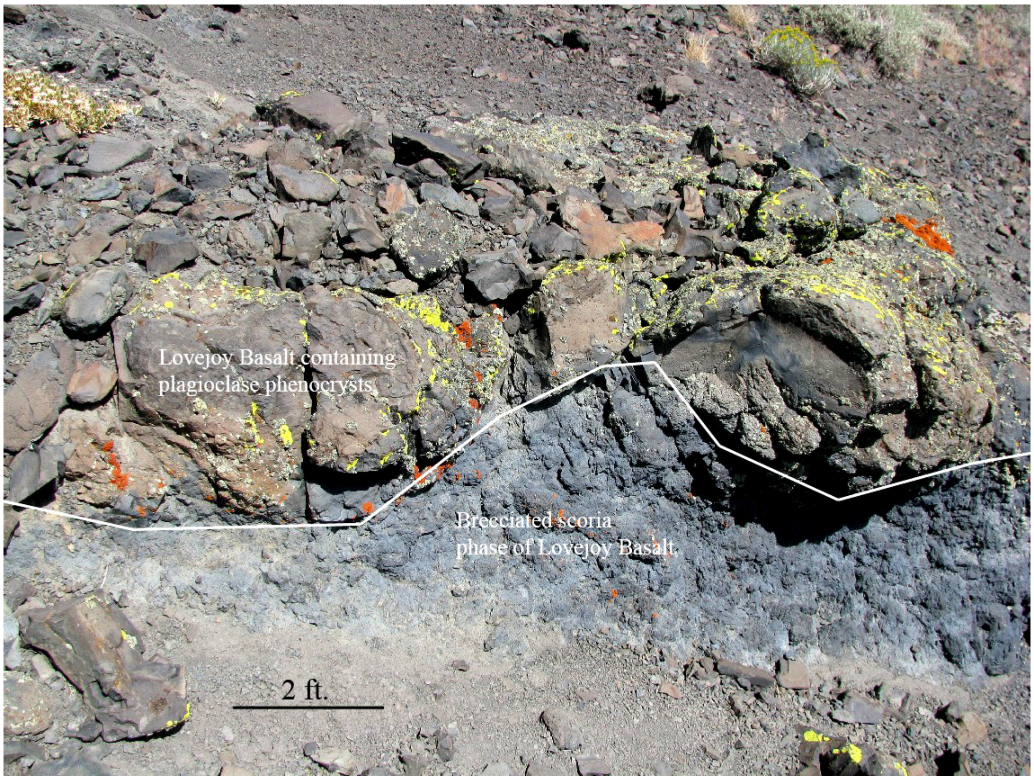


Figure 45. The flow of Lovejoy Basalt which contains plagioclase phenocrysts caps the brecciated scoria along the proposed vent ridge at Thompson Peak. It appears as if the plagioclase-rich flow was deposited upon a rough topography of brecciated scoria material.

On the steep cliff face of the Lovejoy Basalt vent ridge are what appear to be vertically elongated structures composed of horizontal columns (Figs. 46 and 47). Considering the fact that columns are generally formed as a product of the basalt cooling from the outer edges of the flow towards the center, these sub-vertical structures could be an indication of vertical motion of lava, perhaps even the feeder dikes that supplied the vent area with lava during eruption. There is the remote possibility that these horizontal columnar structures, which compose a significant portion of the cliff face, were once oriented vertically and have since been displaced to their current position. Surrounding these structures is the brecciated scoria material mentioned above, which could represent the more explosive aspect of the vents eruption.

Figure 46. Tilted columnar structures along the vent ridge at Thompson Peak. If the motion of the lava was perpendicular to the columns then it would appear that the lava was traveling sub-vertically and towards the S/SW at this location. Column structures are highlighted in white.

Figure 47. Near-horizontal basalt columns indicating possible sub-vertical lava motion along the vent ridge at Thompson Peak. The column structures may be the remnants of feeder dikes and the surrounding brecciated scoria material may represent zones in which different phases of basalt were mixing together in a semi-liquid state. Column structures are highlighted in white.

Near the contact between the northwestern edge of the Thompson Peak Basalt and the underlying Lovejoy Basalt, it becomes apparent that there is a buttress unconformity between the two volcanic units. Another smaller outcrop of Thompson Peak Basalt further down the vent ridge also appears to be buttressed against the Lovejoy Basalt.

Considering that the Thompson Peak is definitely the younger unit, these outcrops can be explained either by faulting, in which the sections of Thompson Peak Basalt were down-dropped relative to the Lovejoy Basalt, or by the possibility that the Thompson Peak Basalt was deposited in a previously incised channel within the Lovejoy Basalt (Fig. 48), similar to the relationship found at Red Clover Creek between the Lovejoy Basalt and the younger, but not always overlying Delleker Formation. These features can be seen clearly from the Honey Lake Valley below (Fig. 49).

The lookout tower on top of Thompson Peak was built on a section of the volcanic flows and interstratified fluvial deposits of the Thompson Peak Basalt. It is less glassy, more porphyritic, and more andesitic in composition than the Lovejoy Basalt. Within some of its thicker sections are radial, columnar, structures up to 10 feet in diameter, of unknown origin (Fig. 50).

Near the contact between the Lovejoy Basalt and Thompson Peak Basalt, interstratified fluvial deposits within the Thompson Peak Basalt become apparent. They are primarily volcaniclastic breccias containing fragments of Thompson Peak Basalt up to 6 inches in diameter as well as extremely decomposed granitic clasts of a similar size range, supported by unsorted, yellowish sandstone of granitic composition (Fig. 51).

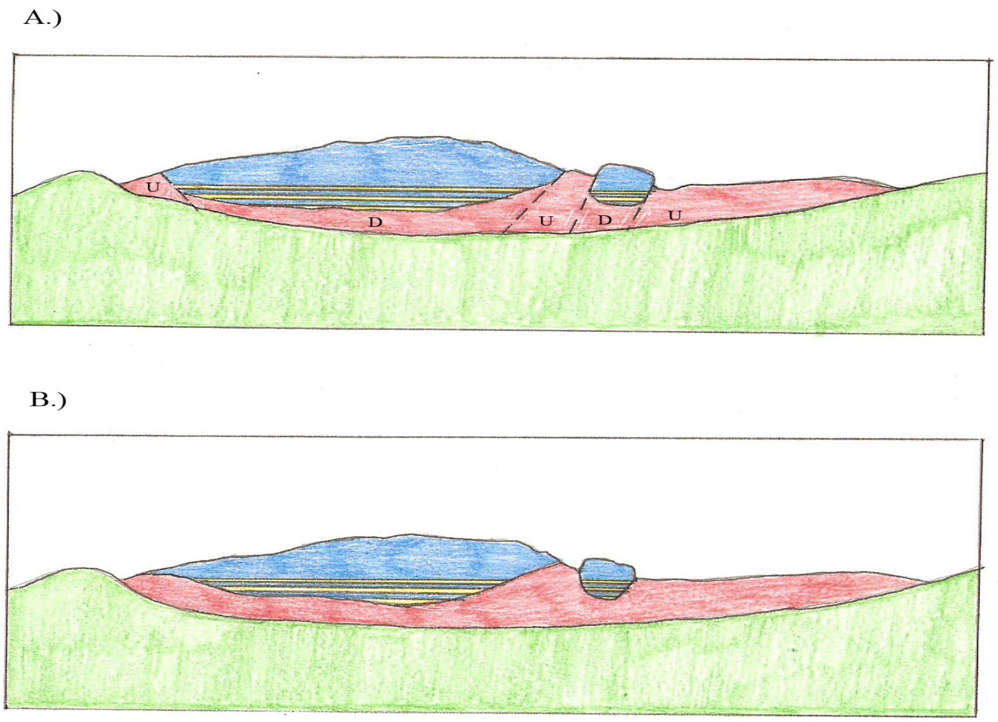


Figure 48. Diagram showing two possible relationships between Lovejoy Basalt (red) and overlying Thompson Peak Basalt (blue) at Thompson Peak. (A) Normal faulting. (B) Channel fill.

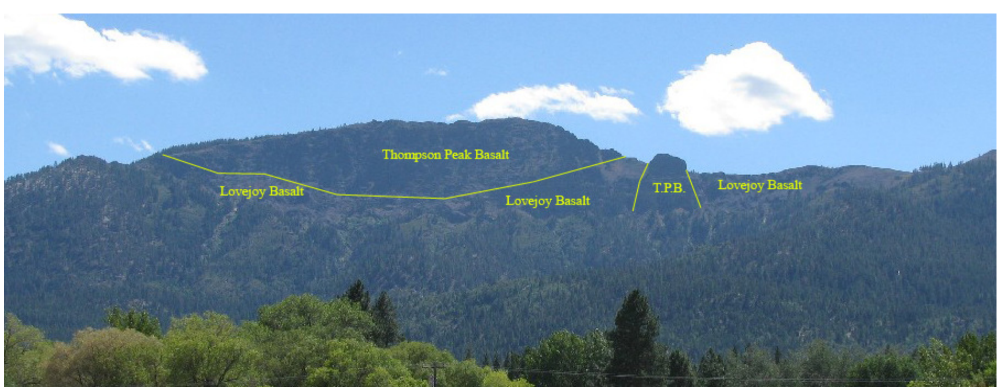


Figure 49. Photograph of Thompson Peak from the town of Janesville, showing Lovejoy Basalt and the overlying Thompson Peak Basalt.

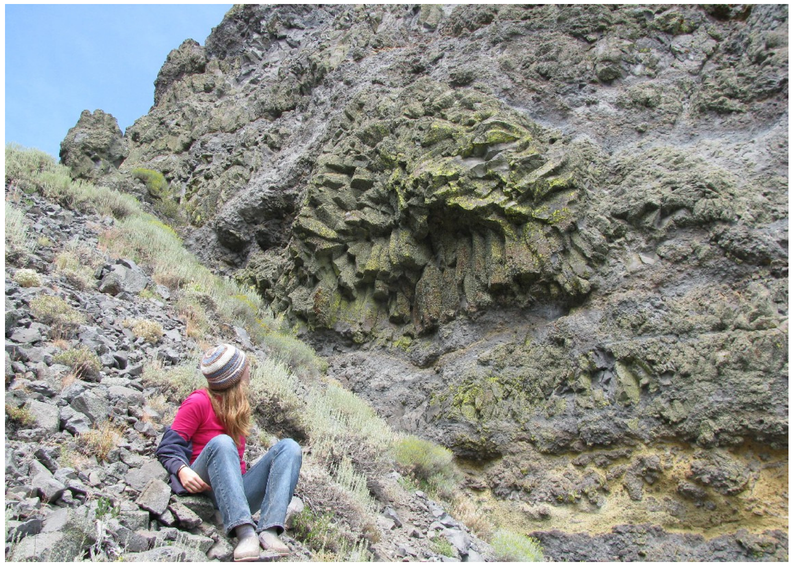


Figure 50. Radial, columnar, cooling structure in the Thompson Peak Basalt.

Figure 51. One of many interstratified fluvial deposits within the stratigraphy of the Thompson Peak Basalt. The section of sedimentary rock exposed is approximately 4 feet thick.

The thickest of these layers observable from the ridge is about 10 feet thick but thicker layers are present near the base of the cliff. The basal surfaces of the fluvial deposits appear somewhat wavy, having been deposited on a somewhat undulating, irregular surface. The upper contact of the fluvial deposits appear even more irregular than the lower contact, and contain large, angular clasts of Thompson Peak Basalt which have been incorporated into the upper section of the sedimentary unit, suggesting either erosion prior to deposition and/or turbulence during deposition.

It should be noted that the fluvial deposits begin just below the top of the Lovejoy Basalt ridge, which could be an indicator that they were deposited in a channel incised into the Lovejoy Basalt (Fig. 52).

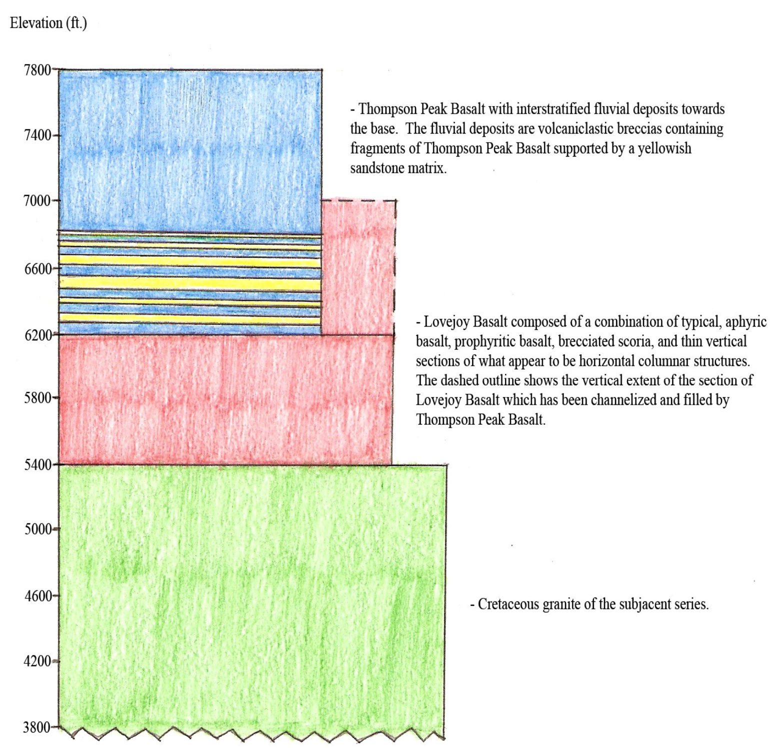


Figure 52. Columnar section showing the rock units beneath the lookout tower on Thompson Peak.

CHAPTER V

FINDINGS AND RESULTS

X-Ray Fluorescence Analysis of Basalt Cobbles

Although not all major outcrops have been analyzed, it has recently been shown that the geochemistry of the Lovejoy Basalt is consistent between the source area at Thompson Peak and the most distant outcrops at Orland Buttes and Putnam Peak (Garrison, 2004). Because of this chemical consistency, X-Ray Fluorescence analysis can be used to determine whether or not similar looking basalts are Lovejoy Basalt.

Many of the well-rounded basalt cobbles found in conglomerates directly underlying the Lovejoy Basalt, particularly at Oroville Table Mountain, have a very similar appearance to Lovejoy Basalt. The oxide contents of some of these cobbles were qualitatively analyzed using the S2 Ranger energy dispersive X-Ray Fluorescence machine manufactured by Bruker Advanced X-Ray Solutions in Germany. The analyses were run without using a standard. This introduces significant errors, particularly in SiO_2 (underestimate) and Al_2O_3 (overestimate), due to matrix effects. These values should be considered qualitative, whereas the other oxides are semi-quantitative and are only for comparison. Despite these considerations, the results clearly exhibit some differences, such as the higher amount of Titanium (Ti) in the Lovejoy Basalt versus the more calc-alkaline Paradise and Cohasset basalts. This may be due at least partly to the higher magnetite/titanomagnetite content in the Lovejoy Basalt.

The results of the X-Ray Fluorescence analysis show the likelihood that the cobbles are the erosive remnants of a Lovejoy Basalt outcrop which had previously existed somewhere upstream (Table 2). Though the sequence is not found *in situ* at one location, it can be thought of as similar to the interstratified sedimentary deposits within the Thompson Peak Basalt (Fig. 51). Two of the cobbles used for the initial analysis were taken from conglomerates directly underlying the Lovejoy Basalt at Phantom Falls and Beatson Falls. Each of these two conglomerates has a distinctly different appearance. The one at Beatson Falls is more clast-supported and contains much larger clasts. Samples of Paradise Basalt and Cohasset Basalt were also analyzed for comparison.

The conglomerate at Phantom Falls is well exposed. The third cobble used in the analysis comes from a conglomerate overlying the Cretaceous Chico Formation along Big Chico Creek which appears to be underlying the Lovejoy Basalt, although the contact is covered.

The chemistry of all three of these cobbles is very similar to that of the analyzed samples from Lovejoy Basalt outcrops. There are slight exceptions, such as the scarcity of Barium in the cobble from Beatson Falls and of Copper in the cobble from Big Chico Creek. When compared to other younger, more phyric basalts, the similarity between the cobbles and Lovejoy Basalt becomes more apparent (Figs. 53 and 54).

The sample from the base of the Lovejoy Basalt containing linear grooves as well as the cobble from Beatson Falls both appear to have slightly lower concentrations of sodium and aluminum.

Table 2. Table of results of X-Ray Fluorescence Analysis of oxide content of basalt cobbles found underlying Lovejoy Basalt outcrops.

Oxide	Paradise Basalt	Cohasset Basalt	Lovejoy Basalt 1	Lovejoy Basalt 2	Basalt clast from Red Bluff Formation	Lovejoy Basalt from Table Mtn. 1	Lovejoy Basalt from R.C.C.	Lovejoy Basalt from Table Mtn. conglomerate 1	Lovejoy Basalt from Table Mtn. conglomerate 2	Lovejoy Basalt from B.C.C. conglomerate	Putnam Peak Basalt	Basalt clast from Milford 1	Basalt clast from Milford 2
Na_2O	8.44	4.97	6.41	6.21	6.26	5.92	4.77	6.71	5.85	6.21	6.64	6.94	6.32
MgO	3.09	3.71	3.45	3.46	3.35	4.04	3.1	3.25	3.06	3.02	2.73	3	2.84
Al_2O_3	25.53	27.92	20.17	20.81	19.21	17.63	15.6	19.75	18.67	18.51	20.06	19.9	20.25
SiO_2	39.42	39.8	39.75	40.49	40.31	39.13	39.21	39.19	39.63	41.31	43.08	41.43	43.58
P_2O_5	<.001	<.001	0.43	0.413	0.588	0.797	0.841	0.495	0.584	0.74	.711	0.547	0.735
SO_3	.044	.062	0.055	0.051	0.086	0.493	0.127	0.072	0.163	0.124	.048	<.001	<.001
Cl	<.001	.095	0.1	<.001	<.001	<.001	<.001	0.085	<.001	0.053	<.001	0.074	0.057
K_2O	1.23	.525	2.22	3.02	2.07	5.84	2.23	2.51	2.28	1.71	2.33	3.06	1.93
CaO	9.71	9.54	8.52	8.35	8.35	8.14	9.05	8.09	8.5	8.75	7.77	7.43	7.35
TiO_2	.812	.852	2.5	2.12	2.75	3.34	2.26	2.28	2.64	2.97	2.59	2.29	2.34
V	<.001	.022	0.033	0.047	0.035	0.029	0.05	0.046	0.033	0.04	.039	0.057	0.051
Cr	.049	.050	<.001	0.036	<.001	0.019	<.001	0.027	0.37	0.031	.021	0.026	0.023
MnO	.276	.232	0.338	0.351	0.339	0.169	0.539	0.387	0.37	0.292	.295	0.328	0.29
Fe_2O_3	11.07	12.14	15.53	14.08	16.1	13.46	21.47	16.7	18.02	15.87	13.22	14.39	13.73
Ni	<.001	.005	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Cu	.031	.003	<.001	0.016	0.007	0.021	0.001	0.006	0.006	<.001	.004	0.005	<.001
ZnO	.018	.007	<.001	0.02	0.011	0.021	0.009	0.015	0.014	0.018	.015	0.015	0.012
Rb	.035	.001	0.056	0.023	0.044	0.082	0.046	0.013	0.025	0.007	.013	0.018	0.006
SrO	<.001	.034	0.069	0.044	0.072	0.099	0.093	0.045	0.066	0.081	.053	0.045	0.047
ZrO_2	.185	.013	0.227	0.134	0.179	0.296	0.193	0.054	0.103	0.025	.053	0.091	0.019
BaO	.059	.009	0.139	0.316	0.246	0.463	0.413	0.26	<.001	0.242	.319	0.333	0.414
Sum	100	100	100	100	100	100	100	100	100	100	100	100	100
M.S.	96	70	195	145	156	302	108	487	415	114	129	210	194

The oxide content of Lovejoy Basalt from outcrop as well as other, more phyric basalts are also listed for comparison. Values are not calibrated to a standard with a known weight percent.

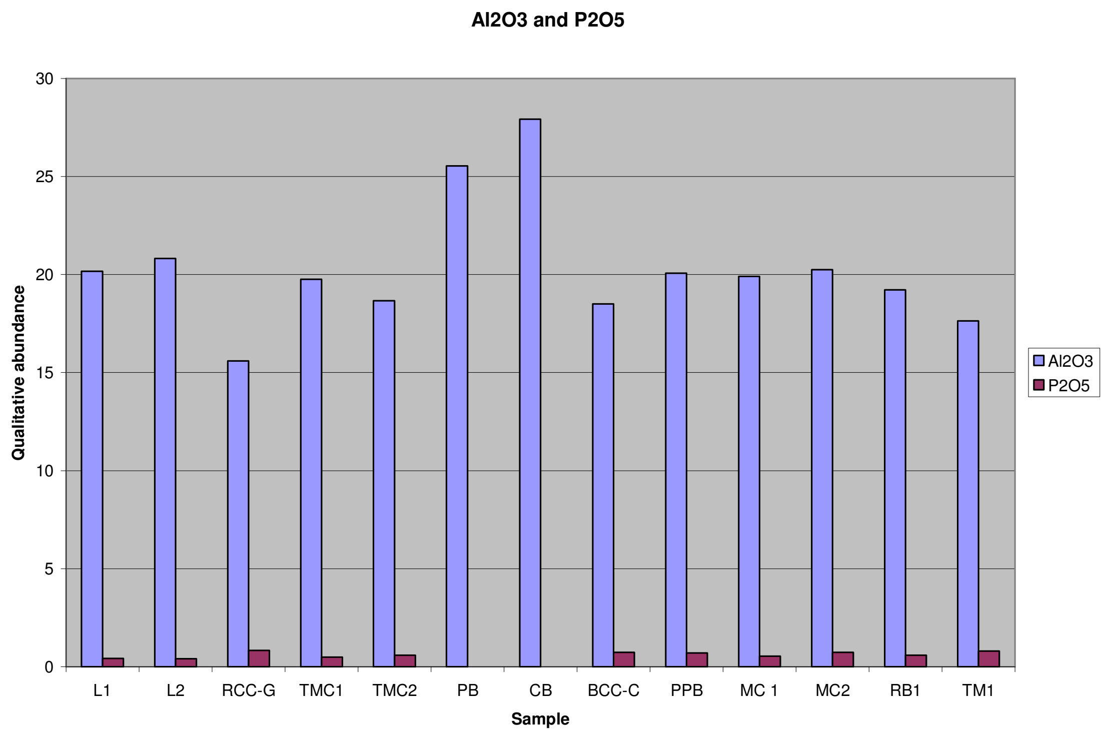


Figure 53. Graph comparing XRF results of basalt samples using Al_2O_3 and P_2O_5 to emphasize differences and similarities.

It might be possible that the basal flow layer containing the pipe vesicles and pahoehoe toes could have a slightly different chemical composition than the rest of the Lovejoy Basalt flows. Further geochemical analysis would undoubtedly be necessary to confirm or refute this.

Prompted by a map in a M.S. Thesis by Maria Tobia (1997) which showed the approximate locations of Lovejoy Basalt outcrops in the Honey Lake Valley, samples MC1 and MC2 were collected in the town of Milford along Highway 395. Although the original outcrop could not be located, sub-angular basalt clasts which appear very similar to Lovejoy Basalt were in unconsolidated conglomerates along road-cuts in the town. The analysis showed them to be very similar in composition to the Lovejoy Basalt.

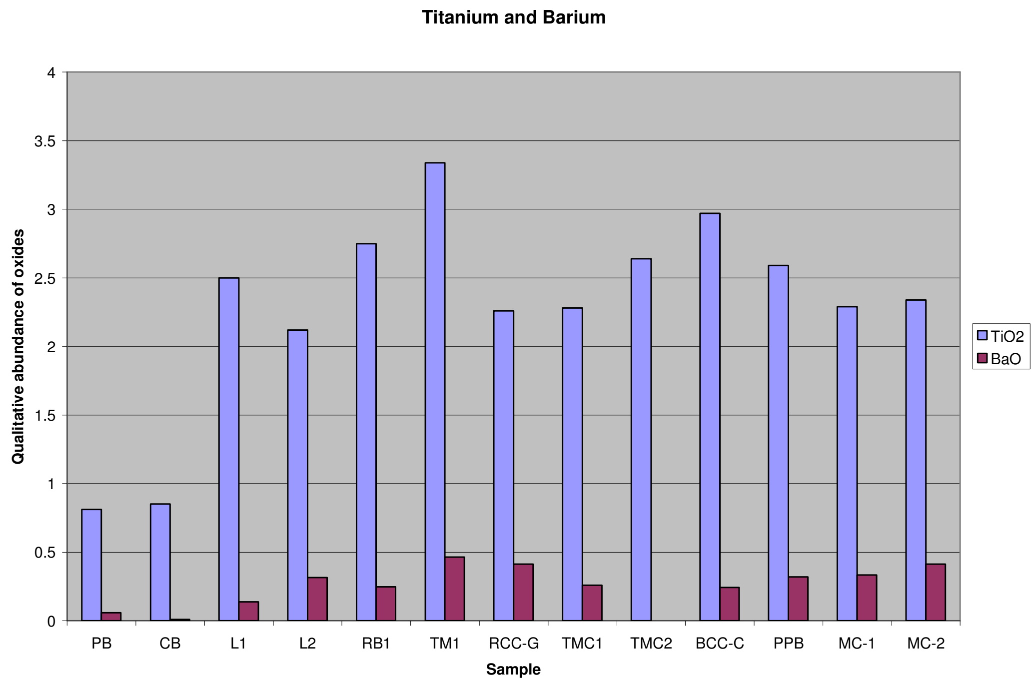


Figure 54. Graph comparing XRF results of basalt samples using trace elements to emphasize differences and similarities.

Because this was a qualitative geochemical analysis, it should serve only as a preliminary study of the possibility that some of the cobbles in the underlying sedimentary units were derived from Lovejoy Basalt outcrops. The analysis also showed that some of the basalt clasts within the same conglomerate units were definitely not Lovejoy Basalt, having a significantly different chemical composition.

If some of the cobbles were derived from Lovejoy Basalt, it would indicate that it was one of a number of basalts exposed at the surface at the time the erosive forces responsible for creating the conglomerates were active. Furthermore, if the entirety of Lovejoy Basalt was erupted over a short period of time, then it would also imply that these conglomerate units are approximately of the same age. Alternatively, the data may suggest that there was more time for Lovejoy Basalt eruption than previously thought.

It should also be noted that the magnetic susceptibility of the cobbles found in the conglomerates underlying the Lovejoy Basalt at Table Mountain are abnormally high for this area, which might be a further indication that they were transported in from distant outcrops, rather than of local origin (see magnetic susceptibility section in Chapter V).

Assessment of Magnetic Suceptibility Data

Magnetic susceptibility measurements were taken at multiple outcrops of Lovejoy Basalt (Table 1) between the vent area at Thompson Peak and the most distant exposures at Orland Buttes and Putnam Peak (Fig. 55). Analyses were made utilizing a Bartington Magnetic Susceptibility Meter with a field probe. Directional aspects of the magnetic susceptibility, such as those used in anisotropy of magnetic susceptibility (AMS) studies, were not measured. The premise of this experiment was based on the possibility that by analyzing the relative intensities of magnetic susceptibility over a regional span of outcrops, patterns might emerge which could give insight into the nature of the original eruption/s. The results were mostly inconclusive, yet hint at various possibilities.

If the measurements were to show a consistent decrease in magnetic susceptibility, and hence, titanomagnetite content, between the proposed vent area and the most distal outcrops, it could support the likelihood that the lava was erupted from a single source area. Because magnetite has a high specific gravity relative to other basaltic minerals, it is presumed that it would settle out of suspension over the course of a long flow.

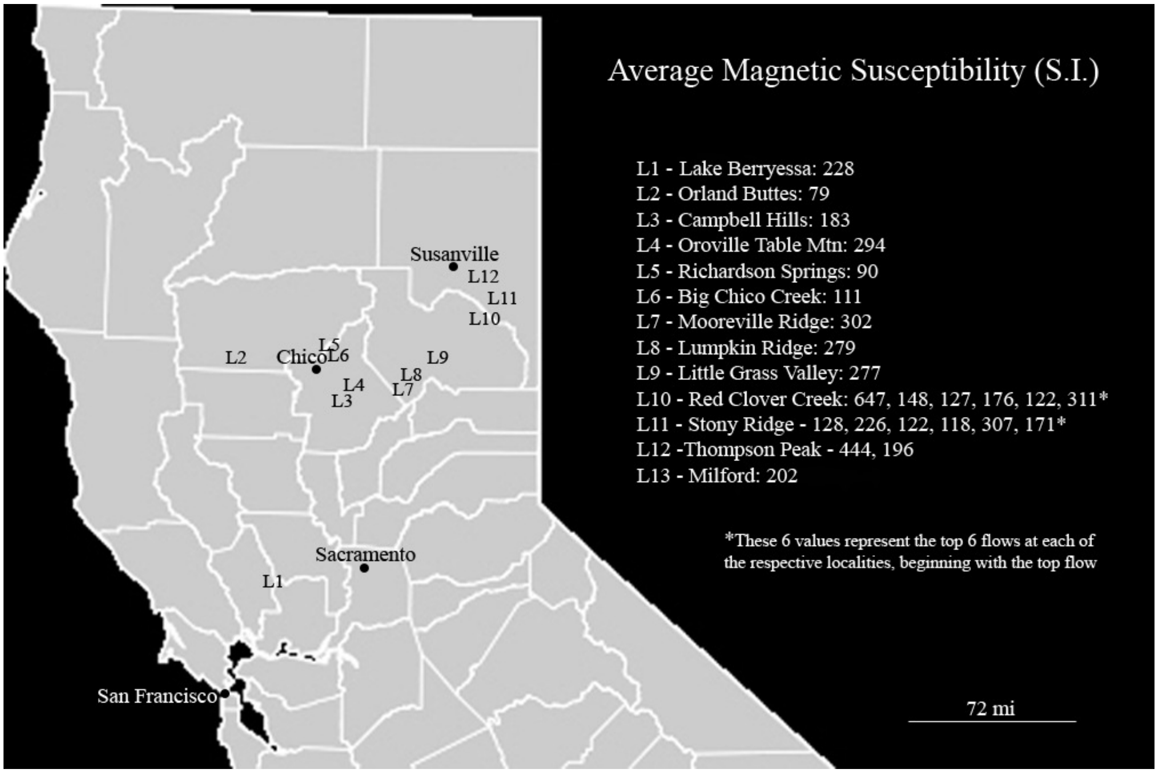


Figure 55. Regional map showing the average magnetic susceptibilities of Lovejoy Basalt outcrops visited during this study.

Furthermore, because titanomagnetite is an accessory mineral, composing a relatively small percentage of the basalt, its content can vary enough to affect the magnetic susceptibility of the rock without affecting its chemical classification (Lindsley, 1966).

Initially, the results of the data seemed to show a crude linear decrease in titanomagnetite content away from the source, at least in the foothills of the Sierra Nevada. Dramatic fluctuations of measurements taken in the general vicinity of the proposed vent area, however, made the pattern much more irregular (Fig. 56). Although perhaps unlikely, one way to explain this would be the possibility that there is a major vent somewhere in the vicinity of Little Grass Valley Reservoir, at the apex of the linear section of the magnetic susceptibility data. The more variable data between Little Grass

Valley Reservoir and Thompson Peak could represent a zone of multiple vents, or multiple eruptions from a single vent, each of which contained varying titanomagnetite contents and hence, magnetic susceptibilities.

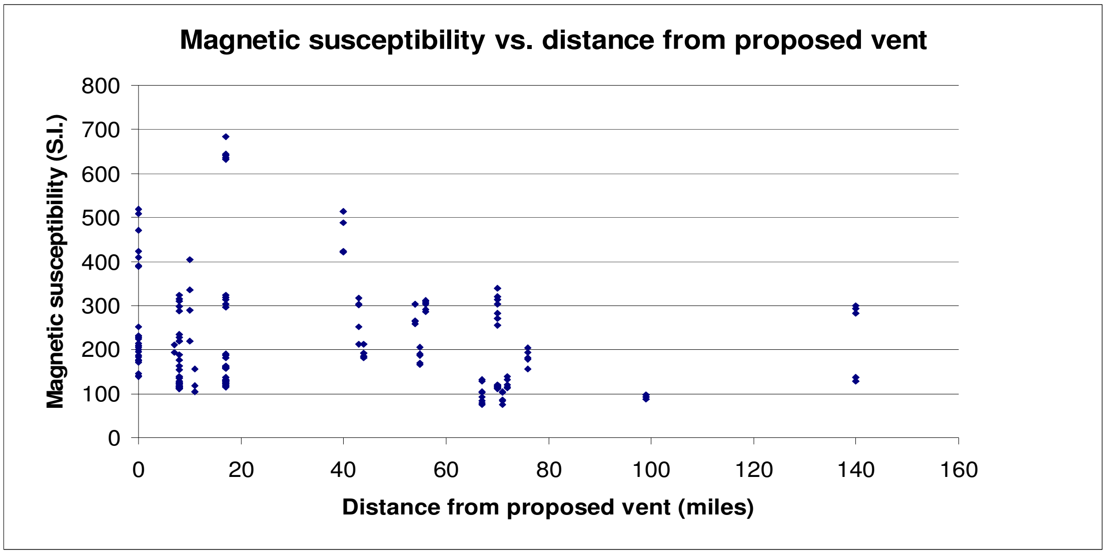


Figure 56. Graph of Magnetic Susceptibilities of regional Lovejoy Basalt outcrops with distance from the proposed vent.

Color coding the data in the graph according to distinguishing characteristics of individual flows brought out new patterns in the measurements (Fig. 57). Each of the categories: aphyric; olivine/garnet phenocrysts; plagioclase phenocrysts; and brecciated scoria, show different variation ranges. The aphyric basalt varies up to approximately 300 S.I units (dimension-less), whereas the basalt containing olivine and garnet phenocrysts and the brecciated scoria both vary up to approximately 130 S.I. The uppermost flow containing the plagioclase phenocrysts varies the most dramatically at nearly 500 S.I.

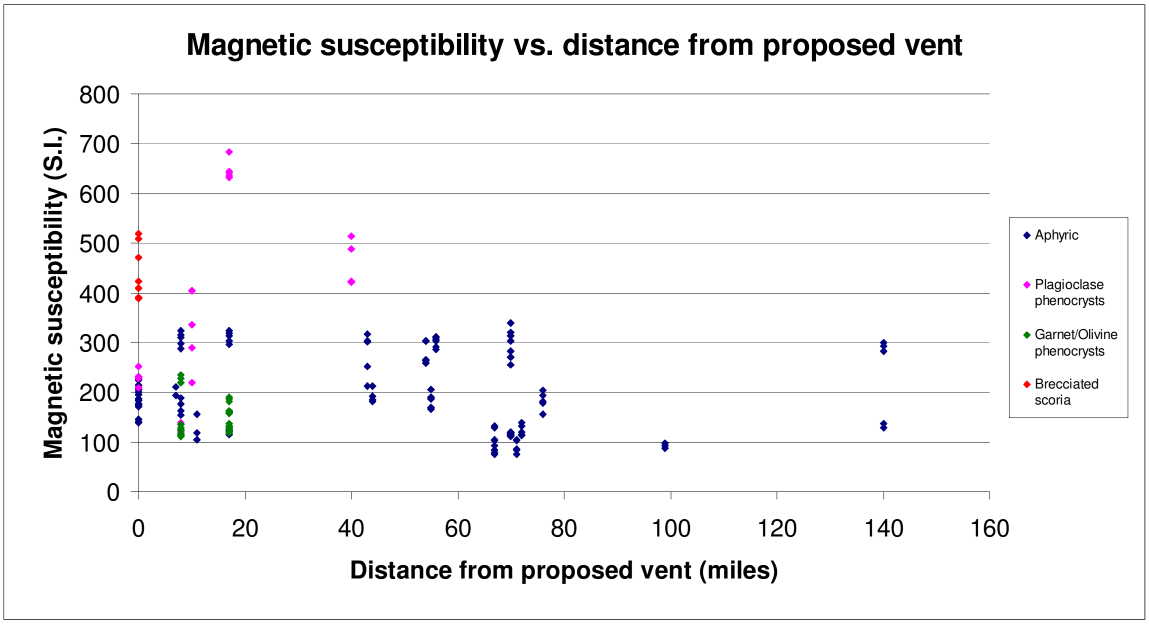


Figure 57. Graph of Magnetic Susceptibilities of regional Lovejoy Basalt outcrops with distance from the proposed vent area, color coded according to distinctive lithological characteristics.

It is possible that rather than showing an overall fluctuation of titanomagnetite content within the Lovejoy Basalt as a whole, these patterns of variation may be representative of the stratigraphy of flows within the basalt, wherein each of the flows is restricted to a particular range of magnetic susceptibility. If this is the case, the data patterns may serve as a physical characteristic which can be measured to help understand the distances that individual flows traveled. Varying the color of the data on the graph according to particular ranges of magnetic susceptibility values, then, could show the lateral extents of particular individual flows within the Lovejoy Basalt (Fig. 58).

If all the Lovejoy Basalt flows did come from the same vent, and if the magnetite does not become depleted with distance from the vent, it would then be necessary to compare this magnetic susceptibility data to measurements taken of the more

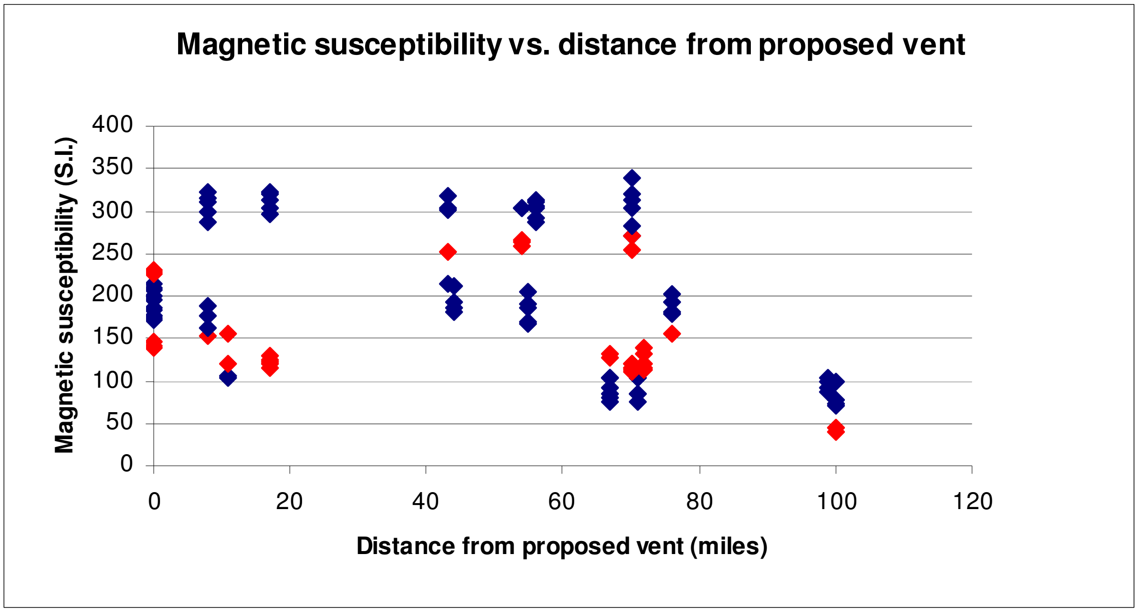


Figure 58. Graph of magnetic susceptibilities of regional Lovejoy Basalt outcrops with distance from the proposed vent area, showing the possibility of characterizing individual flows based on magnetic susceptibility range restrictions.

definitive individual flows found at Red Clover Creek and Stony Ridge. It has been noted that sequences of flows in this area do not seem to correspond, even across relatively short gaps (Durrell, 1959). Magnetic susceptibility data taken at these locations supports this.

The upper plagioclase phenocryst-bearing flow varies dramatically in magnetic susceptibility between Stony Ridge and Red Clover Creek, whereas the three olivine/garnet-rich flows below it seem to correspond, remaining well within 100 S.I. The two aphyric flows below the porphyritic flows, however, do not seem to correspond (Table 3). This could be taken as evidence against the hypothesis that all Lovejoy Basalt erupted from Thompson Peak, but could also simply indicate the likelihood of a more complex distribution of titanomagnetite.

Table 3. Table comparing the average magnetic susceptibilities of the top six flows at Red Clover Creek and Stony Ridge.

Flows	Red Clover Creek		Stony Ridge	
	Magnetic susceptibility	Phenocrysts	Magnetic susceptibility	Phenocrysts
1	647	Plagioclase	128	Plagioclase
2	148	Olivine	226	Olivine, Garnet
3	127	Garnet	122	Garnet
4	176	Olivine	118	Olivine
5	122	Aphyric	307	Aphyric
6	311	Aphyric	171	Aphyric

Although no solid evidence has been found to show that the magnetic susceptibility of a single flow of Lovejoy Basalt can vary more than 130 S.I. in a given area, the uppermost flow found at Red Clover Creek, Stony Ridge, and Thompson Peak varies almost 500 S.I. between all three localities. This is assuming, of course, that all three outcrops are part of the same, once-continuous, flow. Finding only one flow at a particular location, however, does not necessarily exclude the possibility that there were multiple flows containing plagioclase phenocrysts, just as there are multiple flows containing olivine and garnet phenocrysts, as well as multiple aphyric flows.

It should be noted, however, that the magnetic susceptibility of boulders in the seemingly dismantled Lovejoy Basalt outcrop at Dark Canyon varies over 450 S.I. units. This might be an indication that the boulders did not all come from the same flow of basalt, but rather ended up here as the result of landslide activity.

It is likely that the uppermost flow with the plagioclase phenocrysts was once continuous at all three localities, and that it is possible for the magnetic susceptibility of a single flow of Lovejoy Basalt to vary as much as 500 S.I. over a relatively long distance.

If the magnetic susceptibilities of other individual flows vary that much as well, then it could be useful to examine similar patterns to see if it a product of the unpredictable distribution of magnetite in the magma before and during eruption. Stoke's Law ($V = CD^2$ where V is the velocity, C is a constant, and D is the particle diameter) would indicate that the settling velocity of a denser particle in suspension would increase as the square of the radius. The larger radius of magnetite/titanomagnetite crystals within the magma chamber or ascent to the surface might lead to higher variability in magnetite settling rates. Evidence showing that the magnetic susceptibilities of individual flows consistently vary more than 130 S.I. would render this data mostly useless for fingerprinting of individual flows.

It is important to keep in mind that the plagioclase phenocryst-bearing flow, which varies the most in titanomagnetite content, has previously been shown to be anomalous insofar as remnant magnetism. Resolvable changes in the earth's geomagnetic field direction generally happen within a few centuries, and while most of the Lovejoy Basalt flows have an extremely high correspondence to each other, the uppermost flow with the plagioclase phenocrysts has an anomalous remnant magnetic direction, indicating that it may have been erupted significantly later than the other flows (Coe, 2000).

If titanomagnetite content does decrease with distance from the vent, then it would appear from the data that the uppermost plagioclase phenocryst-rich flow could have erupted from a vent near Little Grass Valley Reservoir and traveled both towards the southwest as well as towards the northeast to cap the remnants of the brecciated scoria material from previous eruptions at Thompson Peak.

Considering all the available information, one possible conclusion is that titanomagnetite content is likely to vary within individual flows, and the pattern by which it varies is not well understood, making it difficult, if not impossible, to use regional variations in magnetic susceptibility to fingerprint individual flows. There remains the possibility, however, that titanomagnetite falls out of suspension over the course of the flow, thereby decreasing the magnetic susceptibility with respect to distance from the vent, although direct evidence to support or refute this possibility has yet to be found.

An alternative explanation is that the titanomagnetite content is consistent within individual flows, and that the variation is accounted for by multiple vents which have been long removed and/or covered. If other vents did exist, and if they were anything like the heavily fractured, brecciated, easily eroded, scoria material at Thompson Peak, it is not surprising that they no longer remain. Similar to the way the Lovejoy Basalt protects its softer, underlying, sedimentary rocks in the foothills of the Sierra Nevada, the resistive cap of the Thompson Peak Basalt may be the reason that the Lovejoy Basalt vent at Thompson Peak remains.

Flow Direction Indicators and Fracture Patterns

It is widely accepted that the Lovejoy Basalt flowed southwest from a vent in the Thompson Peak area at least 150 miles to Putnam Peak, near Vacaville, Ca (Busby et al., 2004; Garrison et al., 2008; and others). Particularly, it is thought that the lava flowed south in a broad channel towards the Red Clover Creek area, at which point it turned southwest and flowed the rest of the way down the channel to the ancient Sacramento Valley. Upon reaching the paleo-Sacramento Valley, it became a true flood-basalt, covering much of the northern section of the valley (Van den Berge, 1968; Busby et al, 2004; Garrison et al, 2008). It is questionable whether or not the portion of the Lovejoy Basalt found in the Sierra Nevada can accurately be called a flood-basalt, considering the extent to which it is believed to have been channelized.

Direct indications of flow direction are scarce in the Lovejoy Basalt. Stretched vesicles, perhaps the most reliable indication of flow direction (Peterson, 1972; Bagdassarov and Pinkerton, 2004; Philpotts, 2007), are found only in a few locations, and often at the bases of the flows, many of which have been covered by thick talus slopes and grass-covered sediments. They can be found in abundance at Stony Ridge and in less abundance at Red Clover Creek, where they correspond with the accepted southwards flow direction.

Oroville Table Mountain presents a unique look at multiple indicators which can be compared to each other to help resolve a more precise flow direction for the area. Interestingly, these indicators show a somewhat different flow direction for the area than previously assumed.

An overhang at Phantom Falls, along the west side of Oroville Table Mountain, preserves a large section of the original basal surface of the Lovejoy Basalt (Fig. 20). Along this surface are a variety of linear features, all of which occur within the first few feet of the base of the Lovejoy Basalt, and all of which have a similar westward to northwestward orientation. These linear features include: stretched vesicles up to several centimeters long and up to 3 centimeters in diameter; small tube vesicles less than half of a centimeter in diameter which stretch back several centimeters into the rock; linear groove marks, possibly representing clasts on the surface of the underlying sedimentary rock which resisted the flow of the lava; and pipe vesicles resembling small lava tubes up to 5 inches in diameter which stretch several feet back into the rock (Fig. 24).

Pipe vesicles, which have been used as indicators of flow direction and paleoslope (Peterson, 1972; Walker, 1987), are the result of gas bubbles rising through a lava flow at a point in the cooling history when its yield strength prevents the lava from closing behind the vesicles. It has been shown that they occur only in thin pahoehoe units and on slopes less than 4 degrees (Philpotts, 1987). All of these requirements are met by the Lovejoy Basalt, although the presence of pahoehoe lava remains somewhat controversial.

It has been stated previously that the Lovejoy Basalt entirely lacks pahoehoe toes or ropes (Busby et al, 2004). However, some evidence of a possible pahoehoe flow does exist in a very thin section of lava near the basal surface of the Lovejoy Basalt underneath Phantom Falls at Oroville Table Mountain, at the exact location where the pipe vesicles and other flow direction indicators were found.

A few hundred feet directly above these basal surface flow indicators are a series of linear protrusions and depressions which have long been noted to cover much of the surface of Oroville Table Mountain. There are varying opinions as to the relationship between these linear features and any sort of internal structure of the basalt flows. According to Creely (1965), they seem to be directly related to an internal joint system that could be the result of differential consolidation of the lava while it was in motion. According to Garrison (2004), however, they have no apparent relationship to the internal joint system of the basalt.

Following the linear undulations to the edge of the flow in numerous locations supports the hypothesis that they do appear to connect to vertical joints which open up into steep, wedge-shaped gullies. This relationship can be seen in the field as well as with Google Earth (Fig. 59).

Although they are also clearly visible on the surface of Lovejoy Basalt outcrops at Campbell Hills and Orland Buttes, due to dense foliage and/or severe erosion, these features are concealed from examination via aerial photo at all other known localities. They are, however, visible via direct examination in the field, appearing as extensive parallel to sub-parallel low-lying ridges up to 15 feet tall and extending many meters in length.

Taking the bearings of some of these linear features directly above the flow indicators found on the basal surface consistently yielded approximately perpendicular orientations. This leads to the possibility that there may be a direct relationship between the orientation of the linear features found on the surface of Lovejoy Basalt, the preferential vertical fracturing, and its original flow direction. The nature of this relationship remains unknown, however, as it is uncertain what internal mechanisms within the lava flow would result in a manifestation of all three structural features. It is clear, however, that there is no apparent relationship between the orientations of these linear features and orientations of structural features associated with the Chico Monocline.

The relationship could, of course, be a coincidence. However, the same relationship between flow direction indicators and linear surface features exists at Campbell Hills and Orland Buttes, as well as at outcrops in the Sierra Nevada (Table 4).

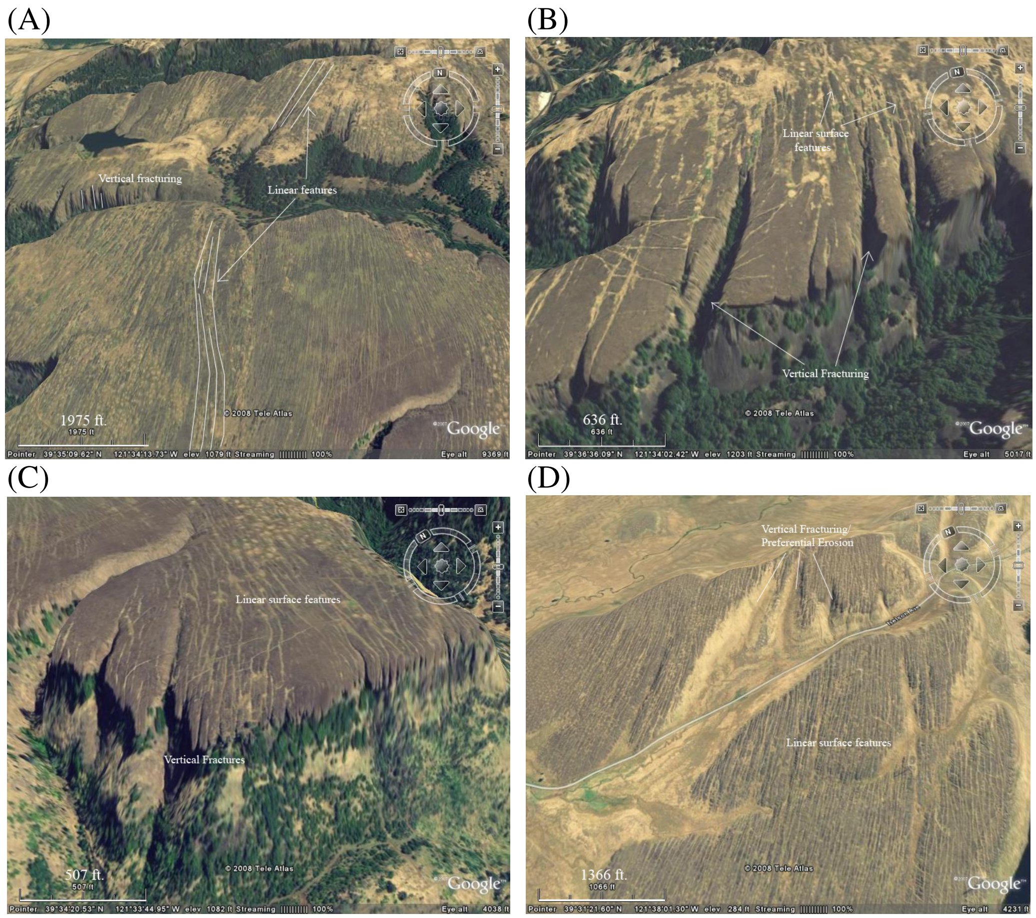


Figure 59. Images showing the relationship between the linear surface features and preferential vertical fracturing at Oroville Table Mountain and the Campbell Hills. The images were accessed in January 2009 from Google Earth (http://earth.google.com).

Assuming these relationships are consistent, an estimate of the flow path of the Lovejoy Basalt from Thompson Peak to Putnam Peak can be approximated using a combination of data collected in the field and on Google Earth (Fig. 60).

Some of the flow direction approximations shown on the map are based on measurements taken of the orientations of extensive vertical fractures seen in the field which seem to correspond to the linear undulations found on the surface, the most prominent of which

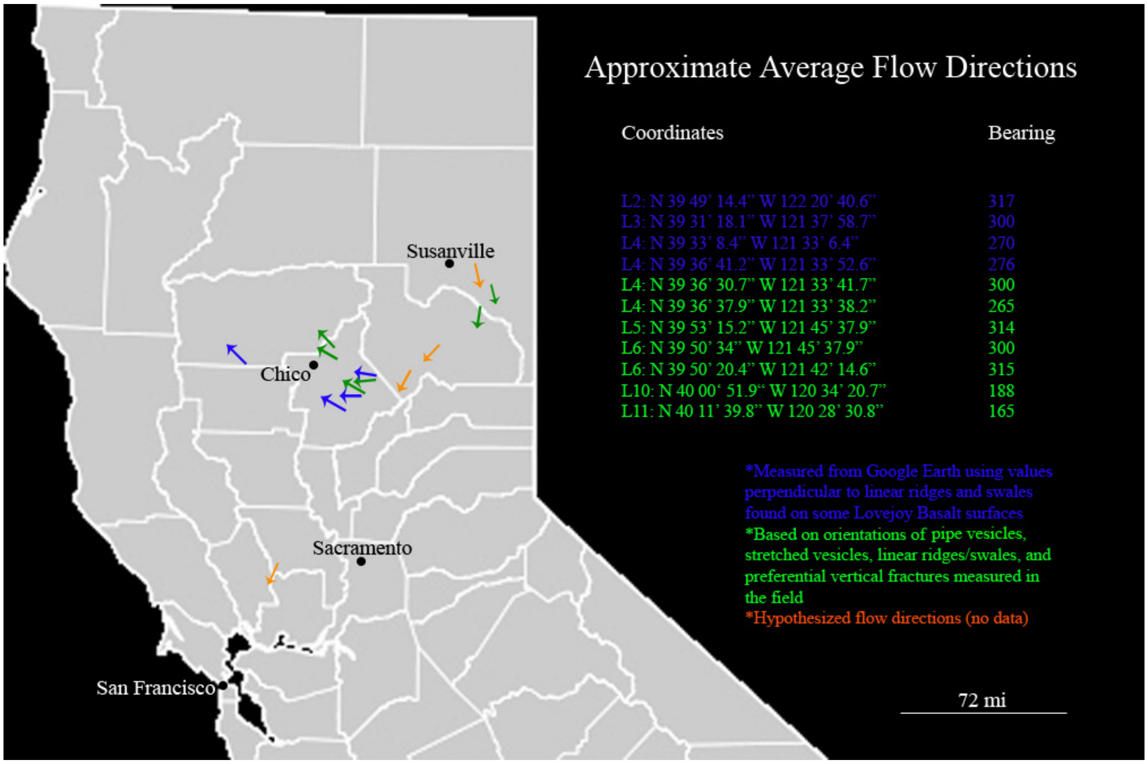


Figure 60. Regional map of approximate, hypothesized, flow directions of Lovejoy Basalt in northern California.

was found in the Big Chico Creek Ecological Reserve (Fig. 30). Less prominent fractures (Fig. 40) as well as significant protrusions (Fig. 41) were found at the edges of the flows at Red Clover Creek and Stony Ridge, all of which correspond with the generally accepted flow direction for those areas.

Most of what is known about fracture patterns in basalt lava flows comes from studies of the Columbia River flood basalt group to the northeast (Schaefer, 2002). Because the Lovejoy Basalt is similar to the Columbia River Basalt group in many ways, it is likely that these fracturing characteristics also apply to the Lovejoy Basalt.

Typically, basalt lavas are classified as being either pahoehoe, aa, or blocky, each of which reflects differences in how the surface of the lava fractures during the

Table 4. Table of flow direction data.

Location	G.P.S.	Method	Measurements	Average Flow Bearing
Orland	N 39 49’ 14.42”	Google Earth	047, 049, 044	317
Buttes	W 122 20’ 40.6”	Flattened Vesicles	NW-SE*	
Campbell	N 39 31’ 18.1”	Google Earth	035, 033, 034,	300
Hills	W 121 37’ 58.7”		023, 027, 028	
Oroville	N 39 33’ 8.4”	Google Earth	000, 355, 357,	270
Table	W 121 33’ 6.4”		003, 005	
Mountain				
	N 39 33’ 5”	Google Earth	044, 040, 039,	312
	W 121 33’ 51.4”		042, 045	
	N 39 36’ 30.7”	Stretched vesicles	300, 306, 302,	301
	W 121 33’ 41.7”		297, 299, 303,	
			301	
		Flow grooves	296, 298	297
	N 39 36’ 37.89”	Stretched vesicles	272, 288, 281,	283
	W 121 33’ 38.2”		291	
				253
		Lava tubes	260, 250, 245,	
			253, 242, 270	264
		Tube vesicles	261, 268	276
		Google Earth	008, 010, 003,	
			005, 004	
Richardson	N 39 50’ 34.0”	Linear ridges	026, 030, 037,	300
Springs	W 121 45’ 37.9”		022, 033	
	N 39 53’ 15.16”	Linear ridges		314
	W 121 46’ 43.55”		060, 027	
Big Chico	N 39 50’ 20.4”	Vertical fracture	045	315
Creek	W 121 42’ 14.6”			
Red Clover	N 40 11’ 39.8”	Stretched vesicles	170, 167, 172,	165
Creek	W 120 28’ 30.8”		150	
Stony	N 40 00’ 51.9”	Fracturing/Swales	109, 91, 87,	188
Ridge	W 120 34’ 20.7”		99, 103	

Only the stretched vesicles and flow grooves are definite indicators of flow direction. Fractures and linear ridges measured using Google Earth and in the field are hypothetically perpendicular to flow direction. The last column lists inferred approximate average flow directions for each location. *Note that the NW-SE measurement of flattened vesicles at Orland Buttes comes from a M.S. Thesis by Maria Tobia (1997).

course of the flow (Kilburn, 2004). Except for the thin, atypical section of basalt containing possible pahoehoe ropes mentioned above, it appears that the Lovejoy Basalt is almost entirely of the blocky variety, lacking pahoehoe and aa features.

There are four types of fractures which typically develop in basalt lavas: column-bounding, column-normal, entablature, and inflation fractures (Kattenhorn and Schaefer, 2008). The first three are directly related to cooling, whereas inflation fractures are caused solely by the internal pressure, and hence, motion of the lava (the force suggested by Creely to be responsible for the linear surface features). Blocky lavas, such as the Lovejoy Basalt, are distinguished by their ability to fracture without cooling, due to significant eruption strength (Kilburn, 2004).

It is possible that the linear undulations found on the surface of the Lovejoy Basalt are the surface expression of inflation fractures which formed within the basalt during motion while it was pouring down into the ancient Sacramento Valley. The relationship between the lateral orientation of inflation fractures and the flow direction, however, remains unconfirmed at this point.

It should be noted that fracture patterns also vary depending on the aspect ratio (width divided by depth) of the basalt (Kattenhorn and Schaefer, 2008). The Lovejoy Basalt probably had a much lower aspect ratio in the upper reaches of the Sierra Nevada than it did in the foothills and in the Sacramento Valley.

A more comprehensive study of the relationship between the lateral orientation of inflation fractures and the flow direction of basalt lavas could be useful for understanding not only the Lovejoy Basalt, but also a wide variety of basalt lava flows in the Pacific Northwest and elsewhere.

Paleo-topographic Obstructions to Lava Flow

Assuming the Lovejoy Basalt was extruded from a single vent, it is then necessary to attempt to determine the extent to which the Lovejoy Basalt was channelized along its exceptionally long journey. Much erosion has taken place since the mid-Miocene, although the Lovejoy Basalt is considerably more resistant to erosive forces than rocks of the Subjacent Series of the Sierra Nevada. Due to topographic evidence from the following cross sections (Figs. 63-70), it is likely that some of the basement rocks which currently exist along the path of the Lovejoy Basalt may have been topographic barriers the lava had to flow around en route to the ancient Sacramento Valley.

When tracking the journey of the Lovejoy Basalt from Thompson Peak to Putnam Peak, it is necessary to speculate about the original distribution of the basalt based on what subcrops and exposures remain (Fig. 61). It is also necessary to have an understanding of what pre-Miocene rocks existed at the surface just prior to eruption of the Lovejoy Basalt (Fig. 62).

Previous studies assume that the Lovejoy Basalt flowed approximately southwest down a broad, paleo-channel cutting across the ancient northern Sierra Nevada (Creely, 1959; Van den Berge, 1967; Durrell, 1987; Garrison and Wagner, 2008; and others). When it reached the Sacramento Valley it apparently spread out and covered much of the northern valley on its path towards its maximum southern extent in the Putnam Peak area, near Vacaville, Ca. The new topographic evidence presented in this paper, however, shows that there was likely more than one channel directing the lava in the Sierra Nevada before it reached the ancient Sacramento Valley.

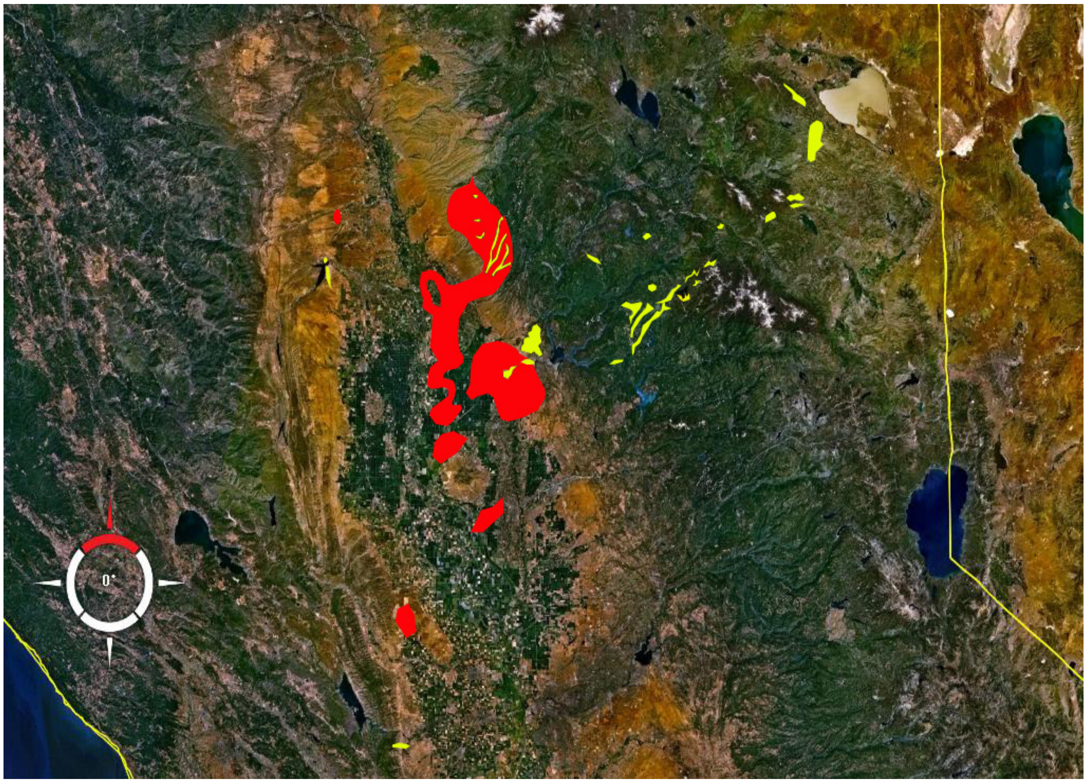


Figure 61. Regional map of all the remaining Lovejoy Basalt in northern California. The outcrops (yellow) were transposed onto this satellite image from geologic maps of northern California produced by the California Division of Mines and Geology. Subsurface basalt (red) was transposed from a previously published map showing the distribution of the Lovejoy Basalt in the subsurface Sacramento Valley (Harwood and Helley, 1987). The image was accessed in January 2009 using N.A.S.A. World Wind (http://worldwind.arc.nasa.gov).

Construction of cross sections between various outcrops of Lovejoy Basalt in the central and western belts of the Sierra Nevada show that there were topographic highs which prevented the lava from flowing to certain areas. Most of these topographic barriers were Mesozoic plutons but a few were Mesozoic/Paleozoic metamorphic rocks. In only one area could the Eocene age sedimentary rocks have presented a topographic barrier.

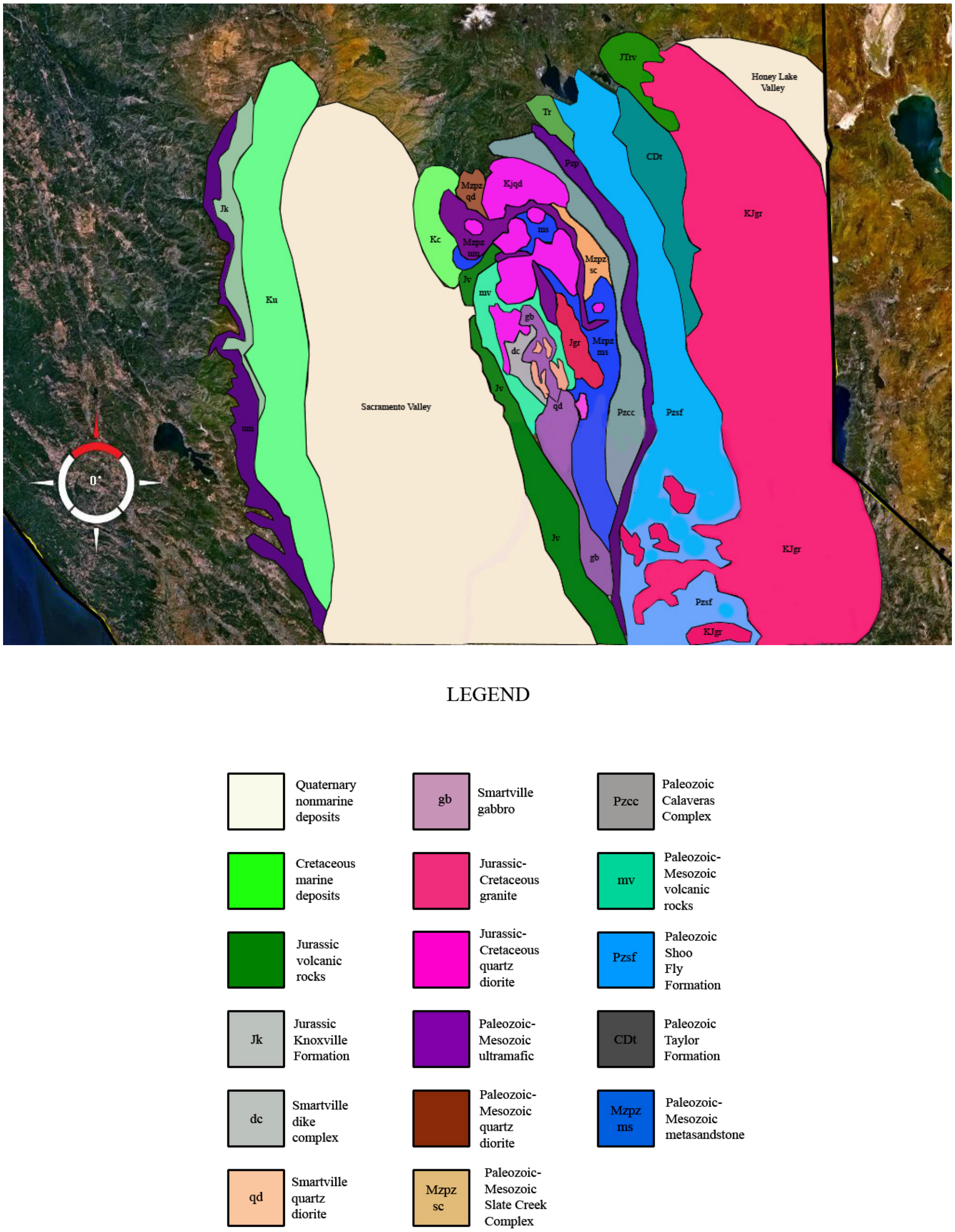


Figure 62. Regional paleo-geologic map of northern California showing pre-Miocene rocks which existed at the surface prior to eruption of the Lovejoy Basalt. Eocene gravels and other sediments are not included because not enough remaining outcrops are available to accurately project the original distribution. The underlying image was accessed in January 2009 from N.A.S.A. World Wind (http://worldwind.arc.nasa.gov).

Thompson Peak to Red Clover Creek.

With the exception of the cobbles found in the town of Milford in the Honey Lake Valley, the ridge along Thompson Peak represents the northeastern-most outcrop of the Lovejoy Basalt. The undeniable vent indicators such as agglutinated clasts, scoria, and bombs, are what lead researchers to this ridge as the source of all known Lovejoy Basalt outcrops. It is difficult to disprove the existence of other vents, however, because the physical indications may have been eroded.

There are two primary possibilities for the direction the lava flowed away from the vent area. Either it traveled southeast to Stony Ridge then took a turn towards the south to flow to Red Clover Creek, or the vent was longer than previously assumed and extended through an area just to the northeast of the of Stony Ridge. If the latter possibility is true, then the lava from the vent may have actually begun its flow towards the south/southeast from both Thompson Peak as well as the northeastern edge of Stony Ridge.

The only flow direction indicators found on Stony Ridge (stretched vesicles) showed a southward flow direction for the lava (Fig. 37), implying that there was likely a topographic barrier directly to the east of Stony Ridge during the mid-Miocene. From Stony Ridge, the lava appears to have taken a slight turn towards the southwest towards the outcrops which remain at Red Clover Creek.

Red Clover Creek to Little Grass Valley.

Although there is significant east-down normal faulting in the Eastern belt of the Sierra Nevada offsetting Lovejoy Basalt contacts, it is likely that the outcrops at Red Clover Creek and the outcrops near Little Grass Valley were once continuous. A possible exception is the anomalously tilted outcrop found northeast of Little Grass Valley reservoir (Fig. 35).

Between Little Grass Valley Reservoir and the Sacramento Valley, however, the original distribution of the Lovejoy Basalt is more complex, branching off into multiple channels. This is also the area where the magnetic susceptibility of Lovejoy Basalt outcrops reaches its maximum value and becomes more complex compared to other areas. Furthermore, this area also represents the maximum southern distribution of the flow which contains conspicuous plagioclase phenocrysts and caps the brecciated vent material at Thompson Peak.

Little Grass Valley to the Sacramento Valley.

A cross section between the small Lovejoy Basalt outcrops southeast of Bucks Lake through the outcrop in the middle of the Hartman Bar Pluton and through the western edge of Lumpkin Ridge shows the possibility that some sections of the basement rocks may have prevented the three outcrops from being continuous (Fig. 63). It is likely, however, that the lava flowed over the top of these minor obstructions and that the three outcrops were continuous as a single sheet of lava.

A cross section between the outcrop at the northern edge of the Merrimac Pluton and the outcrop on the Hartman Bar Pluton shows more prominent topographic obstructions of Mesozoic/Paleozoic basement rock (Fig. 64). In this case, the two outcrops of Lovejoy Basalt were not continuous with each other in all dimensions. However, they may represent two distinct channels of lava within a broader, generalized paleo-channel. If this is the case, the channels may have come together up or downstream of the location.

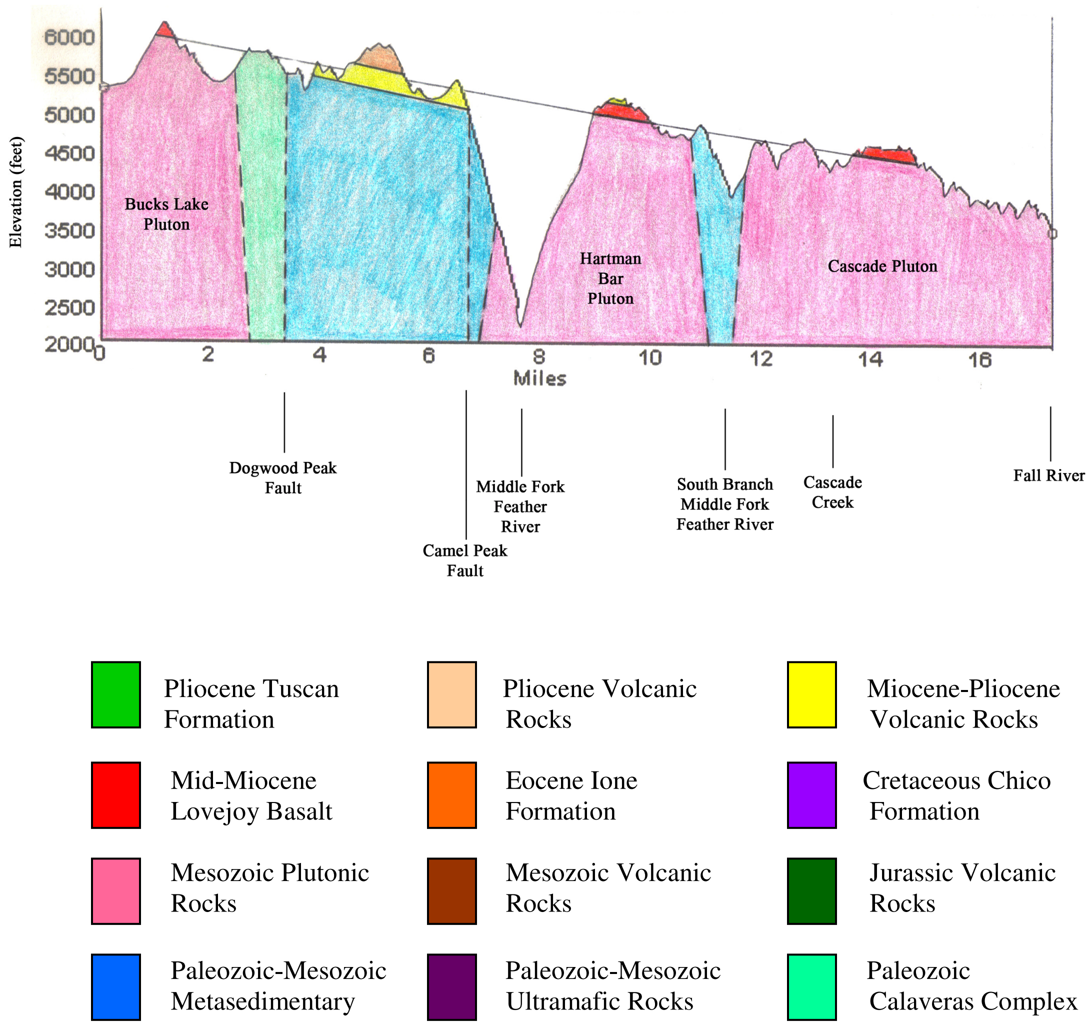


Figure 63. Cross section between the Bucks Lake area and Lumpkin Ridge showing continuity between the three Lovejoy Basalt outcrops.

Similarly, a cross section between Big Chico Creek and the outcrop on the northern edge of the Merrimac Pluton shows that it is unlikely the two outcrops were connected as a single, planar, sheet of lava (Fig. 65). They may have been continuous, but the lava would have had to have flown around topographically high sections of Mesozoic/Paleozoic basement, implying a sinuous distribution.

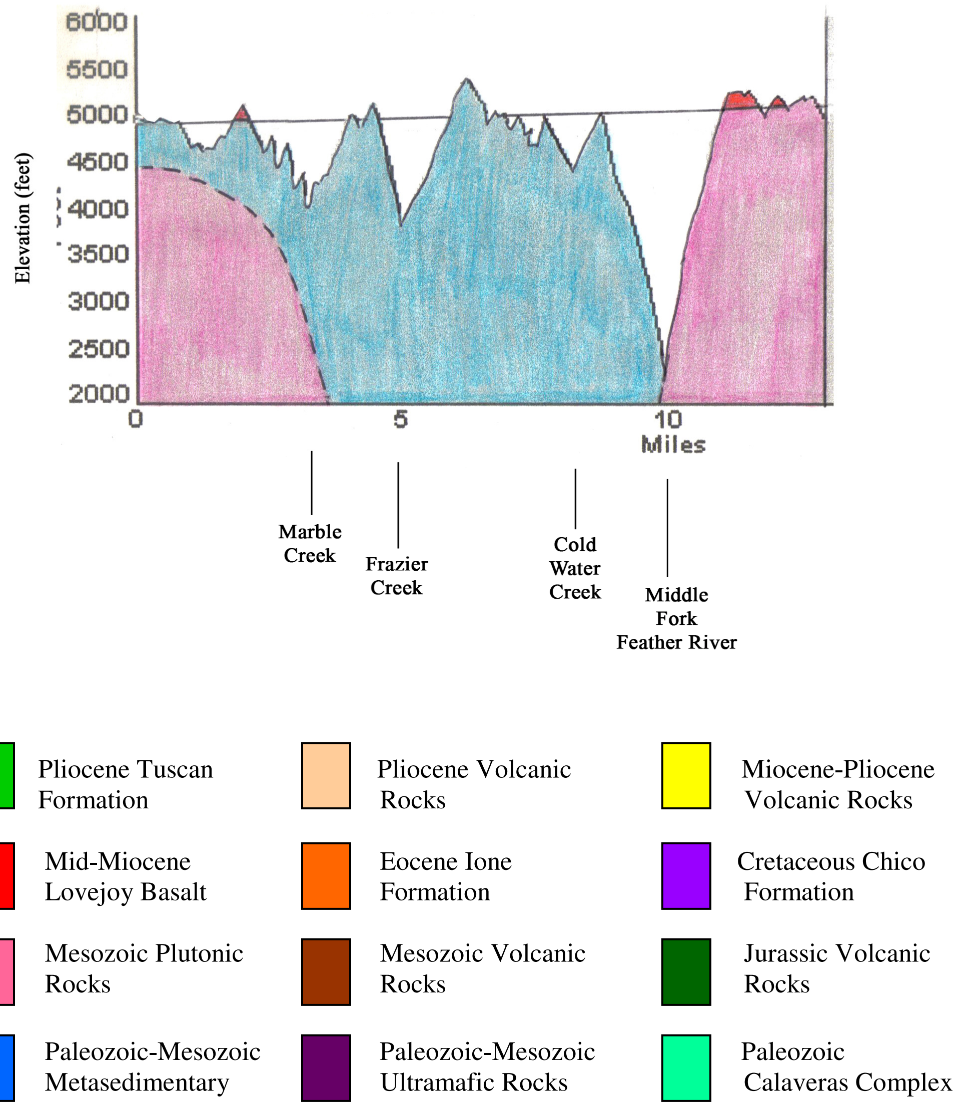


Figure 64. Cross Section between northern Merrimac Pluton and Hartman Bar Pluton showing prominent topographic obstructions. Basement rock likely prevented the two Lovejoy Basalt outcrops from being continuous as a planar sheet of lava.

Furthermore, the Lovejoy Basalt terminates in the Little Chico Creek area, which could either mean that there was a channel edge or the basalt was preferentially eroded prior to the emplacement of the overlying Tuscan Formation. A third, less likely possibility is that there was a vent somewhere in the area. A section of Lovejoy Basalt at the northern edge of the Lovejoy Basalt distribution in Big Chico Creek is raised up higher than the surrounding flow. This topographic anomaly of the Lovejoy Basalt has been referred to as a possible vent source by Burnett (in Tobia, 1997).

A cross section between Wicks Corner, southeast of Oroville Table Mountain, and the same outcrop at the northern edge of the Merrimac Pluton, on the other hand, shows no visible obstructions (Fig. 28). The two outcrops could have once been connected as a single sheet of lava or topographic barriers may have been present and since eroded away. If the two outcrops were connected as a relatively planar sheet then there seems to be a gradient change at approximately the same location where the underlying Eocene deposits are projected to end. This indicates that the gradient of the lava was somewhat higher when traveling directly over basement rocks, becoming shallower as it poured onto the upper reaches of the Eocene deposits.

The outcrop located in Dark Canyon, near the northern edge of Lake Oroville, does not line up topographically with any of the other regional Lovejoy Basalt outcrops. In the field, it does not appear to be *in situ*. The apparent dislocation may indicate that it was either brought to its current position by vertical faulting (unlikely) or as the product of landslides at the edge of the steep surface associated with the erosion of the Mesozoic/Paleozoic basement rock by the ancient Feather River.

Further evidence that this outcrop is out of place is the fact that magnetic susceptibility measurements taken here were much more varied than at any other location indicating that it is composed of rocks from multiple flows of Lovejoy Basalt.

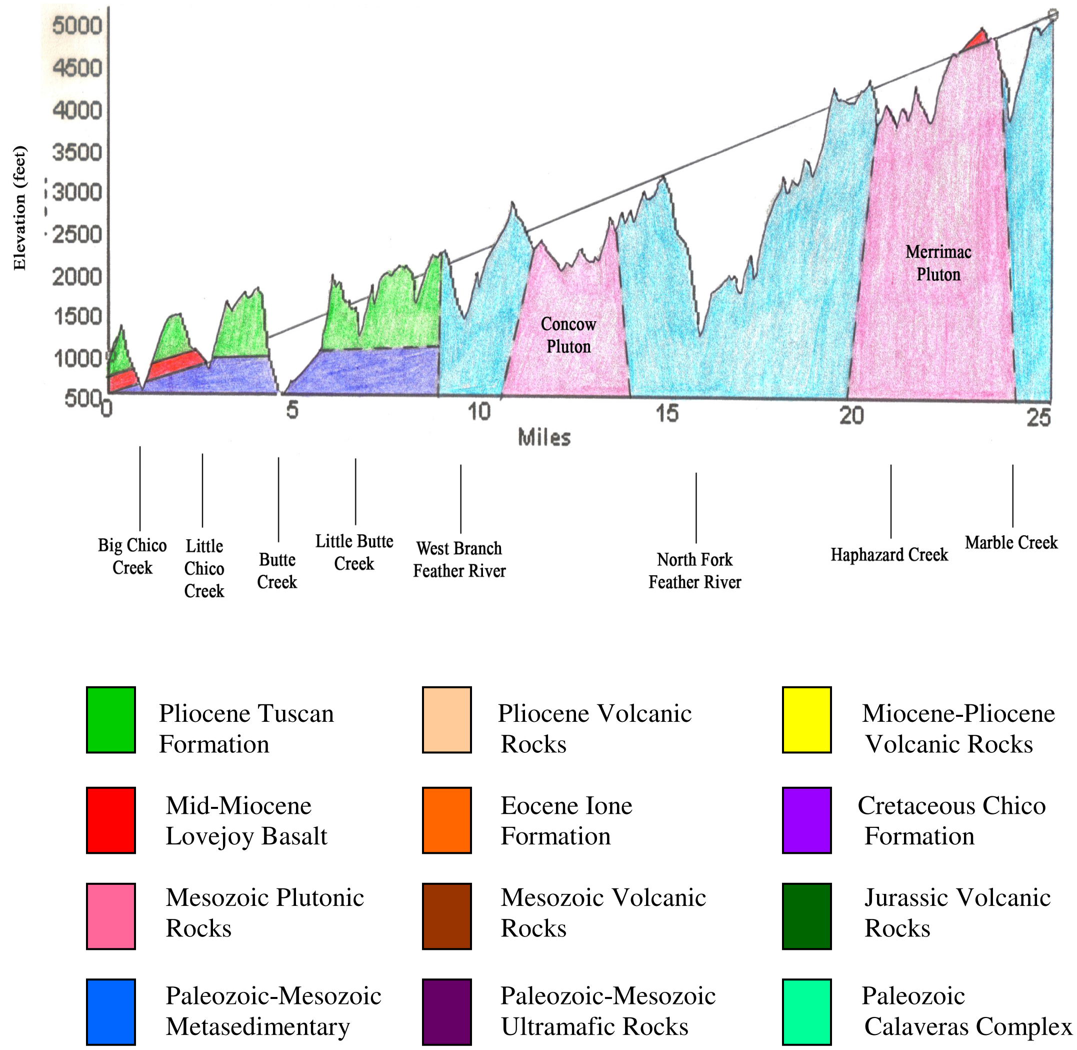


Figure 65. Cross Section between Big Chico Creek and the northern Merrimac Pluton showing topographic basement obstructions. The obstructions probably prevented the two Lovejoy Basalt outcrops from being continuous as a planar sheet of lava.

A cross section between Oroville Table Mountain and Lumpkin Ridge shows that the two relatively large outcrops were not connected as a planar lava sheet (Fig. 66). Parts of the Cascade Pluton, the Bald Rock Pluton, and sections of Mesozoic/Paleozoic basement rock presented significant topographic barriers.

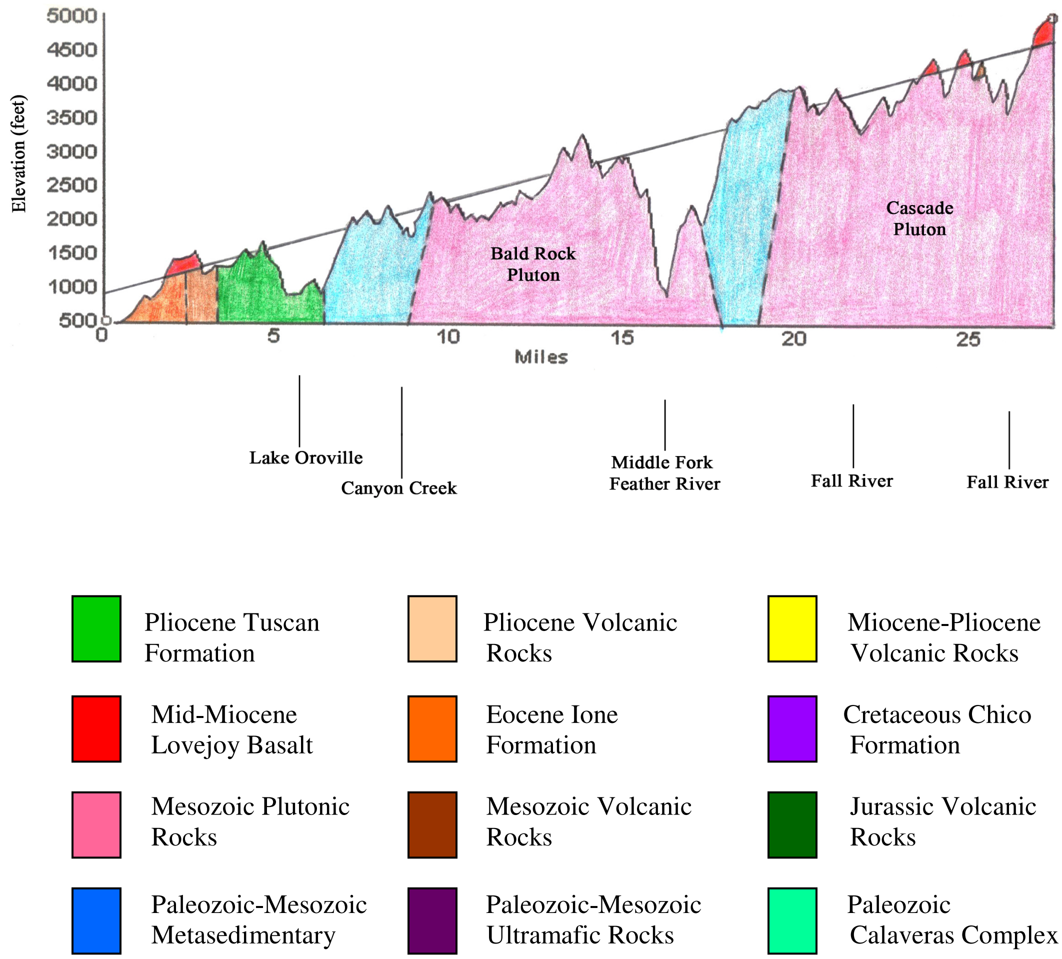


Figure 66. Cross Section between Oroville Table Mountain and Lumpkin Ridge showing prominent topographic basement obstructions. The obstructions probably prevented the two large outcrops of Lovejoy Basalt from being continuous as a planar sheet of lava. They may have been continuous, but I interpret a higher degree of channelization than has been previously noted.

However, a cross section between Campbell Hills and some Lovejoy Basalt outcrops near the southern edge of the Bald Rock Pluton show no topographic barriers between them (Fig. 67). Although the Bald Rock Pluton was a topographic obstruction preventing the lava at Lumpkin Ridge from flowing directly to Oroville Table Mountain, it may have flowed around the southern edge of the pluton to reach the same destination.

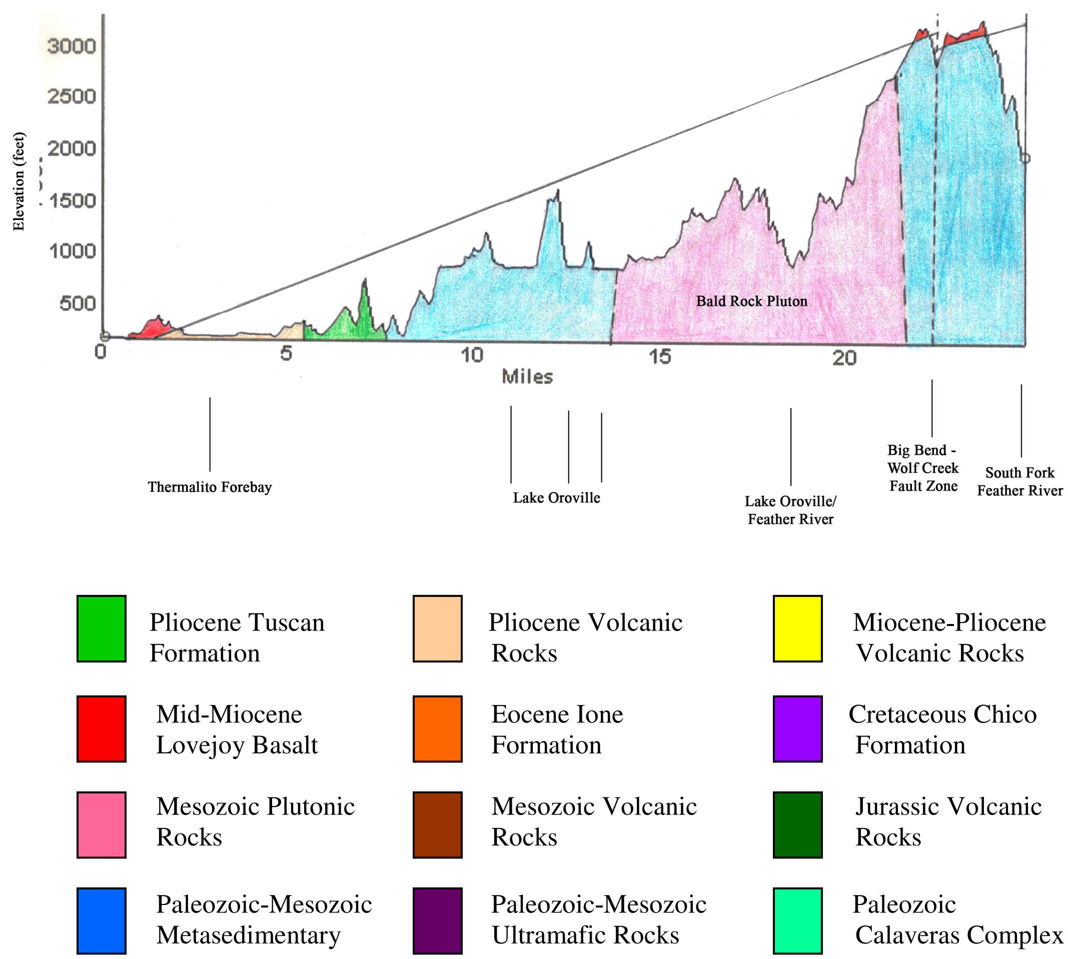


Figure 67. Cross Section between Campbell Hills and the southern edge of Bald Rock Pluton showing no apparent topographic obstructions that could have prevented the two Lovejoy outcrops from being continuous as a planar sheet of lava. This may have been the path that the lava took from Lumpkin ridge to Oroville Table Mountain.

The Lovejoy Basalt outcrops in Mud Creek, Rock Creek, Big Chico Creek, and Little Chico Creek were most likely connected as a single, planar sheet (Fig. 68). However, cross sections between Rock Creek and Table Mountain show that it is inconclusive whether or not the Lovejoy Basalt ever existed in the Butte Creek area.

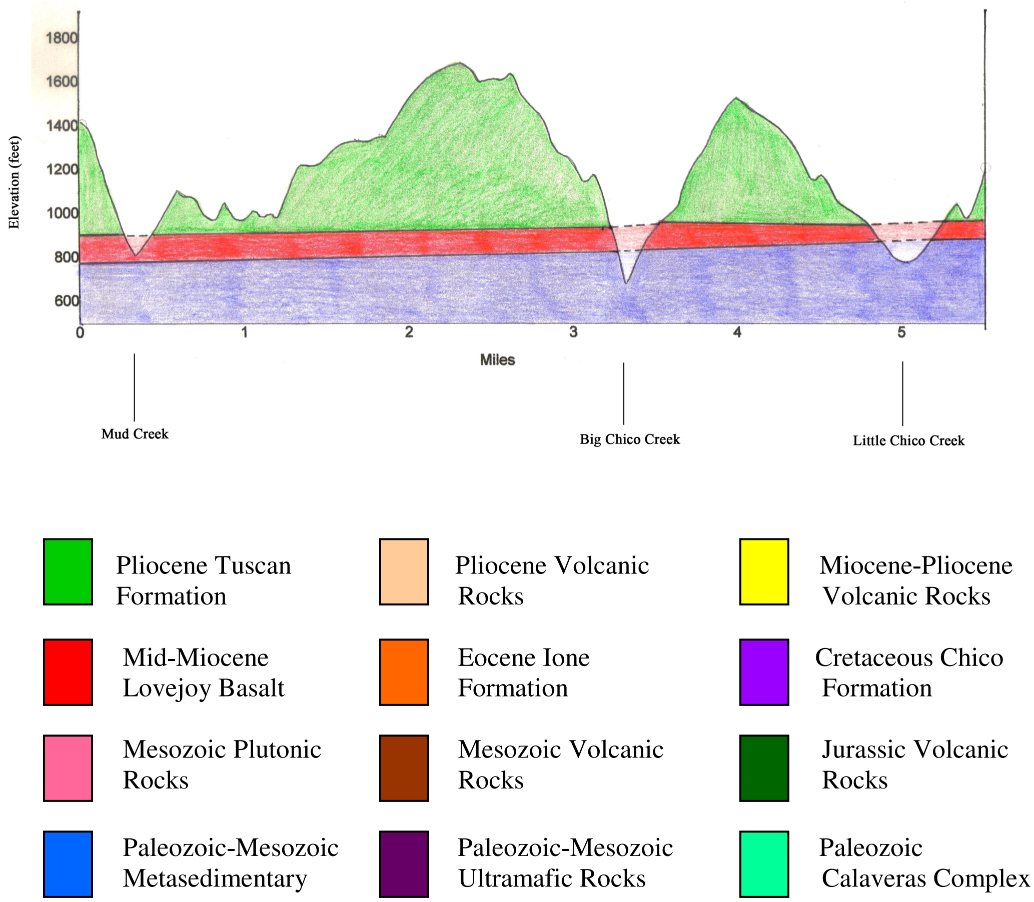


Figure 68. Cross Section between Mud Creek and Oroville Table Mountain showing continuity between the three Lovejoy Basalt outcrops.

The first of the two cross sections shows the possibility that the Lovejoy Basalt may have been continuous between Big Chico Creek and Table Mountain (Fig. 69). If so, the erosive force of the ancient Butte Creek would have had to remove the Lovejoy Basalt as well as some of the underlying Cretaceous Chico Formation before the deposition of the Tuscan Formation began in the Pliocene. This could have created the deeply incised, relatively broad paleo-channel that the Tuscan Formation filled. This could explain why the Tuscan Formation is thicker in the Butte Creek area than it is in the Big Chico Creek area (visible in cross sections).

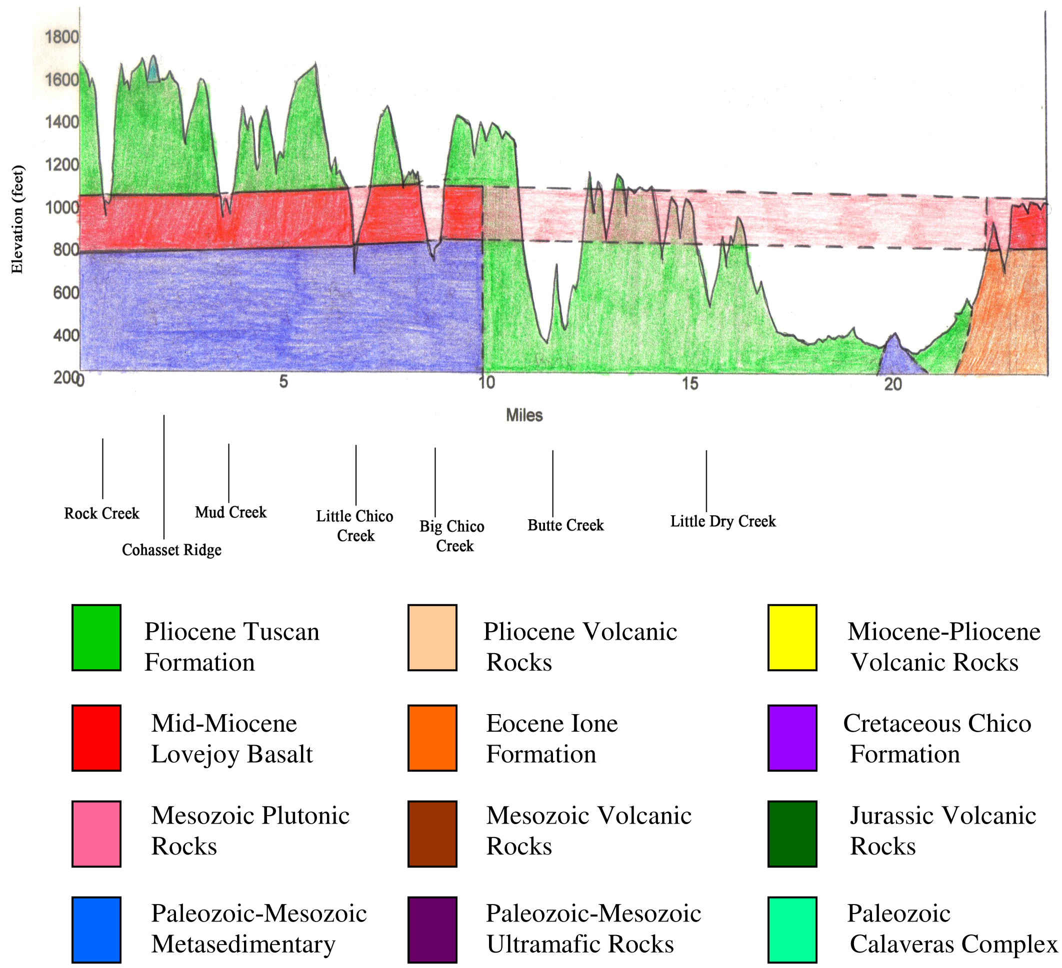


Figure 69. Cross Section between Rock Creek and Oroville Table Mountain. One interpretation of the missing section of Lovejoy Basalt in the Butte Creek area is that the basalt and underlying Chico Formation were removed by erosive forces, later to be filled in by the Tuscan Formation.

Alternatively, if the Lovejoy Basalt was never in the Butte Creek area (Fig. 70) (as the result of topographic barriers) then this could help explain why erosion of the ancient Butte Creek was incised more deeply relative to Big and Little Chico Creek.

Without the protective cap of the Lovejoy Basalt to slow the denudation, the Butte Creek area would have been incised more deeply relative to surrounding areas.

It could also be a combination of the two interpretations. The Lovejoy Basalt in the Butte Creek area could have been eroded early; those same erosive processes continued, incising deeply into the underlying Chico Formation prior to the beginning of the deposition of the Tuscan Formation.

A small topographically high outcrop at the northwestern edge of Oroville Table Mountain (seen on the cross section as a small, pointed outcrop just to the left of Oroville Table Mountain) is marked on the Geologic Map of the Chico Quadrangle as being Eocene sedimentary rock. If this is the case, then it could represent the edge of a paleo-channel, which would favor the model showing the Lovejoy Basalt never having existed in the Butte Creek area. However, closer inspection using Google Earth shows that it is difficult to determine whether or not the outcrop is Lovejoy Basalt or the underlying Eocene deposits.

Upon reaching the ancient Sacramento Valley, the Lovejoy Basalt apparently spread out, forming thicker individual flows than those found higher in the Sierra Nevada. Even supposing that the lava traveled down the slope of the ancient Sierra Nevada in multiple channels, rather than one broad channel, it is highly likely that they converged in the valley, becoming a more extensive flood basalt.

The surface of the paleo-Sacramento Valley had, according to a M.S. thesis written by Van den Berge (1967), significantly more relief than it does today. However, it remains controversial as to whether the slope of the Sierra Nevada during the mid-Miocene was steeper or shallower than it is today. Considering that much of the

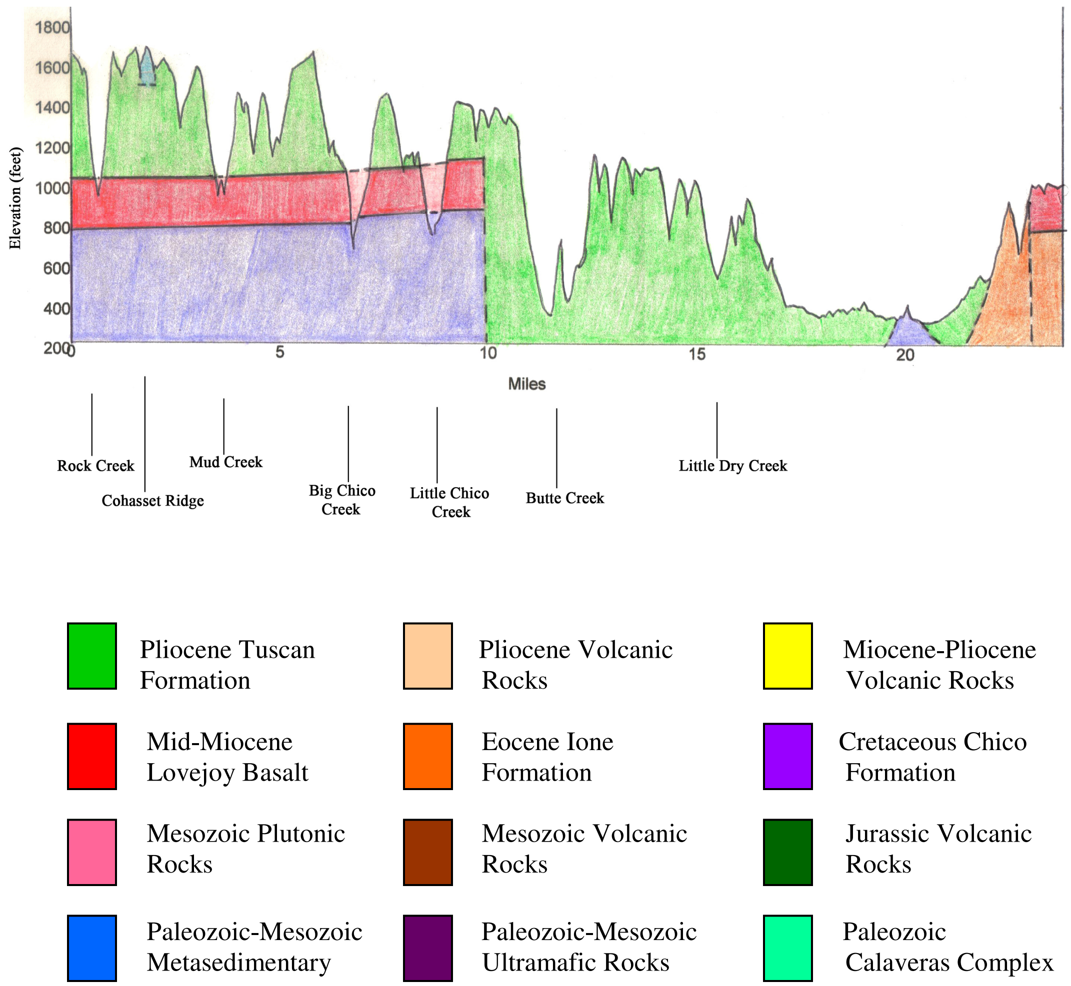


Figure 70. Alternative cross section between Rock Creek and Oroville Table Mountain. A second interpretation of the missing Lovejoy Basalt in the Butte Creek area is that the basalt was never there (due to channelization). Without the protection of the overlying, erosion-resistant basalt, the sedimentary rocks may have been removed at a more rapid pace, resulting in a thicker sequence of Tuscan Formation deposition.

northern Sierra Nevada was greatly reduced by the Eocene (e.g. Lindgren, 1911; Creely, 1955; Durrell, 1966) and the fact that the most dramatic uplift occurred after the extrusion of the Lovejoy Basalt (Wakabayashi, 1999), it is more likely that the ancient Sierra Nevada had less relief during the mid-Miocene than it does today.

<u>The Sacramento Valley to the Coast Range</u>.

After initially ponding at the eastern edge of the northern Sacramento Valley where it covered the Eocene auriferous gravels of the Ione Formation and the Cretaceous marine deposits of the Chico Formation, the lava then proceeded to cover the Eocene nonmarine deposits of the Nord Formation in a series of stream valleys (Van den Berge, 1968).

The lava appears to have flowed directly west to the Orland Buttes as a nearly continuous sheet. However, as it traveled southeast towards Putnam Peak, the relief of the basal surface of the Lovejoy Basalt varied as much as 400 feet over short distances. The relief of the upper surface of the basalt was considerably less, indicating the likelihood that it filled in topographically low areas as it traveled.

Similar basalt conglomerates to the ones found directly underling the Lovejoy Basalt at Oroville Table Mountain and Big Chico Creek are also reported in the subsurface of the Sacramento Valley (Van den Berge, 1968).

The distribution of the remaining Lovejoy Basalt in the subsurface of the Sacramento Valley, as determined by well-log data, shows that it is much more abundant in the northern part of the valley than in the south towards Putnam Peak, although this could simply be a result of preferential erosion removing the outcrops in the south.

Although Putnam Peak, the Orland Buttes, and Thompson Peak represent the apices of the maximum known extent of the distribution of the Lovejoy Basalt, the original distribution may have exceeded these boundaries. It may be possible to further determine the northernmost extent by examining the distribution of Lovejoy Basalt cobbles within the Red Bluff Formation, which are abundant in the Big Chico Creek area. If they are present in the Red Bluff Formation north of the northernmost known outcrop, it could indicate that the maximum northern extent was greater than currently believed.

There are many possible ways to model channel distribution of the flows between Thompson Peak and Putnam Peak. A few possibilities seem more likely than others considering flow direction indications and topographic barriers. The distinctive geochemical similarity of all Lovejoy Basalt outcrops as well as the magnetic evidence showing that it was all likely erupted in a geologically short span of time, it is likely that the Lovejoy Basalt was extruded from a single vent source in the Thompson Peak area. The possibility of multiple vents, however, cannot be excluded. Although unlikely, it could be that multiple events erupted very similar volcanic material over a short period of geologic time.

Previously, it has been generally assumed that the Lovejoy Basalt flowed down the ancient Sierra Nevada in one large, relatively low-relief paleo-channel (Fig. 71). By combining data from previously published geologic maps, new cross sections, and flow direction data accumulated during this study, a new interpretation of the channelization of Lovejoy Basalt can be constructed (Fig. 72).

In the new interpretation, the primary lava channel from the Thompson Peak vent diverged into two channels somewhere in the vicinity of Big Grizzly Creek. The northern flow continued down slope to pour into the Big Chico Creek area and out into the ancient Sacramento Valley. The southern flow likely diverged again to flow around both sides of the Bald Rock Pluton before reaching the valley.

The Lovejoy Basalt seems to have flowed over nearly every rock type available in the northern Sierra Nevada. However, it does appear that many of the Cretaceous plutonic rocks were flow obstructions. Definite exceptions are the Hartman Bar Pluton, upon which the Lovejoy rests, and the Cascade Pluton. Judging by the elongated pattern of the Lovejoy Basalt on the surface of the Cascade Pluton, it is apparent that either the basalt was deposited in previously incised channels within the granitic rock or both rock units were deeply incised by the ancient Feather River sometime after the eruption of the basalt.

It is interesting to note that the apparent “hole” in the subsurface Lovejoy Basalt southwest of Big Chico Creek was likely caused by a paleo-topographic flow obstruction which existed during the mid-Miocene. Another pattern is visible in the subsurface Lovejoy Basalt southwest of the Butte Creek area which highly resembles a meandering river channel (Fig. 72). This channel, which seems to cut right through the subsurface Lovejoy Basalt could be taken as evidence that the ancient Butte Creek was a highly erosive force sometime after the extrusion of the basalt. Nonetheless, it remains difficult to be certain of whether or not the Lovejoy Basalt ever inhabited space in the area between Big Chico Creek and Oroville Table Mountain.

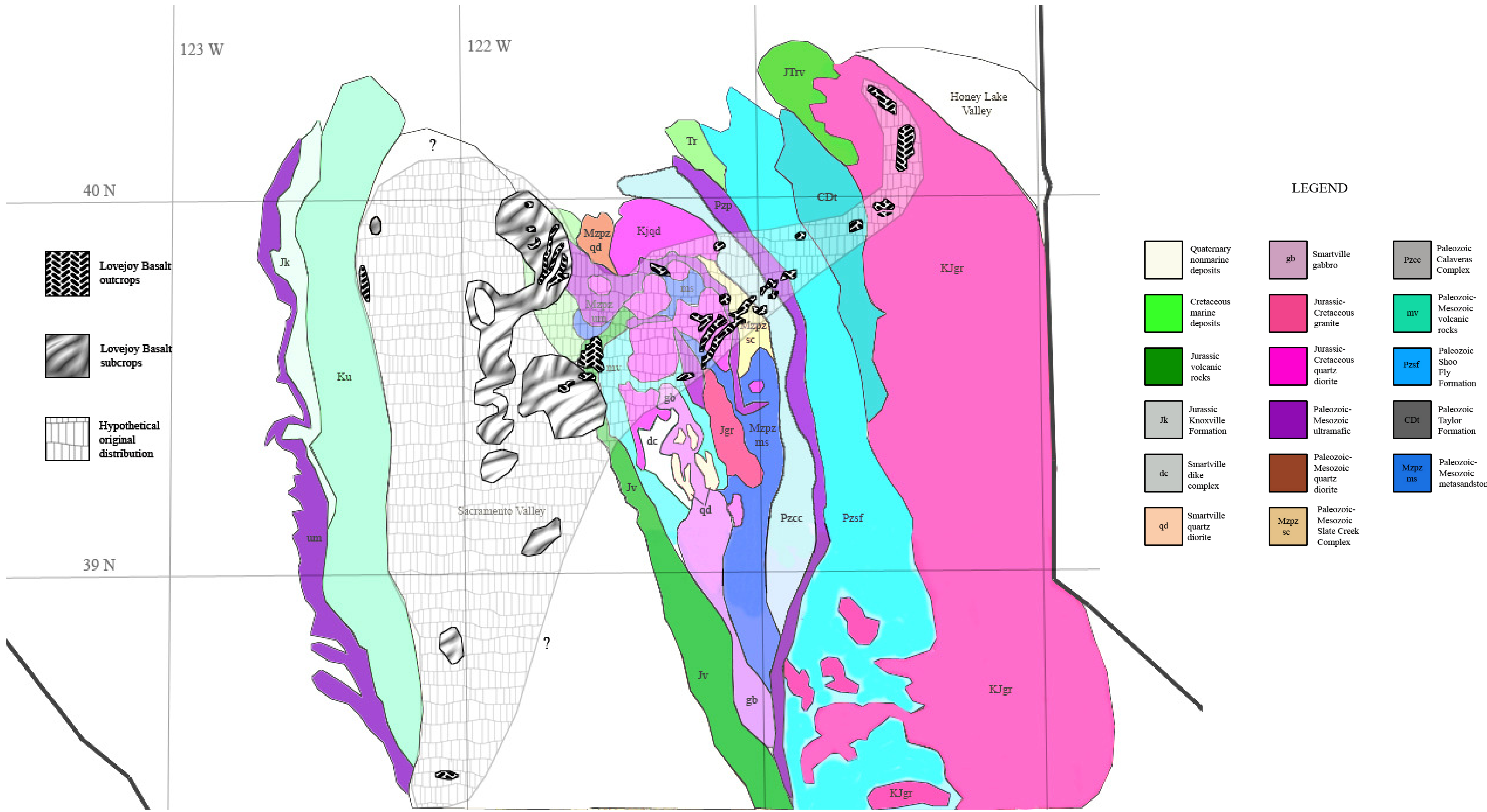


Figure 71 – Geologic map of northern California showing remaining Lovejoy Basalt outcrops and subcrops. Also shown is a projection of the hypothetical original distribution of the lava in which it flowed down a singular broad paleo-channel and broadly flooded the ancient Sacramento Valley.

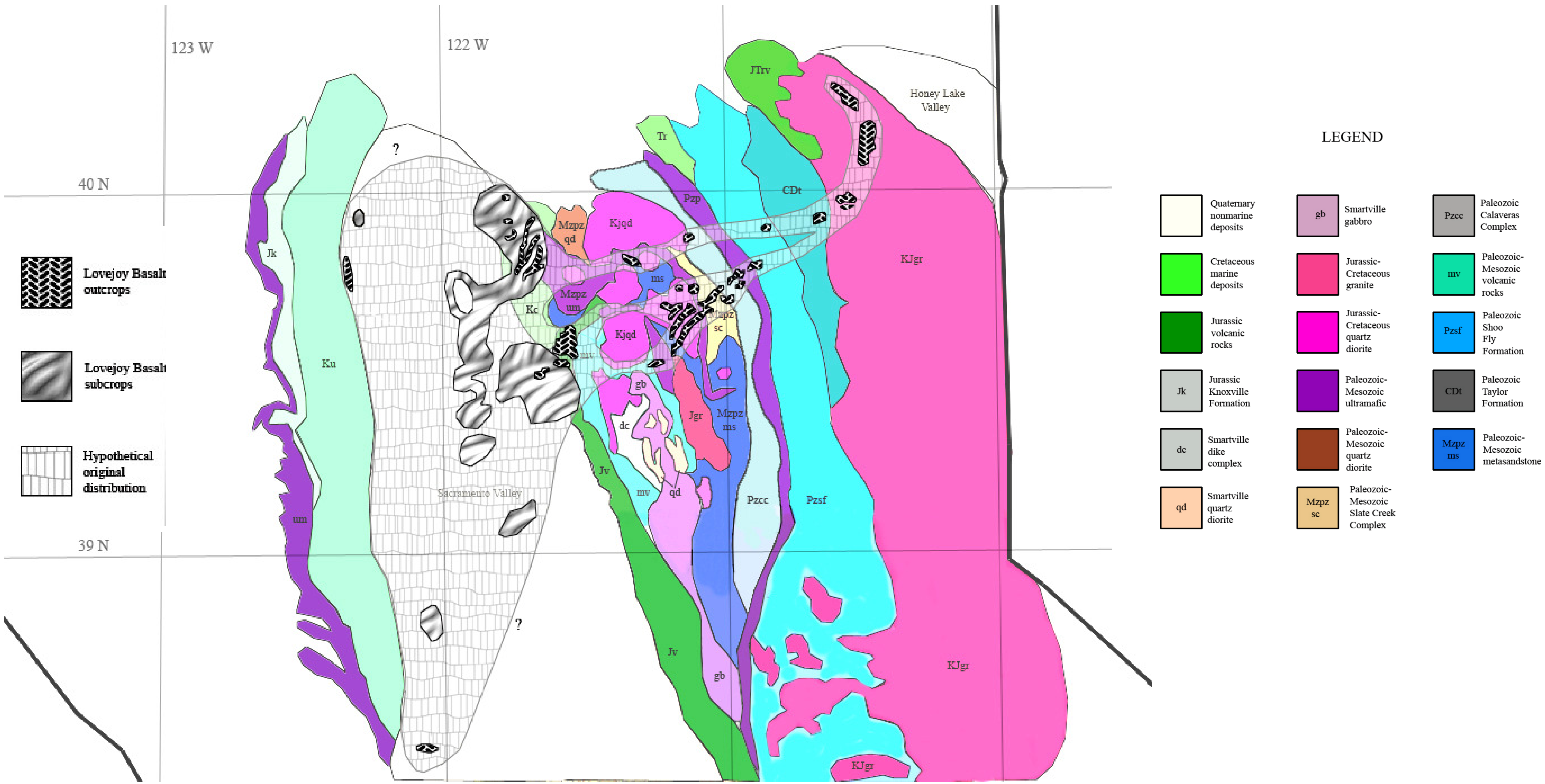


Figure 72 – Geologic map of northern California showing remaining Lovejoy Basalt outcrops and subcrops. Also shown is a projection of a new hypothetical interpretation of the original distribution of the lava in which it flowed down multiple channels. The degree of channelization in the ancient Sacramento Valley remains uncertain. It is likely that the lava was highly channelized and that a great deal of the ancient Sacramento Valley was not once covered by Lovejoy Basalt.

CHAPTER VI

CONCLUSIONS

Summary of Results and Recommended Research

Over time, the collective perception of the Lovejoy Basalt has resolved dramatically and will undoubtedly continue to do so. With the age and chemistry well-confined and an understanding of the tectonic origins of the magma becoming more consistent, there are few remaining mysteries to be solved. However, some aspects remain uncertain, most of them pertaining to details of the original physical distribution of the basalt, such as the stratigraphy and extent of individual flows and the maximum regional extent of its distribution.

Magnetic susceptibility measurements of a wide distribution of Lovejoy Basalt outcrops between the vent source at Thompson Peak and the southwesternmost known outcrop at Putnam Peak have provided vague results, at best, showing no clear patterns in the data. The possibility that there is a regional decrease in titanomagnetite content away from the vent area is indeterminable, or else is confused by multiple flows.

It may be possible to use this type of relative magnetic susceptibility data as a distinguishing physical characteristic to fingerprint individual flows within the Lovejoy Basalt, based on the fact that the magnetic susceptibility of a rock can vary without the chemistry of the rock varying noticeably. A more detailed study would undoubtedly be necessary to arrive at any definite conclusions.

Surprising westward to northwestward oriented flow direction indicators, including stretched vesicles, tube vesicles, pipe vesicles, and flow grooves were measured along the basal surface of the Lovejoy Basalt at Phantom Falls and Beatson Falls. These orientations are likely a result of the lava spreading upon reaching the ancient Sacramento Valley, possibly as it flowed around the southern edge of Bald Rock Pluton.

The prominent linear features seen on the surface of Oroville Table Mountain appear to be related to a system of vertical joints. They have been measured to be nearly perpendicular to the orientations of the flow direction indicators at all places where both are present. More evidence should be obtained, however, to conclude whether or not this relationship is consistent.

The paleo-topography over which the Lovejoy Basalt flowed largely remains debatable, but new cross sections through various outcrops of Lovejoy Basalt between Little Grass Valley Reservoir and the Sacramento Valley show that there were topographically high basement rocks of the Subjacent Series which prevented lava flowage to certain areas. Assuming all of the lava was extruded from the proposed vent area at Thompson Peak, the lava was likely diverted into at least two different channels, a northern branch and a southern branch. The southern branch may have diverted a second time to flow around the Bald Rock Pluton. All three channels may have been part of a broader, generalized paleo-channel. Furthermore, channelization in the ancient Sacramento Valley may have also been higher than suspected.

This higher degree of channelization could help explain why the rigid-tilt-block model overestimated Late Cenozoic Sierra Nevada uplift when using the Lovejoy

Basalt as the stratigraphic reference unit. The possibility of other Lovejoy Basalt vents, however, cannot be excluded at this time. The Stony Ridge, Little Grass Valley Reservoir, and Big Chico Creek areas are candidates for the possible existence of a vent, each for different reasons.

The direct contact between the Lovejoy Basalt and the Cretaceous granitic basement was located along the vent ridge at Thompson Peak, although the relationship between the two units is difficult to determine. The contact is, however, somewhat steeply inclined, which could be indicative of sub-vertical motion of the lava. Vertically oriented sections of what appeared to be horizontal basalt columns were also observed along the vent ridge, which may also indicate vertical motion of lava along feeder dikes. These dike-like features are surrounded by brecciated scoria material with zones of clastogenic texture, possibly representing the more violent aspect of the eruption.

X-ray fluorescence analysis of well-rounded basalt cobbles shows that they have nearly identical chemical compositions to Lovejoy Basalt. The cobbles originate from conglomerate units directly underlying Lovejoy Basalt outcrops at Oroville Table Mountain. Similar conglomerates have been reported to directly underlie the Lovejoy Basalt in the subsurface of the Sacramento Valley. It is difficult to determine how long it took to form such conglomerates but if the cobbles are Lovejoy Basalt, then the units must be approximately the same age as the Lovejoy Basalt, based on the premise that the entirety of the basalt was erupted within a span of several centuries. Alternatively, the Lovejoy Basalt may have erupted over a longer period of time than expected.

The uppermost flow containing the plagioclase phenocrysts has an anomalous remnant magnetic signature. This indicates that it may have erupted at a significantly later time than the rest of the individual flows, supporting the alternative possibility mentioned above. It may have even originated from a different vent, considering it horizontally caps the unstratified, brecciated, scoria material found at the Thompson Peak vent.

Sub-rounded to sub-angular cobbles of basalt with nearly identical compositions to Lovejoy Basalt were found at two different locations in the town of Milford, although no definite outcrop could be located. It is difficult to determine whether they came from Stony Ridge, 4 miles away, or if they are remnants of an outcrop which previously existed northeast of Stony Ridge.

The maximum extent of the regional distribution of Lovejoy Basalt is constrained by the few isolated outcrops which remain, but the original distribution may exceed these boundaries. An examination of Lovejoy Basalt clasts in the Red Bluff Formation, abundant in the Big Chico Creek area, may help determine the northern termination of the original distribution.

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