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The Geology of a Portion of the Quincy 15' Quadrangle, Plumas County, California

Author
Sheeks, Douglas I

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The Geology of a Portion of the Quincy l5' Quadrangle
Plumas County, California

By

DOUGLAS INGRAM SHEEKS
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Thesis

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DAVIS

Approved:

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Eldridge M. Moores, Chairman

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Howard W. Day

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Peter Schiffman

Committee in Charge
2016

DEDICATION

This thesis is dedicated to the late Professor Cordell Durrell and to all past, present, and future students of geology - Alvarez's* "noble science" - whether amateur, professional, or academic, without whose dedication, work, and insight our understanding of this awe-inspiring planet and the rocks that we all live on would be impoverished to become myth, or worse.

ACKNOWLEDGEMENTS

My thanks go to a number of individuals. Chief among them is Professor Durrell, my thesis advisor at the University of California, Davis, and while I conducted the initial fieldwork for this thesis. Included in my appreciation are my dear wife, Gayle, who maintained the hope and the faith that this effort would finally bear fruit; my former, fellow students, including Professor Jad D'Allura, for his important contributions to northern Sierra Nevada geology and gracious permission to include a portion of his mapping in this report's geologic map, and Joe DeVay for his work on the Shoo Fly rocks (and with the late Gerard Bond), encouragement, discussions, reviewing the draft manuscript, and for loaning me his Shoo Fly thin sections. I also thank Larry Garside (University of Nevada, Reno)

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*Alvarez, W., 2005, "The noble (but neglected) history of geology as a science: a tribute to Eldridge Moores." Geological Society of America Abstracts *with* Programs, vol. 37, no. 4, page 55 (April).

for providing the initial spark for me to awaken this project from a long slumber; Professor Thomas A. Anderson (Sonoma State University) for his review of the draft manuscript; and the late Professor William R. Dickinson** (University of Arizona) for his patience and generosity in answering my questions about matrix (cited in this report) and in sending me this: "Happy to be of any service. Our business is a communal effort and anyone energetic enough to generate fresh point counts (few do these days!) has my ear and attention." Sadly, I did not share my results with him before his passing.

My thanks also go to the esteemed members of my thesis committee: Professors Eldridge M. Moores (Chair), Howard W. Day, and Peter Schiffman. I am forever grateful to them for their generosity, guidance, and the opportunity to put into effect the spirit of what Professor Moores expressed in his 1985 editorial in the journal "Geology;"*** to reinterpret and reevaluate my previous mapping in light of new understandings, hypotheses, and questions that had since arisen.

The inclusion as appendices to this thesis of the Measurement Uncertainty tables for the major oxide and rare earth element constituents is with the express permission (2016) of SGS Minerals Services (SGS Canada, Inc.), Lakefield, Ontario, Canada.

**Additional inspiration is available to all through the series of short video interviews with Professor Dickinson that may be viewed here: https://www.youtube.com/channel/UCoJlkm0iPZmptz0-tVROLDw

***Moores, E. M., 1985, "Editorial." Geology, v. 13, n. 1, p. 3. January.

A typical view along the Middle Fork of the Feather River.   The image is toward the northwest, upstream from the Quincy-La Porte Road bridge (Section 15, T23N, R10E). Here, both sides of the river are underlain by Ordovician-Silurian Shoo Fly Complex rocks that include metamorphosed sandstone, shale (slate), chert, and some pods of limestone. The outcrop in the foreground is grey slate that shows near-vertical cleavage striking northwest.

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ABSTRACT

The rocks studied for this thesis are exposed in a portion of the northern Sierra Nevada that is within the Quincy 15’ Quadrangle, Plumas County, California. The rocks belong to two great stratigraphic groups that are separated by a “profound unconformity.” The older group is the Ordovician-Silurian Shoo Fly Complex and its rocks are designated “Subjacent Units.” The younger group includes a series of Miocene to possibly Pliocene volcanic, sedimentary, and volcaniclastic deposits and are designated “Superjacent Units.”

The Shoo Fly Complex is composed predominantly of metamorphosed and tectonized sandstone, siltstone, shale, and chert. Subordinate rock types include limestone, felsic dikes, serpentinite, a quartz porphyry granite stock, and an exposure of meta-diabase. Bedding and facing evidence preserved in the clastic meta-sediments is rare, but is generally to the east. The limited bedding evidence includes partial Bouma-sequence layering. All Shoo Fly rocks display lower-greenschist facies regional metamorphism and varying degrees of deformation attributed to the Jurassic Nevadan Orogeny and an earlier orogeny. The clastic meta-sediments and cherts are the most deformed. They are folded and sheared and display a dominant slaty cleavage that strikes northwest and is vertical to sub-vertical; dipping steeply northeast or southwest. Four episodes of deformation have affected the Shoo Fly rocks. The first episode led to the development of the angular unconformity that separates the Shoo Fly from the overlying Devonian Sierra Buttes Formation. The second and third episodes involved, respectively, isoclinal and kink folding that are displayed at outcrop scale. The fourth episode involved high-angle

Cenozoic faulting that is evidenced by the exposures of the Tertiary units. The up to approximately 15-kilometer exposed thickness of the Shoo Fly is anomalous when compared to other ancient and modern sedimentary accumulations and may be best attributed to imbricate thrusting that attended obduction of the assembled Complex onto the continental margin of western North America. However, evidence of the Sierra City melange, the youngest of the allochthons that form the Complex and which was mapped previously as extending through the study area, was not found during this study.

The metasandstones in the Shoo Fly studied for this thesis are quartz rich and contain significant amounts of quartz-phyllosilicate “pseudomatrix.” The source of the pseudomatrix and mode of its formation are important questions that remain to be resolved. The metasandstones involve material derived from continental crust, based on petrologic examinations and new whole-rock geochemical analyses. A “Recycled Orogen” provenance for the metasandstones is inferred, based on averaged QFL statistics. The depositional setting of the Shoo Fly sediments was most likely along a passive continental margin. However, continental rift and/or arc depositional settings are also possible. The northern Laurentian margin is a possible source of the clastic sediments in the Shoo Fly Complex. A possible alternative source is the Peace River Arch region of Canada. Both possibilities require transport of the assembled Complex over significant distances before arriving at its present geographic position relative to western North America.

The Tertiary units in the study area include the Lovejoy basalt, Bonta formation and its associated basal gravels, Warner basalt and presumably associated intrusives, and an areally-limited intrusive dike complex. The Lovejoy, Bonta, and Warner exposures form a belt across the lower half of the study area that marks the location of a paleovalley. The paleovalley was one of a series through which these materials moved to the west and into the ancestral Sacramento Valley from sources located in northeastern California. The Lovejoy also helps to indicate that its main paleochannel was bifurcated into two routes across the study area. The Lovejoy has also become the focus of increased interest and importance because of its distinctiveness as a stratigraphic marker, providing a strain gauge to help identify and quantify late-Cenozoic tectonic deformation of the northern Sierra Nevada region, and because its age has been redefined as Middle Miocene (i.e., ~16 Ma) through improved radiometric dating techniques. The ages for the younger Tertiary units are reported, based on radiometric dating, to range from Middle Miocene to possibly Pliocene as follows: the Ingalls and Bonta formations are Middle Miocene; the Penman formation, “intrusive andesite,” and Warner basalt are Late Miocene; and the Warner intrusives are possibly Late Miocene to Pliocene. However, the mapping for this thesis demonstrates that the reported overlapping isotopic age ranges for these units carry significant uncertainties. These Tertiary units also help to define the Cenozoic faulting that has affected the northern Sierra Nevada region. The faulting includes the Mohawk Valley fault system which led to the formation of the Plumas Trench; a regionally-important structural feature. The faulting and available seismic data add to the evidence that basin-and-range deformation continues to migrate westward into the northern Sierra Nevada.

I. INTRODUCTION

I.A. Location

The study area for this thesis is situated within the Quincy 15' Quadrangle and includes portions of the Quincy, Spring Garden, Onion Valley, and Blue Nose Mountain 7.5' Quadrangles (Figure 1). The area investigated covers approximately 90 square kilometers (~35 square miles), is centered about latitude 39º52'N, longitude 120º52'W, and is approximately 11 kilometers (~7 miles) southeast of the town of Quincy, Plumas County, California (Figures 2, 3, 4). The Middle Fork of the Feather River traverses the southern portion of the study area (Plate I) and extends from east to west downstream approximately 16 kilometers (~10 miles); from the Carmack Mine (Sec. 9, T23N, R11E) to near Bachs Creek (Sec. 18, T23N, R10E). Adjacent areas originally mapped by Durrell (1976) and D'Allura (1977) are within the outline of this study's geologic map (Plate I). The geology mapped in those areas is included for continuity, with their generous permissions.

I.B. Purpose and Objectives

This study was conducted to satisfy the thesis requirement for the degree of Master of Science in Geology and involves a portion of the northern Sierra Nevada that had not for the most part been mapped since the publication of the geologic map of the old Downieville Quadrangle (Turner, 1897). However, certain portions of the present study area were previously studied and/or mapped to varying degrees as parts of other partially-overlapping or adjacent investigations by Wilhelms (1958), Strand (1972), D'Allura (1977), D'Allura et al. (1977), Standlee (1978), Bond and DeVay (1980), Varga (1980), and DeVay (1981).

The original, main objective of this study was posed by Durrell and included continuing to the west the geologic mapping that was begun in the Blairsden 15' Quadrangle (Durrell, 1959a), thus adding to the investigations conducted nearby by Wilhelms (1958), Strand (1972), Durrell (1976), and D'Allura (1977). That initial fieldwork was contemporaneous with investigations conducted in quadrangles that neighbor the Blairsden Quadrangle to the northeast, east, and southeast by Berry (1979) and Matsutsuyu (1979). Results from that initial work are also reported here.

However, the present study is concerned with two new, basic questions:

1. What are the possible sources of the Shoo Fly Complex quartzose metasandstones found in the study area and how do those possibilities compare with inferences about provenance reported by other geologists, including Bond and DeVay (1980), DeVay (1981), and Girty et al. (1991)? Data from field and petrographic examinations plus new whole-rock geochemical analyses are used in addressing these questions. The answers will help in defining what constitutes the Shoo Fly Complex north of the following areas:

- Gold Lake (approximate latitude 39º40'N), where Schweickert (1974), Varga (1980), and Mount (1990) conducted investigations;
- Bowman Lake (approximate latitude 39º27'N), where a series of studies were focused by, for example, Girty and Schweickert (1983b), Schweickert et al. (1984), Girty and Wardlaw (1984), Girty et al. (1984), Pardini (1986), Girty and Pardini (1987), Lawrence (1996), and Girty and Lawrence (2000).

2. What relationship does the distribution of Tertiary volcanic rocks exposed in the study area have with respect to the paleovalleys discussed by, for example, Wagner et al. (2000), Wakabayashi and Sawyer (2000), and Garside et al. (2005), that served as conduits for the movement of those materials (Garside et al., 2005) through the northern Sierra Nevada region and into the ancestral Sacramento Valley?

This report also includes some revisions to the stratigraphy of the Tertiary units that was originally reported by Durrell (1959a) and is based on updated relationships that are necessitated by recent radiometric dating and detailed examinations discussed by, for example, Wagner et al. (2000), Grose (2000), and Garrison et al. (2008).

I.C. Geographic Setting

The study area is situated mainly on a northeast-facing flank of the northern Sierra Nevada that is partly formed by Bachs Creek Ridge (Section 7, T23N, R10E) along the western edge of the study area (Plate I). To the east below the Sierra crest is a portion of the Plumas Trench and its eastern wall, Grizzly Ridge (Figure 3), which define the eastern boundary of the area mapped on Plate I. Durrell (1959a, p. 163) invoked the name “Plumas Trench” for the northwest-trending complex graben that extends approximately 58 kilometers (~36 miles) from the North Fork of the Feather River southeast to Mohawk Valley (Figure 3).

The Plumas Trench is characterized by a number of alluviated valleys that are successively separated by relatively low-lying and incised ridges lying transverse to the trench axis. Two of these valleys (Figure 4), Spring Garden (Section 21, T23N, R11E) and Thompson (Sections 20 and 21, T24N, R10E), are wholly within the area of this study's map (Plate I). The ridge that includes Lee Summit (Sections 8 and 9, T23N, R11E), near the central east-edge of Plate I, forms part of the drainage divide between the North and Middle Forks of the Feather River. The divide continues west across the middle of the study area and meets the Sierra crest near the west edge of Plate I. Greenhorn Creek (Section 28, T24N, R11E) is the main drainage north of the divide and flows northwest along the axis of the Plumas Trench to its confluence with Spanish Creek in Section 1, T24N, R9E. The main drainage south of the divide is the Middle Fork of the Feather River (Figure 3; Plate I). The river breaches the Sierra crest (Wakabayashi and Sawyer, 2000, p. 174, 176) below Little Volcano (Section 17, T23N, R10E), separating it into Bachs Creek Ridge to the north and The Hogback and Washington Hill (Sections 29 and 32, T23N, R10E) to the south (Figure 4).

The highest points in the study area are on Bachs Creek Ridge (Section 1, T23N, R9E) and Eureka Ridge (Section 30, T23N, R11E); both at 1,970 meters (~6,460 feet) above mean sea level (msl). The lowest point, at about 1,061 meters (~3,480 feet) above msl, is in the suburb of East Quincy (Sections 19 and 20, T24N, R10E) which occupies the southeastern arm of American Valley (Figure 3) near the northwest corner of the study area (Plate I). The topography is generally characterized by a series of step-like ridges that descend gradually to the northeast, away from the Sierra Nevada crest, into the Plumas Trench, and then ascend toward Grizzly Ridge. Durrell (1987, Ch. 2) provided a very useful discussion of the geography of the Sierra Nevada as a whole and the Plumas Trench and its neighboring areas in particular.

I.D. Accessibility

The main access route (Figure 4) into and through the study area is the northern section of the Quincy-La Porte Road that extends from Thompson Valley south to its crossing over Nelson Creek (Section 22, T23N, R10E). The Feather River Highway (combined State Routes 70 and 89) traverses the northern and eastern portions of the study area from East Quincy southeast to Lee Summit. Secondary routes include the eastern portion of the Peoria Creek Road that traverses from east to west the southeastern quarter of the study area from near Sloat (Section 15, T23N, R11E) and across Eureka Ridge (Sections 14 and 24, T23N, R10E).

The bed of the Middle Fork of the Feather River provided some of the best exposures of the Shoo Fly Complex and, in some cases, the Tertiary deposits. However, the banks of the river were often difficult to reach and overgrown with vegetation. These same conditions necessitated similar approaches to examining the Shoo Fly Complex by Clark and Huber (1975), Standlee (1978), Bond and DeVay (1980), Varga (1980), and DeVay (1981). The portion of the northern Sierra Nevada that includes the study area was not glaciated as were the two key areas to the south, Lakes Basin and Bowman Lake, where the Shoo Fly Complex and other formations are fortuitously exposed. Measurements of attitudes within Shoo Fly exposures were mainly limited to those along ridges and in stream beds and gullies because of extensive creep. Thus, examinations of road cuts were limited to rock types.

The principal objective of the recent fieldwork was to collect available Shoo Fly metasandstone samples and information along the accessible bed of the Middle Fork of the Feather River; from the vicinity of the Quincy-La Porte Road bridge (Section 15, T23N, R10E) to the west end of the alluvium whereon the Buckhorn Mine is situated (Section 18, T23N, R11E).

II. GEOLOGIC SETTING

Northern Sierra Nevada geology is defined for the purposes of this report as the rocks within the Sierra Nevada physiographic province (Bailey, ed., 1966) that are found from the northern-most limit of the province at approximately the latitude of Lake Almanor (40º15'N), where the younger volcanic rocks of the Cascade Range province obscure the Paleozoic and Mesozoic formations of the Sierra Nevada, to south of Placerville (~38º35'N; Clark and others, 1962; Harwood, 1992).

Coinciding with this areal definition is the regional extent of exposures belonging to the Ordovician-Silurian (Varga and Moores, 1981) Shoo Fly Complex described by Clark and others (1962) and McMath (1966), with subsequent refinements by, for example, D'Allura and Moores (1979), Schweickert et al. (1984), Harwood (1992), and Moores et al. (2006).

The various studies involving the Shoo Fly Complex (summarized below in "Previous Investigations in the Northern Sierra Nevada") within this geographic scheme have helped to inform subsequent regional studies and paleogeographic syntheses by, for example: D'Allura (1977), Schweickert et al. (1977), D'Allura and Moores (1979), Bond and DeVay

(1980), Varga and Moores (1981), Burchfiel and Davis (1975, 1981), Schweickert and Snyder (1981), Girty and Wardlaw (1984), Girty and Schweickert (1983a ,1983b, 1983c), Girty et al. (1996a; 1996b), Hannah (1980), Day et al. (1985), Hannah and Moores (1986), Sharp (1988), Moores et al. (1999; 2006), Dickinson (2004, 2006), Wright and Wyld (2006), and Colpron and Nelson (2009). These regional syntheses advance the respective interpretations that place the Shoo Fly Complex within certain orogenic events that affected the formation of the Cordillera of the western United States[1].

The rocks that occur within the study area and other areas in the northern Sierra Nevada are fundamentally divided into those that are below (i.e., Paleozoic and Mesozoic rocks) and above (i.e., Cenozoic rocks) the "marked unconformity" of Turner (1894a, p. 445). D'Allura (1977, p. 14) adopted the grouping of these rocks whereby those below the unconformity belong to the "Subjacent Units" and those above it belong to the "Superjacent Units." This subdivision is similarly used in this thesis.

The pre-batholithic rocks of the Subjacent Units occupy a northeastern portion - the Eastern Belt - of the Western Sierra Nevada Metamorphic Belt (Clark and others, 1962; Clark, 1964, 1976; Day et al., 1985; Day, 1992). Within the outline of Plate I, these rocks include the Shoo Fly Complex and a sequence of metamorphosed Devonian volcanic and

[1] The first and seventh volumes in the Rubey commemorative series (Ernst, ed., 1981 and 1988) are convenient collections of articles that provide various hypotheses on the evolution of the western U.S. Many of these articles include discussions involving the Shoo Fly Complex.

sedimentary formations, successively the Sierra Buttes, Elwell, and Taylor (Durrell, 1976; D'Allura, 1977). Brief summary descriptions of the Sierra Buttes, Elwell, and Taylor rocks that were mapped by Durrell (1976) and D'Allura (1977), which are shown within the outline of this report's Plate I, are included later in this thesis for consistency with Plate I. In-depth discussions about the Devonian formations and their relationships are provided by D'Allura (1977) and Durrell (1987) plus other pertinent works by, for example, Brooks et al. (1982), Hanson and Schweickert (1986), Harwood (1992), Brooks (2000), and Wright and Wyld (2006).

Also mapped on Plate I are limited, but important (Moores, pers. comm., 2013), exposures of serpentinite that D'Allura (1977, p. 190) suspected might be intrusive and possibly Silurian(?) in age. Contacts between the Sierra Buttes, Elwell, and Taylor Formations include both high-angle faults and unconformities (D'Allura, 1977). Neither Durrell nor D'Allura found within the limits of Plate I either the Elwell or Taylor in contact with the Shoo Fly other than in some few places by high-angle faults. All these Paleozoic rocks, plus areally-limited intrusives, are grouped together as the "Subjacent Units" (D'Allura, 1977, p. 14).

Shoo Fly Complex rocks form a "belt" over a lengthy expanse of more than 160 kilometers (>100 miles), from near the southern end of Lake Almanor to southeast of Placerville (McMath, 1966, p. 173). They comprise the northern half of the "central belt" described by Schweickert and Cowan (1975). The Shoo Fly Complex is juxtaposed against and east of the Melones Fault Zone and Feather River Peridotite Belt; a major suture (Day et al., 1985; Moores et al., 2006). The rocks of the Shoo Fly are structurally complex, have been multiply deformed (Standlee, 1978; Varga, 1980), and are metamorphosed to the prehnite-pumpellyite to greenschist facies (Day et al., 1988, p. 750-751; Day, 1992). They are foliated, isoclinally folded as displayed at the outcrop scale (D'Allura, 1977, p. 243; Varga, 1980, p. 92), and sheared to varying degrees. The foliation is represented predominantly by slaty cleavage that strikes regionally northwest and is subvertical.

Unconformably overlying the Subjacent Units is a sequence of Tertiary sedimentary, volcanic, and volcaniclastic rocks described by Durrell (1959a, 1959b, 1966) and subsequent investigators, including Wilhelms (1958), Strand (1972), D'Allura (1977), Berry (1979), Wagner et al. (2000a; 2000b), Garside et al. (2005), Garrison et al. (2008), and Street (2009). These Tertiary units include the Lovejoy basalt; Ingalls, Bonta, and Penman formations; and Warner basalt; as they were named by Durrell (1959a). The volcanic rocks also include limited occurrences of andesitic and basaltic intrusives that are associated with faults. All these Tertiary rocks are grouped together with Quaternary sedimentary deposits as the "Superjacent Units" (D'Allura, 1977).

The Tertiary rocks are distributed primarily in an east-west belt across the middle of the study area and, as such, define a portion of one of a series of Sierra Nevada paleovalleys (Garside et al., 2005) through which material moved toward and into the ancient Sacramento Valley (Durrell, 1959b; Wagner et al., 2000b; Street, 2009).

In many instances (Plate I), high-angle, mainly Cenozoic[2], block faulting has caused the Tertiary rocks to be juxtaposed against each other and against the Shoo Fly Complex. However, unconformable depositional and intrusive contacts are present between the Tertiary formations and the Paleozoic rocks. Thus, to a large extent, the study area is situated within the Basin and Range geomorphic province (Bailey, ed., 1966) at a point that is transitional between it and the Sierra Nevada province (Durrell, 1987, p. 212-213).

III. PREVIOUS INVESTIGATIONS IN THE NORTHERN SIERRA NEVADA

Bateman and Wahrhaftig (1966, p. 107-111) provided a comprehensive general introduction to studies of Sierra Nevada geology. McMath (1958, p. 5-6 and 29-33) discussed the geology of the Taylorsville area and D'Allura (1977, p. 16-19) focused mainly on the post-Shoo Fly, Paleozoic metavolcanic formations and regional correlations from near Lake Almanor to the Cisco Grove area. Both McMath and D'Allura provide good summaries of the pioneering geologists who, in the second half of the nineteenth and early twentieth centuries, conducted initial reconnaissance surveys and later, more systematic studies of the geology of the northern Sierra Nevada. McMath and D'Allura also provided definitive descriptions on the evolution of the geologic uses of the name "Shoo Fly."

[2] Epicenter locations and magnitude data, available on line through the Northern California Earthquake Data Center (U. C. Berkeley Seismological Laboratory), indicate that the northern Sierra Nevada region, including the study area, remains active (albeit mostly low-magnitude events), with events as recent as May 2015 (Figure 5) superimposed on this report's geologic map (Plate I).

Turner (1894a, 1894b, 1894c, 1896, 1897) and Diller (1892, 1908) were among the first to describe rocks in the northern Sierra Nevada. Subsequent works that add to our knowledge include those by Durrell, either alone or in collaboration with others (1944; and Proctor, 1948; 1950, 1959a, 1959b, 1965, 1966, 1976; and D'Allura, 1977; and 1987), McMath (1958), Wilhelms (1958), Clark et al. (1962), Clark (1964, 1976), Strand (1972), D'Allura (1977), D'Allura et al. (1977), Durrell and D'Allura (1977), Standlee (1978), Berry (1979), Matsutsuyu (1979), Varga (1980), Hannah (1980), Hannah and Verosub (1980), Bond and DeVay (1980), Varga and Moores (1981), DeVay (1981), Schweickert et al. (1984), Girty and Schweickert (1984), Girty and Wardlaw (1984), Girty et al. (1984; 1991; 1996a; 1996b), Day et al. (1985), Pardini (1986), Hannah and Moores (1986), Girty and Pardini (1987), Mount (1990), Harwood (1992), Wagner et al. (2000), Garside et al. (2005), Garrison et al. (2008), Street (2009), and Henry (2009; et al., 2012). The principal contribution by Turner was to set the foundation upon which succeeding geologic investigations have rested. This includes the subdivision of the stratigraphy of the Downieville area (Turner, 1896), that covers this report's study area, into a "Subjacent Pre-Cretaceous Series" (which included an "Auriferous Slate Series") and "Superjacent Terranes" that included "Pleistocene and Tertiary Terranes." The Auriferous Slate Series of Turner contained the "Calaveras formation" (1894a, p. 446; with references to prior uses of the name published in 1893). Within the Subjacent Pre-Cretaceous Series are the rocks that belong to what is now named the Shoo Fly Complex. Grouped within the "Superjacent Terranes" are all rocks, including the Tertiary, that are separated from the

Subjacent Series by the major unconformity between these two groups.

Diller (1908)[3] elaborated on Turner's stratigraphic scheme in the Taylorsville area and began the redefinition of the Calaveras formation as the "Calaveras group" and adoption of the name "Shoo Fly beds" (1892), then later "Shoo Fly formation" (1908, Plate IV in text: "Geologic Column of Taylorsville Region") for those rocks within the group that were described as being situated stratigraphically between the underlying "Taylor meta-andesite" and overlying "Peale formation" and "occupies the southwest corner of the Taylorsville region..." This relationship proved to be a stratigraphic misinterpretation. However, Diller (1908) correctly placed the Shoo Fly formation in that region east of what is now referred to as the "Feather River Peridotite Belt" (Day et al., 1985). Diller also showed the Shoo Fly in depositional contact with the Taylor meta-andesite to the east; implying that the section is overturned, but without the presence of the Devonian Sierra Buttes formation between the Shoo Fly and Taylor shown by D'Allura et al. (1977) and by Harwood (1992) in the region between Lake Almanor and the Lakes Basin area.

McMath (1958, 1966, p. 177) reconciled discrepancies between the stratigraphies of Turner and Diller in the Downieville Quadrangle and the Taylorsville area, respectively, whereby Calaveras in these areas equates to the "Shoo Fly Formation" and the ascending sequence of formations immediately above the Shoo Fly is the Grizzly, Sierra Buttes,

[3] Diller's 1892 article in the Bulletin of the Geological Society of America uses the name "Taylorville" throughout, whereas Diller's 1908 paper (U. S. Geological Survey Bulletin 353) uses "Taylorsville."

Taylor, Peale, and others shown by McMath (1966, p. 176).

Clark et al. (1962), Clark (1976), and D'Allura (1977) subsequently expanded the Shoo Fly of Diller and McMath to include other units farther south of the Taylorsville area. The result of these redefinitions is that the Shoo Fly Complex in the northern Sierra Nevada is situated east of the Feather River Peridotite Belt and the younger Calaveras is situated west of the Belt (Ehrenberg, 1975, p. 1241; Clark, 1976, p. 11; Burchfiel and Davis, 1981, p. 54; Day et al., 1985; Day et al., 1988; Day and Bickford, 2004). However, from south of approximate latitude 38 degrees 15 minutes North, Shoo Fly Complex rocks are in thrust fault contact with the structurally lower Calaveras rocks to the west along the Calaveras-Shoo Fly Thrust (Schweickert and Snyder, 1981; Merguerian, 1985; Schweickert et al., 1988, p. 800).

Day et al. (1988); Harwood (1988); Day (1992), Bevins and Robinson (1995), Fagan, et al. (2001), and Day and Bickford (2004) contributed important information covering metamorphism in the northern Sierra that either involves or has bearing on the Shoo Fly Complex. The common findings reported in these works are that the Shoo Fly Complex has undergone lower greenschist facies metamorphism, with its rocks having retained many primary textures. However, Day et al. (1988), argue that "the commonly reported assemblage, quartz + white mica + chlorite, is equally compatible with prehnite-pumpellyite facies metamorphism."

This study draws particularly on the works of Durrell (1976) and D'Allura (1977) for their generous contributions to this study's geologic map (Plate I) and the distributions of the Tertiary units therein. The definition by Durrell of the Tertiary stratigraphy of the Blairsden Quadrangle (1959a) remains the original authoritative work on the Cenozoic rocks for that portion of the northern Sierra Nevada. D'Allura (1977) extended the work of McMath (1958, 1966) from south of Taylorsville to the area around Cisco Grove (Placer County) and south of Interstate 80. Although D'Allura examined the Shoo Fly and Tertiary rocks, the focus was on the post-Shoo Fly, Devonian to Permian metavolcanic and Mesozoic rocks of the "Subjacent Units" ("Bed-rock Series" of Turner) and maintained that focus in collaboration with Durrell (Durrell and D'Allura, 1977) in describing these formations from the Lakes Basin to Mohawk Saddle areas (along the border between Plumas and Sierra Counties). D'Allura also collaborated with Moores and Robinson (D'Allura et al., 1977) in further describing Shoo Fly rocks, the "Devonian (?) volcanic sequence," and the overlying "Permo-Triassic" to possibly Jurassic "volcanic sequence."

IV. DESCRIPTIONS OF THE MAPPED UNITS

IV.A. Introduction

The fundamental stratigraphic framework employed here (Figure 6) is the same as that used by D'Allura (1977), as modified from Turner (1894a, 1894b, 1894c, 1896, and 1897). This framework is a two-fold division based on the region's major unconformity that separates, with angular discordance, Paleozoic and Mesozoic meta-sedimentary and meta-igneous rocks ("Subjacent Units") from the overlying Cenozoic deposits ("Superjacent Units").

This report's Plate I, including the contributions by Durrell (1976) and D'Allura (1977), shows the Paleozoic units in the following ascending order: Shoo Fly Complex, Sierra Buttes Formation, Elwell Formation[4], and Taylor Formation. The Sierra Buttes, Elwell, and Taylor are not mapped in the study area of this thesis. In addition, Plate I shows the Tertiary units in the following ascending order: Lovejoy basalt; Ingalls, Bonta, and Penman formations; "intrusive andesite;" Warner basalt; and intrusive bodies ("Warner intrusive") which are associated with faults and may be feeder dikes associated with the Warner basalt. The Ingalls and Penman formations are not mapped in the study area of this thesis. Brief summary descriptions of the Ingalls and Penman are also included in this report for consistency with Plate I. In-depth discussions about these Tertiary formations and their relationships are also provided by D'Allura (1977) and Durrell (1959a, 1987).

No conclusive evidence was found in this study to support the subdivisions shown by D'Allura et al. (1977, p. 397) or Harwood (1992) who, respectively, mapped the "SF 1" in contact with the "SF 2" and the "Lang sequence" in thrust contact with the structurally-higher Sierra City melange. Neither Varga (1979, 1980, p. 33), Varga and Moores (1981), nor DeVay (pers. comm., 2014-2015) found evidence for the Sierra City

[4] Brooks et al. (1982, p. 1209) questioned the formal formational status accorded the Elwell by Durrell and D'Allura (1977, p. 852). Harwood (1992, p. 13-14) cited the concern raised by Brooks et al., along with Harwood (1983, p. 416) and Hanson and Schweickert (1986, p. 996), and included the rocks described as Elwell in the Sierra Buttes Formation.

melange north of the Lakes Basin area as was suggested by Bond and Schweickert (1981), Girty and Schweickert (1983a, p. 39), and Mount (1990, p. 9)[5]. That the Sierra City melange does not underlie the study area is consistent with the findings by those other geologists.

Indeed, Colpron and Nelson (2009) recognized that the Sierra City melange "...differs radically from the underlying (Shoo Fly Complex) allochthons (including the Lang) in all aspects." Varga studied the Shoo Fly in a traverse along the Middle Fork of the Feather River and near Wades Lake in the Lakes Basin area. DeVay studied the Shoo Fly in the Florentine Canyon-Jamison Creek area near Plumas Eureka State Park.

The rocks of the Lovejoy basalt, Bonta, and Warner basalt are Middle Miocene; possibly Early to Middle Miocene, based on radiometric dates discussed in later sections. Each successive Tertiary volcanic unit mapped on Plate I, aside from the intrusives, is presumed to be separated from the one below by an unconformity (e.g., Figure 7). Durrell (1959a, p. 163-165) believed that, for the Tertiary formations described in the Blairsden quadrangle, "All formations were originally in (a) nearly horizontal position..." and, despite later faulting, "...are still essentially horizontal." Durrell (1959a, p. 183) contended that, except for the Auriferous gravels and Lovejoy basalt, "...planation after (Tertiary) faulting resulted in surfaces of unconformity on which no significant relief can

[5] Moores (pers. comm., 2016) points out that rocks in the Grizzly Peak area northeast of Quincy include blocks of the Ordovician Montgomery limestone of Diller (1908) and McMath (1958, 1966) that are set in a matrix of metashales and that these rocks together constitute a melange.

be detected."

However, Wagner et al. (2000, p. 161) found through detailed field examinations, coupled with newer radiometric age data, that significant erosion occurred in the Tertiary which resulted in the carving of "...new canyons and valleys...cut into older volcanic rocks" that were occupied by volcaniclastic materials whereupon "Subsequent erosion produced still newer drainages..." and where later volcanic materials were deposited.

Except for the "intrusive andesite" (discussed below), reinterpreting the geologic mapping contributed by Durrell and D'Allura, or reconciling that mapping with what is reported in this work, is beyond the scope of this thesis, including the exposures that were interpreted as Ingalls and Penman (Plate I).

Grose (2000) and Wagner et al. (2000) expressed important concerns about the difficulty in distinguishing between the Tertiary volcaniclastic deposits that were described by Durrell (1959a), including the Bonta and Penman formations and Warner basalt. Wagner et al. (2000, p. 159-160), reported that with regard to the Ingalls, Bonta, and Penman in the mapping done by Grose (2000) in the Blairsden Quadrangle and with others in the Diamond Mountains (Grose, 1991) that Grose was "...unable to recognize Durrell's formations as mappable units." Wilhelms (1958, p. 36), in a study area that overlaps the eastern portion of this report's Plate I, apparently had a similar concern and may have presaged the approach by Grose since the exposures that might otherwise have been interpreted as Bonta, Penman, and Ingalls formation (Durrell, 1959a) were grouped under the informal name "Estray andesite." Despite these concerns, the Bonta and Warner basalt constitute the bulk of the volcaniclastics exposed within the present study area.

IV.B. Subjacent Rocks

IV.B.1. Shoo Fly Complex

IV.B.1.a. Previous Studies

Turner (1894a, 1894b, 1896) originally included the rocks now belonging to the Shoo Fly Complex in the "Calaveras formation" which was applied for use in the "Gold Belt sheets" (1896, p. 629) to include "...all of the Auriferous slate series older than the Juratrias and Upper Carboniferous beds, known as the Robinson formation." Yet a key provision of Turner's scheme was that "As fast as definite horizons are recognized within the Calaveras formation they will be separated and designated under other names, so that if finally the age of all the contained horizons is ascertained there will be no longer any use for the term." Subsequent investigators have honored this provision (e.g., D'Allura et al., 1977; Girty and Pardini, 1987; Harwood, 1992). D'Allura initially subdivided the Shoo Fly, with specific application to the "Quincy district" (1977, p. 20-29), into a "lowermost Spanish Creek subunit and an uppermost Tollgate Creek subunit." The Spanish Creek subunit was described as "…dark slate and subfeldspathic wacke, subfeldspathic-lithic wacke, and quartz wacke and minor chert, limestone, and rudite (conglomerate)." The Tollgate Creek subunit was described as "…black to light grey chert, siliceous argillite, phyllite, and slate." This subdivision was not applied within the present study area. Subsequently, D'Allura et al. (1977, p. 399) described three main lithologic subdivisions that form the Shoo Fly Complex from the approximate latitude of Lake Almanor south to about Gold Lake (39º40'N) in the Lakes Basin area (Table 1). From the structurally lowest to highest, these subdivisions are the lowermost Shoo Fly ("SF 1"), a middle unit ("SF 2"), and an upper unit ("SF 3"). These informal names are retained in this thesis because of the precedence over the renaming by subsequent workers; particularly for the "SF 1" that includes the "Lang-Halsted sequence" by Schweickert et al. (1984), or "Lang sequence" by Harwood (1988), and "Sierra City melange" for the "SF 2" by Schweickert et al. (1984). D'Allura et al. (1977, p. 397) reported that the "SF 1," "SF 2," and "SF 3" form the informally-named "Almanor Anticline;" with its axis mapped mainly northwest of Quincy.

Harwood (1988, 1992) reported the subdivision of the Shoo Fly from roughly the latitude of Gold Lake to that of Interstate 80 (~39º15'N) that includes four main thrust blocks, with further subdivision into four formations for the rocks exposed from Interstate 80 south to the Middle Fork of the American River, the latter region being where the work by Harwood was primarily focused (pers. comm., 2013). Harwood informally named the lowest of these thrust blocks the "Lang sequence" (referred to as allochthonous by Colpron and Nelson, 2009, p. 291). Structurally above the Lang sequence in succession are the "Duncan Peak allochthon" (Schweickert et al., 1984), "Culbertson Lake allochthon" (Girty and Schweickert, 1983a, 1984), and "Sierra City melange" (Schweickert et al., 1984). Depending on location, the Sierra City melange occurs above and in west-directed thrust contact with either the Lang sequence or Culbertson Lake allochthon (Harwood, 1992). In addition, Harwood subdivided the Shoo Fly in the area around Quincy into two main thrust sheets; the Lang sequence and Sierra City melange. These and the other Shoo Fly subdivisions discussed by Harwood (1992, p. 3) are based to a large degree on various dissertation studies and regional syntheses conducted by many of the investigators who are cited in this report.

Harwood (1992, p. 10) apparently justified the interpretation that the Lang sequence is equivalent to the "SF 1" and that the "SF 2" is the Sierra City melange by stating the following: "The melange has been traced north from Bowman Lake, where it is unconformably buried by Upper Devonian rocks, to the vicinity of Taylorsville…" Harwood did not show in mapping rocks in the Quincy area that would apparently match the "SF 3" and did not recognize the Almanor Anticline.

Standlee (1978, p. 148) also did not recognize the Almanor Anticline; stating that the Shoo Fly "...is not folded on a regional (macroscopic) scale," based on the interpretation that "...isoclinal folds and development of an axial planar foliation is limited to the mesoscopic scale only...," and that the Shoo Fly "...may be considered as a generally homoclinal, eastward dipping stratigraphic sequence;" although faulting within it "...severely limits acceptance of the Shoo Fly Formation as a true stratigraphic unit." Varga (1980, p. 134) also did not find strong evidence for the Almanor Anticline in the exposures examined along the East Branch of the North Fork of the Feather River, stating: "Data gathered along the (East Branch) traverse do not, however, provide unequivocal evidence on the nature of the fold." And, "… facing data are not, however, consistent enough to give a clear indication of whether the large fold is an anticline or syncline."

I did not find evidence for the Almanor Anticline in the present study area.

D'Allura et al. (1977, p. 398-399), in the tripartite subdivision of the Shoo Fly Complex, described the "SF 1" as mostly "...subfeldspathic-lithic sandstone, quartz sandstone, and dark green to black shale with subordinate conglomerate;" "SF 2" as "...a tectono-stratigraphic unit of highly sheared shale and sandstone, lenses of limestone, dolomite, chert, volcanics, and small to several kilometer long masses of serpentinized ultramafics;" and "SF-3" ("upper Shoo Fly") as "possibly correlative" with the unconformably overlying Devonian Sierra Buttes formation and containing "...black to light grey chert, siliceous argillite, and shale" and "...relict shard or pumice shapes, and thin crystal vitric tuff lenses intercalated within the pelitic rocks" that indicate a volcanogenic origin. The description of the "SF 2" includes mention that in the Taylorsville area it is "...represented by a melange, which contains blocks of limestone and serpentine in a chaotically deformed pelitic matrix" and that it "...extends discontinuously to at least south of Sierra City, where (with references to Schweickert, 1974, and Moores, 1977) abundant clasts and larger masses of serpentine, gabbro, chert, limestone and metaclastic sediments are present" and that the unit "...may extend as far south as the North Fork of the American River."

However, Girty and Schweickert (1983a, 1984, p. 184) reported the abandonment of the tripartite subdivision described by D'Allura et al. (1977) and instead described (a) "...an extensive melange as the structurally highest unit of the Shoo Fly in the northern Sierra;" (b) in the Bowman Lake area, the melange is underlain by the "Culbertson Lake allochthon;" and (c) the Culbertson Lake allochthon is subdivided into the "Bullpen Lake sequence" and overlying "Bowman Lake sequence," with the latter two constituting "…major east-dipping stratigraphic sequences."

Harwood (1992, p. 8, 10) generally described the Lang sequence as composed "...primarily of interbedded quartz arenite and pelite with scattered lenses of chert and limestone" and the Sierra City melange as "...blocks of serpentinite, gabbro, pillowed and massive basalt, chert, sandstone, pebbly mudstone, limestone breccia, and bioclastic limestone in a sheared matrix of slate, sandstone, and chert." The description of the Sierra City melange by Harwood is based on the information reported by Schweickert et al. (1984), and Girty and Pardini (1987) for the respective investigations in the Bowman Lake area. Harwood subdivided the Lang sequence in the Duncan Peak area south of Interstate 80 into the following formations in ascending order: the "Antoine Canyon Formation" ("fine-grained quartz arenite"), "Screwauger Breccia" ("massive quartz arenite, chert, and quartz-granule conglomerate in a chaotic matrix of disrupted quartz arenite and dark pelite"), "Big Valley Bluff Formation" ("quartz arenite and pelite," with "coarse-grained quartzite and lenses of quartz-granule conglomerate, chert, and limestone"), and "Barney Cavanah Ridge Formation" ("slate interbedded with...siltstone" and which is partly chaotic with "...blocks of massive quartz arenite, chert, and quartz-granule conglomerate...").

Harwood (1992, p. 1, 10) considered available, recent fossil data for certain areas in the northern Sierra terrane to "...provide the basis for revised structural as well as stratigraphic interpretations" and also stated that the lithologic assemblage in the Big Valley Bluff

Formation is "...most typical of the undivided Lang sequence in the rest of the northern Sierra terrane" and that "...it is composed predominantly of distinctly graded beds of quartz arenite and pelite as much as 2 m thick that contain scattered packets of amalgamated coarse-grained quartzite and lenses of quartz-granule conglomerate, chert, and limestone."

Girty and Wardlaw (1984, 1985), Taylor (1986), Girty et al. (1990; et al., 1993a; et al., 1993b; et al., 1996a; et al., 1996b), and Girty and Lawrence (2000) reported results from petrographic (including point-counting) and/or geochemical assessments of Shoo Fly Complex rocks collected in the Bowman Lake area. Only the reports by Taylor (1986) and Girty et al. (1996b) contained petrographic results obtained from samples of Shoo Fly sandstones collected within the "SF 1" (or Lang sequence). The other reports cited above involve samples of (a) basalt (Girty et al., 1990), chert (radiolarite) and argillite (Girty et al., 1993a), and sandstones (Girty and Wardlaw, 1984; 1985) collected from the structurally higher Culbertson Lake allochthon; (b) mudstones from the Lang, Black Oak Springs, and Zion Hill sequences (Girty et al., 1993b); (c) cherts and argillites (Girty et al., 1996a) from the Culbertson Lake allochthon (Quartz Hill, Toms Creek, and McMurray Lake cherts); and (d) and mudstones (Girty and Lawrence, 2000) from the Culbertson Lake allochthon (Poison Canyon and Red Hill units). Pardini (1986) and Girty and Pardini (1987) reported point-counted results for sandstone blocks in the Sierra City melange in the Bowman Lake area. Mount (1990) also reported point-counted results from petrographic assessments of sandstone blocks within the Sierra City melange in the Lakes Basin area.

Standlee (1978), Varga (1980), Bond and DeVay (1980), and DeVay (1981) reported results from respective investigations that dealt specifically with the Shoo Fly Complex in and/or near the study area of this thesis.

Standlee (1978, p. 13-14) investigated a section of the Shoo Fly between Quincy and La Porte that overlaps both the Melones Fault Zone and the southwest quarter of this report's Plate I. Standlee sought to ascertain (1) "...the tectonic and sedimentological conditions (that were) prevalent during the initial deposition..." of the Shoo Fly and (2) how "...the structural evolution of the northern part of the western metamorphic belt… is related to the widespread tectonism of the western part of North America." Notably, Standlee reported the results from a modal analysis of selected Shoo Fly sandstone samples (1978, p. 43, 50, 56), described as arenites and greywackes, and provided a discussion on the provenance of Shoo Fly sandstones in general. Standlee concluded that the quartz arenite and associated potassium feldspar-rich (to subarkosic) conglomerate were derived "...from an extremely siliceous source, such as sialic igneous rocks, gneisses, or relatively mature quartz sands," and greywacke that was "...apparently derived from a distant, volcanic/plutonic source terrain." Standlee also described a "melange zone" (1978, p. 17) within the western portion of the Shoo Fly (the "SF 1" of D'Allura et al., 1977) as not being "...a part of the normal Shoo Fly Formation." Standlee (1978, p. 33-34) stated that because of the pervasive metamorphism, deformation, and associated recrystallization that have affected nearly all Shoo Fly rocks, "...application of strict sedimentological methods..." and analytical tools to these rocks is "...greatly hampered..." and "...perhaps impractical..." The work by Standlee pre-dated that of, for example, Dickinson and Suczek (1979) and Bond and DeVay (1980) and, thus, did not take the approach to assessing the provenance of the Shoo Fly quartzose sandstones used by these other geologists, including the comparative statistical-graphical methods. However, Bond and DeVay argued (1980, p. 294) that metamorphism had "...limited effects...on the detrital quartz in the (Shoo Fly) sandstones..." and used the quartz types recognized in point-counting analyses to assess provenance.

Nevertheless, the interpretations on the provenance of the sandstones in the Shoo Fly expressed by Standlee and Bond and DeVay are in close agreement, with the former (p. 167) concluding that the derivation was from a "...nearby cratonic/plutonic source terrain" and the latter (p. 296) that "The predominant source of the quartzose sandstones was probably a potassic plutonic and/or metamorphic terrane;" falling "...within the area of sandstones derived from craton interiors..." (also shown by Bond and DeVay, 1980, p. 296, on a "QFL" compositional diagram by Dickinson and Suczek (1979, p. 2171)).

Varga (1980) studied the Shoo Fly in a fashion similar to DeVay (1981), including traverses along the North and Middle Forks of the Feather and the North Fork of the Yuba River. The investigation by Varga along the Middle Fork overlaps the work done for this thesis. Varga also conducted areal examinations and mapping in the Lakes Basin region. However, Varga concentrated on both the macrostructural and microstructural features of the Shoo Fly rocks to assess the periods of deformation that affected them and draw conclusions regarding the ages of those periods and the associated orogenic events. The interpretations by Varga of these episodes relied, in part, on detailed statistical and graphical analyses of observed structural elements and comparisons with structural data from other formations in the northern Sierra Nevada. The focus was on Shoo Fly structures and, thus, Varga did not report in either dissertation (1980) or subsequent investigation involving the Shoo Fly (Varga and Moores, 1981) statistical data derived from petrologic analysis of Shoo Fly meta-sediments similar to those reported by Standlee (1978), Bond and DeVay (1980) and DeVay (1981) and later by Girty and Wardlaw (1984, 1985), Girty and Pardini (1987), and Mount (1990). Instead, Varga cited the Shoo Fly Complex provenance interpretations made by Bond and DeVay (1980) and DeVay (1981).

DeVay (1981) conducted petrologic and provenance analyses of Shoo Fly quartzose metasandstones through cross-structural traverses between the North Forks of the Feather and Yuba Rivers. Bond and DeVay (1980) built on the work by DeVay (1981) by conducting additional sample analyses to support the provenance study of the Shoo Fly. That study resulted in a determination that the Shoo Fly quartzose metasandstones, the dominant constituent of the "quartzose flysch," was derived from a "...potassic plutonic and/or metamorphic terrane;" specifically from a cratonic interior utilizing the interpretive approach of Dickinson and Suczek (1979). The interpretation expressed by Bond and DeVay (1980, p. 287) is of particular interest for this thesis given the statement that "...within the outcrop belt most of the rocks included in the middle Shoo Fly ("SF 2" of D'Allura et al., 1977) are part of the quartzose (sandstone)-phyllite succession..." that is found predominantly in the lowermost Shoo Fly ("SF 1" of D'Allura et al., 1977).

The mapping by Bond and DeVay, together with the structural data reported by Varga (1980), indicated that "…within the outcrop belt in figure 2…with the possible exception of the melange near Sierra City (Schweickert, 1974), none of the Shoo Fly Formation shown in figure 2 was deformed in or emplaced from an early Paleozoic oceanic trench and subduction zone complex." The outcrop belt shown by Bond and DeVay includes the study area of this thesis. Bond and DeVay based this interpretation on petrographic examinations of Shoo Fly quartzose metasandstone samples collected during four traverses across the outcrop belt. The resulting point-count data involving monocrystalline and polycrystalline quartz, observed mineral associations (e.g., inclusions in quartz), and indications of sediment maturity were used to infer "...a source in a predominantly plutonic/metamorphic terrane" and a "...depositional setting (that)…most likely was a passive continental margin." Alternatively, the inferred depositional setting according to the Verma and Armstrong-Altrin discrimination diagram (Figure 8) appears to be a continental rift and/or arc (either continental or island). The Verma and Armstrong-Altrin approach utilizes geochemical analytical results for selected major oxides and is discussed below in the "Results" section under "Shoo Fly Sandstone Provenance."

Girty et al. (in Cooper and Stevens, 1991), described sandstones in the lower Shoo Fly (i.e., "SF 1"); specifically those within the Lang and Black Oak Springs sequences that are exposed in the area from Bowman Lake to Lake Spaulding. The descriptions involved field information, measured sections, and point-count data (citing Taylor, 1986) and included massive sandstone and turbidite lithofacies that thin-section petrography indicated are mainly “...metamorphosed quartz arenites and quartz wackes” containing “...detritus derived from a continental source.” Girty el al. (1991) interpreted the “...Shoo Fly Complex to be a series of trench-wedges that were accreted to a subduction complex” and that “...the trench in which the Shoo Fly Complex developed must have been located near enough to a continental landmass to have received sand-sized detritus derived from it.” The interpretation was based on data and information from the field plus petrographic and U-Pb studies on detrital zircons collected from a sample collected within the Lang sequence. Girty el al. refer to “Limited paleontological data and geochemical data... ” (citing Hannah and Moores, 1986, and Varga, 1982) to infer that the “...trench developed adjacent to the western North American margin...”

Wright and Wyld (2006, p. 381) interpreted the “Tight folding and imbricate thrust faulting...” in the Shoo Fly Complex as indicating that the Complex “...developed in an accretionary wedge setting associated with an east-dipping…subduction zone...” (with references cited therein).

IV.B.1.b. Present Study

New geochemical data from Shoo Fly quartzose metasandstone samples collected in the “SF 1” are reported and discussed in sections below. Such data have not been reported previously for similar samples from that portion of the Complex. Also reported are point-counted results from the same samples. As mentioned above, geochemical data obtained from Shoo Fly samples reported in prior works (i.e., Girty et al., 1990; Girty et al., 1993a; Girty et al. 1993b; Girty et al., 1996a; Girty et al., 1996b; Girty and Lawrence,

2000) did not result from "SF 1" (or Lang) sandstone samples; having been derived instead from basalt, laminated argillite and/or radiolarite chert, and mudstone samples that were collected in map units that lie above the "SF 1."

IV.B.1.c. Definition

All basement rocks in the study area and lying unconformably below the Cenozoic deposits are grouped as Shoo Fly Complex (Plate I). The rocks that compose the Complex are predominantly metamorphosed detrital sediments (sandstone, siltstone, and shale) plus chert, with minor amounts of limestone, serpentinite (Figures 9a and 9b), and associated igneous rocks. The serpentinite exposures were not studied for this thesis.

D'Allura (1977, p. 190-191) provided summary descriptions of the observed geology of serpentinite exposures mapped on Plate I near Massack (Sections 22, 23, 25, and 26, T24N, R10E). D'Allura speculated that the serpentinite in the Massack area may be intrusive; "…interpreted as being 'cooly' emplaced along faults…," with "…talc along many of the margins…," but that the serpentinite "…displays no contact aureoles." Thus, the origin of these exposures is equivocal, the serpentinite may be tectonically emplaced, and are not included in the section below on instrusives in the Shoo Fly.

Original sedimentary and igneous fabrics are recognizable in most cases despite the regional metamorphism (Day et al., 1988) and deformation (Standlee, 1978; Varga, 1980). The Shoo Fly rocks underlie roughly 60 percent of the study area and are separated from the Superjacent Units (discussed in following sections) by the major unconformity discussed above.

A relatively small stock (about 1.9 square kilometers, ~0.75 square miles, in plan view) is exposed in the canyon of the Middle Fork of the Feather River (Sections 7 and 18, T23N, R11E). The stock is composed of quartz porphyry granite (Clark and Huber, 1975; Varga, 1980) and is here informally named the "Buckhorn Mine stock." The stock is indicated as Mesozoic on the Chico geologic sheets (Burnet and Jennings, 1962; Saucedo and Wagner, 1992). Possible resolution of the age of the stock may be provided from isotopic analysis of zircons extracted from samples collected by V. Powerman (Stanford University; pers. comm., 2013).

It is important to note that the Shoo Fly Complex rocks described by others and not found in the study area for this thesis include: (a) metabasalt, "black and white phosphatic cherts," "rare talc-magnetite gneiss," and gabbroic rocks that "retain high temperature deformational fabrics" as described by Mount (1990) in the Sierra City melange in the Lakes Basin area; and (b) gabbro, basalt ("pillowed and massive"), volcanogenic pebbly mudstone, and limestone breccia as described by, for example, Girty et al. (1996b) and Harwood (1992, p. 8) for the Sierra City melange in the Bowman Lake area.

Penetrative deformation renders unknown the true thickness of the Shoo Fly Complex and a base of the Complex is not yet recognized by any investigators (D'Allura et al., 1977; Standlee, 1978). However, Bond and DeVay (1980, p. 297 and 301, with references cited therein) suggested that the Shoo Fly "quartzose flysch" (i.e., quartzose sandstone-phyllite-chert assemblage) was deposited on oceanic basement. The evidence for this suggestion that was cited by Bond and DeVay includes the argument by Kistler and

Peterman (1978) that "...the crust beneath the northern Sierra Nevada is probably underlain by mafic lithosphere" and that oceanic floor lying adjacent to a continental block best explains the petrology and provenance of the quartzose sandstones in the flysch[6].

Girty and Lawrence (2000, p. 175) reported that the Complex exceeds 30 kilometers (>18 miles) at its widest extent. However, Schweickert (2015, p. 327) and Wright and Wyld (2006, p. 381) described the Shoo Fly as up to 15 kilometers wide, with the latter suggesting that it is "...probably on the order of 10 km in structural thickness" (presumably based on Harwood, 1992, whom they cite). The exposed structural thickness of the Shoo Fly along the course of the Middle Fork of the Feather River within the study area (Plate I) is approximately 14.5 kilometers (~9 miles); roughly perpendicular to the tectonic grain. The thickness of the Shoo Fly is discussed further in the section below on the structure of the Shoo Fly rocks.

Regionally, the Shoo Fly Complex forms part of the northern half of the "Eastern Belt" (Schweickert and Cowan, 1975; Day et al., 1985; 1988) of the broader "western Sierra Nevada metamorphic belt" (Clark, 1964). The Shoo Fly lies in irregular structural contact with and to the east of the Melones Fault Zone and Feather River Peridotite Belt (Standlee, 1978; Day et al., 1985), or the "Feather River ultramafic body" of Ehrenberg (1975). Additionally, the Shoo Fly Complex lies unconformably below, although partly in fault

[6] Girty and Wardlaw (1985, p. 520, with references cited therein) also speculated that the Shoo Fly Complex "...probably is underlain by mafic lithosphere."

contact with, the remaining formations of the Subjacent Units that are exposed to the east within the outline of Plate I (Durrell, 1976; D'Allura, 1977). Successive workers (e.g., Durrell and Proctor, 1948; Clark et al., 1962; McMath, 1966; Schweickert and Cowan, 1975; Clark, 1976; D'Allura, 1977; Durrell and D'Allura, 1977; D'Allura et al., 1977; Schweickert et al., 1977; Standlee, 1978) extended the Shoo Fly to include rocks, previously mapped collectively as Calaveras, from Lake Almanor to at least Placerville (38º43'N approximate latitude).

D'Allura et al. (1977, p. 397) depicted the approximately NNW-striking contact (not shown as a fault) between the "SF 1" and "SF 2" crossing the Middle Fork of the Feather River approximately at the 1ocation of the Buckhorn Mine stock (Sections 7 and 18, T23N, R11E). Thus, the study area appeared to be underlain by both these units. However, neither Varga (1980) nor I found the contact mapped by D'Allura et al. (1977) between the "SF 1" and "SF 2" (the latter ostensibly including "melange") across that reach of the Middle Fork, with the essential finding that the same rock types exposed to the west of the proposed contact continue to the east. Indeed, Varga (1980, p. 33) stated the following: "…the sandstone, chert, and limestone present in the Lakes Basin area are not blocks set in a matrix of sheared serpentinite or phyllite" and the "…discontinuous nature of many of the sedimentary components in the Lakes Basin region is believed to have been caused by transposition during F2 folding. Thus the melange near Sierra City either dies out to the north or is present farther to the west of the Lakes Basin area…" It is also important to note that this interpretation is not without some disagreement. Girty and Schweickert

(1983a, p. 39-40) stated the following: “We have examined the Lakes Basin rocks studied by Varga (1980) and Varga and Moores (1981) and believe them to be an element of a larger and more extensive Shoo Fly Complex melange.”

Nevertheless, the rocks in the present study area that belong to the Shoo Fly Complex are grouped herein without subdivision, including exposures of limestone, chert, serpentinite, metadiabase, and the quartz porphyry granite stock that underlies the Buckhorn Mine area.

IV.B.1.d. Lithology

The descriptions of the rocks of the Shoo Fly Complex that follow are based primarily on observations made during traverses along the banks of the Middle Fork of the Feather River and from examinations of thin sections made from samples collected during those traverses. Supplementing these descriptions are observations made over the rest of the study area that were mainly reconnaissance in nature.

The Shoo Fly rocks are primarily foliated metamorphosed clastic sediments and chert, with minor amounts of the associated rock types indicated above. All these rocks display varying degrees of deformation and most were affected by later episodes of high-angle block faulting. Almost all Shoo Fly Complex rocks exhibit a pervasive tectonic foliation, or cleavage, that is sub-vertical and strikes generally northwest (Plate I). Also, Varga (1980, p. 91-92) reported that the margins of the Buckhorn Mine stock (Sections 7 and 18, T23N, R11E) are slightly foliated. However, foliation is not exhibited in either the large dolomitic limestone (Standlee, 1977, p. 99) block at Little Volcano-Limestone Point

(Sections 17 and 18, T23N, R10E) or the metadiabase (Figures 10a. & 10b.) in Section 18, T23N, R11E. Yet, many of the primary features of the Shoo Fly rocks remain recognizable, particularly in the clastic sediments.

Descriptions by Standlee (1977, p. 102-103) of important features observed in the limestone that forms the large block at Little Volcano included “Another peculiarity of the limestone block at Limestone Point is the total absence of any evidence of ductile deformation of the carbonate rock. All of the preserved structures, and especially the spherical ooliths and pisoliths, display no preferred plane of orientation of the greatest dimension of any inequant particles.” The spherical oolith shown in thin section on Figure 11 is consistent with the observations by Standlee that the block at Little Volcano-Limestone Point is not deformed except for “…a widely spaced joint set approximately parallel to the matrix foliation.” Additionally, Varga (1980, p. 112, and citing 1979 pers. comm. with Bond) reported that “Small disharmonic parallel folds observed within the block near Little Volcano…and precleavage folds of probable slump origin near the margin of the block…are strong evidence of a slump origin.” Together, these descriptions are evidence that the large block of dolomitic limestone at Little Volcano-Limestone Point is an olistostrome. Thus, at least that part of the Shoo Fly is a sedimentary melange.

Contacts that are demonstrably original sedimentary bedding or that include evidence of facing are rare. Those that were found are in a relatively small area along the Middle Fork in Section 7, T23N, R11E. That facing evidence (Figures 12a, 12b, and 13) tends to confirm that younger rocks lie to the east; consistent with observations reported by, for example, Standlee (1978, p. 19) and Varga (1980). The one exception to this evidence of facing direction is the outcrop shown on Figures 14a and 14b where the graded bedding is upright and defines a small syncline.

IV.B.1.d.i. Sedimentary Rocks

The descriptions that follow focus on the Shoo Fly metasandstones. The slates and cherts were not studied in detail. The reason for this focus is discussed below in the introduction to the section on Shoo Fly sandstone petrology. The descriptions of slates and cherts that follow are brief summaries. Readers are referred to D'Allura (1977, p. 21-29) for more detailed descriptions of Shoo Fly slates and cherts.

The metamorphosed Shoo Fly clastic sediments include shale (i.e., slate), siltstone, and fine- to coarse-grained sandstones. The sandstones include quartzose, subfeldspathic, and arkosic wackes (Williams, Turner, and Gilbert, 1954, p. 292; Dott, 1964); in decreasing order of abundance and based strictly on hand-specimen observations. The metasandstones are singly-deformed to polydeformed psammitic rocks (Gray, 1978). The metasandstone samples collected for this thesis may be lithic arenites based on the formulae discussed by Lindsey (1999) that involve the averaged results from volatile-free whole-rock geochemical analyses (discussed below). However, Lindsey cautioned (1999, p. 1-2) that "...lithic arenites cannot be identified with great confidence by chemical composition alone" since they vary "...in chemical composition according to the type of rock fragments" and that the addition of modal analyses of thin sections plays an important role in increasing that confidence. Alternatively, the log-based major-oxide ratios approach used by Herron (1988, p. 821, Fig. 2) places the Shoo Fly metasandstone samples analyzed for this thesis within “litharenite,” “sub-litharenite,” and “Fe sand” classes; with the numerical mean in the “sub-litharenite” sand class. However, the sample classified as “Fe sand” by this approach was collected from an exposure where there are limonite(?) pseudomorphs after pyrite, but which constitute less than one percent of the materials seen in thin-sectioned specimens; thus reinforcing the caution quoted above.

Outcrops of Shoo Fly metasandstones are generally much less than a few meters above ground level within forested and other areas beyond drainages, including the canyon of the Middle Fork. The differences in weathering characteristics between the sandstones and the other types of Shoo Fly rocks are best observed in those drainages wherein the sandstones and cherts appear to be slightly more resistant than the slates (Figure 15).

The metasandstones weather either dark greenish-grey, greenish-grey, or reddish-brown. They are either dark to light grey on fresh surfaces or, more commonly, light greenish-grey. The weathered sandstones have cleavage accentuated by reddish or reddish-yellow micaceous surfaces colored by iron oxide staining that give sheens to the partings. Soils developed on Shoo Fly rocks have in common ubiquitous chips of the parent material. Soil colors vary from light grey to light brown or reddish-brown. Outcrops and thin sections rarely contained pseudomorphs after pyrite. Quartz grains vary from colorless to very-dark grey or almost black. The best examples of these quartz grains are exposed on both sides of the Middle Fork of the Feather River near the Quincy-La Porte

Road bridge (Section 15, T23N, R10E). Sorting of the coarser-grained sandstones is generally moderately-well to poorly developed. The distribution of quartz grain sizes shown on Figure 16 suggests that it may be bi-modal. Additional data are needed to resolve this possibility. DeVay (1981, p. 7) reported a bi-modal size distribution for the framework quartz grains in the Shoo Fly quartz sandstones.

Individual, non-deformed clasts are sub-angular to sub-rounded (Figures 17, 18, 19), with sizes ranging to about 2 millimeters (mm). An exposure of Shoo Fly metasandstones on Bachs Creek Ridge (Section 6, T23N, R10E) includes coarse-grained, dark-grey to milky quartz grains that are poorly sorted, with sizes that range from about 0.05 mm to a maximum of 5 to 6 mm. Standlee (1978, p. 35-36) described similar Shoo Fly sandstones exposed on Bachs Creek Ridge.

The colors of the sandstones, cherts, and slates help to accentuate folding where the slates are interlayered with either sandstone or chert (Figure 20). The sandstones and cherts are typically light grey to white, occasionally cut by veins of quartz, or stained with hematite-limonite, whereas the slates are typically dark grey or black in both outcrop and on fresh surfaces. Grains of either dark-grey to black angular slate or chert were found as rare framework components in the thin sections of the sandstone samples that were examined for this study.

Chert forms conspicuous, massive outcrops in a few locations that stand above the surrounding Shoo Fly rocks. One such location is in the southern half of Section 19, T23N, R11E (Plate I), where the chert is laminated (1 to 3 mm) and exhibits a foliation that is consistent with the regional Shoo Fly trend that strikes northwest and, in this case, dips steeply west. Phosphatic chert was not found in the study area; consistent with the observations reported by Varga (1980, p. 91).

IV.B.1.d.ii. Shoo Fly Sandstone Petrography

The thin sections used in this study's point-counting analyses were prepared from quartzose sandstones collected in the "SF 1." Two of the thin sections were prepared while at the University of California, Davis. These thin sections were made from samples (Table 2a) collected in Section 17, T24N, R10E, and Section 20, T23N, R11E, but were not stained for feldspars. The remaining thin sections were prepared from samples collected in Section 15, T23N, R10E, and were made and stained for plagioclase and potassium feldspar by Quality Thin Sections, of Tucson, Arizona. Examining and point-counting the thin sections (Table 2a) followed the approach of DeVay (1981), including (a) defining matrix as grains, mainly quartz and phyllosilicates, with dimensions $\leq$0.04 mm; (b) the difference between fine and coarse framework grains set at 0.8 mm; and (c) counting intervals of 0.5 mm under magnification of 100 times. Also followed is the procedure described by Dickinson (1985, p. 335) that includes the following restrictions: (a) identifying lithic fragments based on "...microcrystalline aphanitic materials containing no crystals larger than the matrix limit" and (b) using sandstones of comparable grain size in provenance studies; where "Favorable counting statistics and ease of identification are best achieved jointly in thin sections of medium-grained to coarse-grained sandstone (mean grain size near 0.5 mm)." The average grain size in the sandstone samples selected for point counting is estimated to be between 0.5 and 0.6 mm, as indicated by the average of 0.57 mm in one sample (Figure 16) and deemed to be representative for the study's set of samples based on visual comparisons.

The selection of 0.04 mm for the size distinction between the framework components and matrix is considered a reasonable compromise between the dimensions used by Bond and DeVay (1980, p. 290) at <0.06 mm; Dickinson (1970, p. 697) at 0.03 mm (based on the cited suggestion by Dott, 1964, p. 630-631); and Girty and Wardlaw (1985, p. 517) also set at 0.03 mm. The differences between the matrix size used for this thesis and the others indicated above are deemed to be incremental (based on visual observations) in terms of the effects on the percentages of matrix in this study's samples had those others been used instead. Thus, the results would have been the same in that matrix would have well exceeded 10 percent and the approach of Cox and Lowe (1996) would still have been used whereby point-counted and whole-rock chemical data are combined to retrieve the "...original framework grain modes of (these) altered sandstones."

The near entirety of each thin-section specimen was counted to the limits of the mechanical stage's travel. This approach follows those suggested by Folk (1980) and Wells (2000), notwithstanding the reliability of point-counting results discussed by Van Der Plas and Tobi (1965), and is a departure from the approach used by DeVay and that of others (for example, Girty and Wardlaw, 1984; Girty and Pardini, 1987) where a set counting goal is reached (e.g., 400 framework and 100 matrix counts).

The sandstones thus examined are poorly to moderately-well sorted and composed of sub-angular to sub-rounded grains. However, it is evident that some angularity resulted from deformation-induced shearing (Figures 18, 21, 22). The fabric of the siltstones (Figure 23) and sandstones includes grain-to-grain contacts, grain alignment that is sub-parallel to parallel to foliation, draping of matrix phyllosilcates against framework grains, and the development of “beards” or “trains” (Standlee, 1978, p. 40) at grain ends where recrystallization of phyllosilcates and quartz has occurred in further response to the penetrative deformation (Figures 21 and 22). DeVay (1981) provided a well-documented discussion of the deformational processes that affected both the matrix (pressure solution) and framework (dislocation creep) components in the Shoo Fly quartzose sandstones and that are similarly reflected in the sandstones in the present study area.

The quartz includes grains that are monocrystalline and polycrystalline and have undulose and/or straight extinction. The percentages in all observed sizes of quartz framework grains >0.04 mm are as follows: monocrystalline quartz grains ranged from 8.5 to 32 percent (average = 16.1%); polycrystalline quartz grains ranged from 3.9 to 39 percent (average = 11.6%). The approach used by Bond and DeVay (1980) and DeVay (1981, p. 84) excluded from analysis quartz grains less than 0.8 mm. Following that approach, the percentages (Table 2b) of monocrystalline quartz grains ranged from 12.6 to 59.7 percent (average = 28.3%) and polycrystalline quartz grains ranged from 40.3 to 87.4 percent (average = 71.7%). Polycrystalline quartz grains frequently contain three or more sub-crystals, with either straight, embayed, or sutured boundaries (Figure 19). It cannot be ruled out that some polycrystalline quartz grains may have been derived from a metamorphic source, or sources. The ubiquitous penetrative deformation and recrystallization that has affected the clastic Shoo Fly sediments makes such identification uncertain. D'Allura (1977, p. 22) makes reference to "mosaics of quartz" indicating recrystallized chert. Nevertheless, I agree with the statement made by DeVay (1981, p. 80) that "Regional metamorphic terranes may also have been present as a source for the Shoo Fly quartzose sandstone and cannot be eliminated with the data presented in this study;" to which may be added that neither can it be confidently confirmed.

Inclusions in quartz grains include bubbles (either gas- or liquid-filled), white mica, and trains of very fine, dust-like material and may show a crudely-defined orientation (Figure 24). The inclusions in quartz found by Bond and DeVay (1980) included tourmaline, euhedral zircon, apatite, rutile, biotite, muscovite, plagioclase and orthoclase. Bond and DeVay (1980), DeVay (1981), and Girty and Schweickert (1983c, p. 106) interpreted these characteristics to be indicative of high-grade metamorphic or plutonic sources. Rarely found in thin section were syntaxial quartz overgrowths on monocrystalline quartz grains (Figure 17). In fact, only two such grains were found among the hundreds that were observed in this study. DeVay (1981, p. 32) reported similar findings. Standlee (1978, p. 38) did not report observing overgrowths on quartz in any of the Shoo Fly sandstones that were examined. Accessory minerals include detrital zircon (sub-rounded), muscovite (possibly detrital since much larger than matrix), tourmaline, rare stilpnomelane[7], iron oxide or hematite (opaque after pyrite), and rare chlorite. Some carbonate (either matrix or cement?) was observed in a few Shoo Fly siltstone samples that were examined in thin section, but these were not assessed by point-counting. Slate and chert fragments were also observed in a few sandstone thin sections, with the latter more common than the former. Pyrite (iron oxide pseudomorphs) and slate fragments are best observed in Shoo Fly sandstones exposed in the road cut on the Quincy-La Porte road in the northwest quarter of Section 15, T23N, R10E (Nelson Point).

The point-counted percentages of recognizable feldspars in the sandstone samples ranged from 0 to 4.6% of the total framework grains and are entirely twinned plagioclase (Figure 25). The percentages of matrix ranged from 33 to 58% (average 42%) of the total point counts. Staining for K-spar showed it to be absent. However, Dickinson (1985, p. 337) cautioned that "...diagenetic albite may replace either original feldspar in some cases. Albite takes neither feldspar stain. Systematic replacement of Kspar by diagenetic albite may frustrate attempts to recover the detrital ratio of Kspar to plagioclase in some instances." DeVay (pers. comm., 2015) believes that all the original Kspar in the Shoo Fly quartzose sandstones was altered to albite.

Thus, the observed salient features of the Shoo Fly sandstones and siltstones

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[7] DeVay (1981, p. 26) qualified the occurrence of stilpnomelane with the following: "…the low iron content and high quartz content of most samples examined indicates that the occurrence of stilpnomelane is restricted to iron rich rocks that apparently are not typical of the epiclastic quartzose sandstone of the Shoo Fly Formation."

examined for this thesis are the following: (a) quartz includes clear grains, with some monocrystalline grains exhibiting inclusions that vary from dust-like material to fine crystals of muscovite; (b) a paucity of feldspar grains, with those that were observed being exclusively twinned plagioclase; (c) lithic grains that are nearly all chert plus a few angular slate fragments; (d) some re-cycled quartz demonstrated by very rare quartz overgrowths; (e) rare detrital zircons and possibly some detrital muscovite among the framework grains; (f) abundant matrix (≤0.04 mm) composed mainly of quartz and phyllosilicates; and (g) deformationally-induced fabric elements.

IV.B.1.d.iii. Intrusive Rocks

Intrusive rocks observed within the Shoo Fly crop out mainly in the eastern portion of the study area (Plate I). These rocks include the Buckhorn Mine stock, an exposure of meta-diabase (Figures 10a and 10b), and a quartz porphyry dike (Figures 26a and 26b). No contact aureoles were observed associated with these intrusives. Thus, the nature of the contacts with the host rocks is uncertain. Varga (1980, p. 91-92) provided a summary description of the observed geology of the Buckhorn Mine stock.

A significant feature of the meta-diabase is the massive blocks that stand above the surrounding area, which is underlain by the same material. The largest of these blocks is about 4.5 to 6 meters (15 to 20 feet) tall. The diabase weathers to dark greenish-grey to black. Fresh surfaces are dark greenish-grey, with light-grey to whitish speckling by the constituent feldspar crystals. Also visible in hand specimen is dark green to black hornblende, light grey-green pyroxene, and possibly olivine (glassy, olive-green, with no discernible cleavage). Crystal sizes are mainly about 1 mm, with a maximum of about 2 mm. The darker minerals appear to constitute about 50 percent of the rock, with feldspar forming the other approximately 50 percent. Thin sections (Figures 27a and 27b) reveal that the diabase is heavily altered and primarily composed of chlorite, that has replaced hornblende, and plagioclase some of which has been saussuritized with epidote to varying degrees. Pyroxene and/or olivine appear to be present in lesser amounts as irregular patches or blebs. Evidence of foliation in the meta-diabase was not observed in either outcrop or thin section.

The exposure of the quartz porphyry dike shown on Figures 26a and 26b may be unique in that no other similarly massive example was observed in the study area, especially along the banks of the Middle Fork. Foliation was not observed in this outcrop. However, thin sections from a sample collected at the margin (Figure 28) show that the groundmass of microcrystalline quartz, feldspar, and phyllosilicates exhibits a foliation. The fact that the observed plagioclase phenocrysts are oriented parallel to the foliation may indicate flow alignment rather than tectonization.

IV.B.1.e. Age and Correlation

Varga and Moores (1981, p. 516) reported the age range of the Shoo Fly is Ordovician-Silurian, at least for exposures immediately below the Sierra Buttes in the Lakes Basin region. The age range stems from comparisons of siliceous microfossils from Shoo Fly samples collected along the North Fork of the Yuba River (south of the Lakes Basin area) and samples collected from the "…Klamath Mountains, Nevada, and elsewhere...”   No fossil evidence was found in the Shoo Fly during the course of this investigation, except for a few samples of cryptalgal limestone from Limestone Point on Bachs Creek Ridge (also see Standlee, 1978, p. 100-102) that is underlain by oolitic to pisolitic limestone.   Varga and Moores (1981, p. 513) also reported that mapping and fossil evidence found in the Lakes Basin area brackets pre-Nevadan (pre-Late Jurassic) deformation in the Shoo Fly “...between Late Devonian and Ordovician-Silurian.”

Girty et al. (1996a; et al., 1996b), speculated that the age range for the Shoo Fly may extend from post-Cambrian to pre-Upper Devonian (or “pre-Late Devonian”), with the older extent tentatively based, in part, on radiolaria extracted from chert samples collected from the Quartz Hill and Toms Creek units in the Culberstson Lake allochthon (Table 1). Girty et al. (1996b, p. 2-4) stated the following: “Though moderately to poorly preserved radiolaria have been extracted from several (Shoo Fly chert) samples, none has yielded significant age control...” and “Because radiolaria are not common in Cambrian rocks (citing White, 1986), it seems likely that the cherts are post-Cambrian in age.   Moreover, conodonts extracted from a thin lense of limestone in the Lang sequence are Middle Ordovician in age (citing Harwood, 1992).   Thus, the Shoo Fly Complex is commonly cited as being post-Cambrian and pre-Late Devonian in age.”

Colpron and Nelson (2009, p. 291-292), citing Saleeby et al. (1987) and Saleeby (1990), state that “The assembly of the Shoo Fly Complex took place after the Late Silurian…,” based on a Silurian U-Pb age (c. 423 Ma) for “…a felsic body (either a tuff or a dyke)…” in the Sierra City melange (i.e., the youngest rocks of the Complex).   Colpron and Nelson included the observation that "Detrital zircon signatures of the terrigenous sedimentary strata (including the Lang sequence; citing Harding et al., 2000) show...Archaean (2.55–2.70 Ga) and Palaeoproterozoic (1.80-2.10 and 2.20-2.45 Ga)... dominant peaks (that) are consistent with the northwestern Laurentian margin in British Columbia and Yukon."

Radiometric ages based on U-Pb data from detrital zircons were also reported by several workers for a variety of samples collected from the Culbertson Lake allochthon and/or blocks within the overlying Sierra City melange that are exposed to the south in the Lakes Basin and Bowman Lake areas. These radiometric ages range from approximately "2.09 b.y. ±20 m.y." (Girty and Wardlaw, 1985, p. 519-520) to "423 +5/-15 Ma" (Saleeby et al., 1987, p. 757). The Paleoproterozoic age reported by Girty and Wardlaw is based on detrital zircons extracted from sandstones (described as "continental") collected in the Poison Canyon formation of the Culbertson Lake allochthon. The Late Silurian age reported by Saleeby et al., is from zircons extracted from a quartzo-feldspathic tuff bed in Florentine Canyon (Section 34, T22N, R11E), near the Lakes Basin. Saleeby et al., interpreted the tuff bed to be in the Sierra City melange. The reported age may represent the youngest Shoo Fly age afforded by the available data. Further constraints on the latest Shoo Fly age include (a) Late Devonian ("apparent igneous age of 378 ±5 Ma") from zircons extracted from the Wolf Creek stock (Saleeby et al., 1987, p. 757-758) southeast of Lake Almanor which "...truncates Shoo Fly phyllite..." and (b) Upper Devonian fauna found in the unconformably overlying "Grizzly Formation" in the Lakes Basin area

(Schweickert et al., 1984).

IV.B.2. Structure of the Shoo Fly Rocks

The dominant structural feature of the Shoo Fly Complex rocks is the ubiquitous foliation that strikes mainly northwest, dips steeply northeast, and parallels axial planes to "...widespread mesoscopic isoclinal folds" (Standlee, 1978, p. 20). This characteristic is recognized over the expanse of the Shoo Fly and is best observed in slate outcrops (see photograph that follows this report's title page) and to a lesser degree in sandstone and siltstone outcrops.

Standlee (1978, p. 71) recognized four generations of folds ("F1" through "F4") in the Shoo Fly and a series of associated structural elements that respectively help to express each generation. Readers are referred to the detailed descriptions of these folds reported by Standlee.

However, Varga (1980, p. 186-193) described three generations of distinct folding within the broader expanse of the Shoo Fly (with "local designations" "F1," "F2," and "F3"), but did not report finding evidence for the oldest of these folds along the Middle Fork. These oldest ("F1") folds are related to a post-Ordovician, pre-late Devonian event that resulted in the tight to isoclinal folds observed by Varga along the North Fork of the Yuba River and in the Lakes Basin area. Varga speculated that this deformation may have led to the formation of the angular unconformity between the Shoo Fly and the overlying Sierra Buttes Formation. Varga described the second-generation ("F2") folds as resulting from the Late Jurassic Nevadan orogenic event that also resulted in tight to isoclinal folds.

Varga (1980, p. 191) stated that this interpretation is "…at variance with that of Standlee (1978) who suggested that this deformation is Permo-Triassic in age." Varga interpreted the third-generation ("F3") folds as resulting from possibly(?) a late Nevadan Orogeny event that yielded "kink-style" folding. Varga found these second- and third-generation folds along each of the three forks of the Feather River, including the Middle Fork.

Standlee (1978, p. 167) suggested that the regional foliation (an element of "F1" deformation) is the result of pre-Mesozoic deformation, based on speculative comparisons with the undeformed carbonates that occur within the so-called "melange" zone that was mapped cutting across the present study area along Bachs Creek Ridge. Standlee maintained that if these carbonates are Mesozoic they attest to "tectonic displacements postdating the major foliation development in the Shoo Fly Formation." However, Varga (1980, p. 111) challenged the Mesozoic age proposed by Standlee for these carbonates by stating: "Absolutely no evidence exists to substantiate the notion that the dolomitic limestone at Little Volcano is Mesozoic in age..."

Varga did not find evidence in the Quincy area for Mesozoic deformation older than Late Jurassic. Varga and Moores (1981, p. 516) reported that "North of the Lakes Basin area, pre-Nevadan folds are not recognized, possibly because intense Late Jurassic deformation obliterated them."

Mention is made above that the exposed Shoo Fly Complex is at least 10 to 15 kilometers (~6 to ~9 miles) wide (Wright and Wyld, 2006, p. 381; Schweickert, 2015, p. 327) and may exceed 30 kilometers (>18 miles) at its widest extent (Girty and Lawrence

(2000, p. 175). For comparison, the Mesozoic sedimentary deposits along the west side of the Sacramento Valley are reported to be more than approximately 10 kilometers (>35,000 feet) thick (Ojakangas, 1968) and the accumulation of sediments within the Great Central Valley of California ranges from approximately 5 to 10 kilometers (about 3 to 6 miles) thick (Faunt, 2009, p. 2). Moreover, a recent world-wide comparison by Moscardelli and Wood (2016, p. 48-55) of ancient and modern "mass-transport deposits" (i.e., "...gravity-induced units that represent an important component of…deep-water stratigraphic successions") showed that the thickest accumulation of these reported deposits is the Miocene "giant chaotic body" off Gibraltar (citing Torelli et al., 1997) that reaches 4 kilometers (>13,000 feet) thick. These example dimensions raise the question about what might explain the thickness of the predominantly sedimentary Shoo Fly assemblage that exceeds these other sedimentary deposits by up to eight times. A possible, perhaps the most likely, explanation includes imbricate thrusting (Moores, pers. comm., 2016) of the Shoo Fly sediments that attended the obduction of the Complex onto the western Cordillera margin. This possibility is also attractive in that it provides an explanation for the lack of west-facing sedimentary evidence.

In summary, two generations of folds are represented in the Shoo Fly rocks that are exposed in the present study area and the formation of these folds is attributed to the Late Jurassic Nevadan orogeny (Varga, 1980). A post-Ordovician, pre-late Devonian event may have resulted in the angular unconformity between the Shoo Fly and the overlying Sierra Buttes Formation (Varga and Moores, 1981, p. 514-516). Additionally, imbricate thrusting of the Shoo Fly sediments during obduction onto the western Cordillera margin may reasonably explain the thickest exposure of the Shoo Fly (~15 kilometers) and the lack of west-facing sedimentary evidence.

IV.B.3 Sierra Buttes Formation

IV.B.3.a. Definition

McMath (1966, p. 177, 179) applied the new name "Sierra Buttes Formation" to the "quartz porphyry" of Turner (1897, Folio 37), "metarhyolite" of Diller (1908, p. 81-82) and "meta-rhyolite series" of Durrell and Proctor (1948, p. 171). D'Allura (1977, p. 37) expanded on that application by suggesting that "...the name Sierra Buttes Formation be extended to include the "granite porphyry" of Lindgren (1911), the quartz porphyry of Clark (1930) and the quartz keratophyre of Stuart-Alexander (1967)."

Durrell and Proctor (1948, p. 175) suggested the existence of the unconformity between the Sierra Buttes Formation and the Shoo Fly Complex (referred to then as "Calaveras formation") on the basis of the apparent greater intensity of deformation within the Shoo Fly Complex, the apparent truncation of the Shoo Fly beneath the Sierra Buttes Formation, and that the "...conglomerate at the base of the meta-rhyolite series near Wades Lake was derived from that part of the Calaveras formation immediately beneath it."

IV.B.3.b. Lithology

The Sierra Buttes Formation contains predominantly dacitic and lesser rhyolitic intrusives, flows, breccia, and tuff. McMath (1958; 1966, p. 179) also described the Sierra Buttes Formation as consisting "…principally of bedded quartz keratophyre breccia, tuff, and perhaps some flows, whose gross chemical composition is probably closer to dacite than to rhyolite. Minor chert, slate, and rare limestone with fragments of marine fossils also are present." D'Allura (1977, p. 38) suggested that the thickness of the Sierra Buttes in the Quincy area varies from approximately 90 to 250 meters (~300 to 825 feet), but expands to 1,250 meters (4,100 feet) in the Lakes Basin area. The exposed thickness of the Sierra Buttes as mapped by D'Allura (1977) within the area of this report's Plate I ranges from less than 30 meters (<100 feet) to approximately 120 meters (~400 feet).

IV.B.3.c. Age

The Sierra Buttes Formation is of probable Upper Devonian age, based on fossil evidence reported by Anderson et al. (1974) and Harwood (1992, p. 14).

However, D'Allura (1977, p. 68b) stated the following: "The Late Devonian age reported by Anderson and others…and the Devonian age of the "quartz porphyry" of Clark (1930) both date the Elwell, not the Sierra Buttes Formation…the Sierra Buttes can be no younger than the Late Devonian Elwell and no older than the Silurian(?) Taylorsville Formation[8]. Since it bears a gradational and conformable relation to the Elwell and a probable unconformable relation to the Taylorsville, it is considered to be Middle(?) to Late Devonian." D'Allura (1977, p. 32) also pointed out that the age of the Taylorsville Formation is speculative because "...the Silurian fossils of the Taylorsville Formation may

[8] Per Durrell and D'Allura (1977, p. 846): "…not to be confused with the Taylor Formation…"

have been incorporated in melange."

IV.B.4 Elwell Formation

IV.B.4.a. Definition

Durrell and D'Allura (1977, p. 846-847) invoked the "new name" Elwell Formation to "...what Turner (1897) mapped as lenses of siliceous argillite with radiolaria" and considered the formation to be "...transitional between the Sierra Buttes Formation below and the Taylor Formation above."

IV.B.4.b. Lithology

Durrell and D'Allura (1977, p. 846) described the Elwell Formation as "...characterized by gray to black radiolarian chert with streaks, lenses, and nodules of exceedingly fine grained phosphate rock, probably apatite" and that "Alternations of chert with quartz keratophyre tuff and andesite tuff…" are evidence supporting the transitional nature of the formation. Additionally, Durrell and D'Allura suggested that "...the metasedimentary rocks that occur locally within the porphyries are radiolarian chert and, together with the porphyries, which are quartz keratophyre tuff, compose the Elwell Formation..."

D'Allura (1977, p. 69) did not suggest a thickness for the Elwell in the Quincy area, but reported that "...it may be at least 180 meters (~590 feet) thick in Little Long Valley Creek..." However, the exposed thickness of the Elwell as mapped by D'Allura (1977) within the area of this report's Plate I ranges from approximately 30 to 60 meters (~100 to 200 feet).

IV.B.4.c. Age

Turner (1894a, p. 449) described an exposure of “black siliceous slate” that was presumed to have yielded the fossil impression of an ammonite of “Juratrias” age based on an anecdotal account that a piece of the slate with that impression was found where the old Phoenix mine was located (presumably in Section 28, T20N, R12E, slightly northeast of Sierra City). Turner later (1896, p. 621) referred to the slate as “siliceous argillite,” with specific reference to “The finding of an ammonite in the argillite lens of the Phoenix mine (as) was noted in the (1894a) report.” Turner expressed confidence that the ammonite impression was representative of similar evidence “...found in the slates of the Sierra Nevada at other points, as reported by Whitney, and there is no good reason to doubt the find in question. This gives evidence of the Juratrias age of the argillite.”

Durrell and D’Allura (1977, p. 846-847, 852) described a partly phosphatic “...gray to black radiolarian chert...” that is “...best seen...” in Section 12, T21N, R11E, west of Long Lake in the Lakes Basin area and named the chert the Elwell Formation. Durrell and D’Allura stated that the chert is what Turner mapped as lenses of “siliceous argillite with radiolaria” and concluded that “The lenses...compose a valid lithologic unit...named the Elwell Formation.” However, Durrell and D’Allura also stated that “...the Elwell Formation is Late Devonian in age by virtue of a most fortunate and significant discovery of fossils at Dugan Pond on the north side of Sierra Buttes…” (Anderson et al., 1974). Yet the description of the Elwell as a separate unit by Durrell and D’Allura was and may remain controversial. Hanson and Schweickert (1986, p. 996-997) reported observations of the Sierra Buttes Formation and the contact with the overlying Taylor Formation in the Dugan Pond-Grouse Ridge area (from Section 8, T20N, R12E, north of the Sierra Buttes in Sierra County, to Section 34, T18N, R12E, south of Bowman Lake in Nevada County). Based on those observations, Hanson and Schweickert described the fossiliferous chert named Elwell by Durrell and D'Allura as typical of the Sierra Buttes Formation; considered the Dugan Pond fossils of Anderson et al. (1974) "...to occur within...the Sierra Buttes Formation; " and stated that "...the Elwell Formation is not recognized as a valid lithostratigraphic unit in the Dugan Pond-Grouse Ridge area, and the contact between the Sierra Buttes Formation and the overlying Taylor Formation is abrupt and well defined."

IV.B.5 Taylor Formation

IV.B.5.a. Definition

Durrell and D'Allura (1977, p. 847) reported that the "Taylor Formation is the lower part of the augite porphyrite of Turner (1897, p. 2), who believed it to be Jura-Trias in the section…" In addition, "The same augite porphyrite is the unit that Diller (1908, p. 82-84) named the Taylor Metaandesite" and that "McMath (1966) verified the presence of the Taylor Metaandesite in both plates of the Taylorsville thrust (and) renamed it the Taylor Formation…"

IV.B.5.b. Lithology

Durrell and D'Allura (1977, p. 848) reported that the Taylor is "...essentially volcaniclastic. Lavas, both massive and pillowed, form only a minor fraction of the section. No chemical analyses are available, but there is sufficient reason to believe that the composition is andesitic." McMath (1966, p. 179) reported that "The Taylor meta-andesite of Diller (1908, p. 83), or the augite porphyrite of Turner (1897), is characterized by augite andesite breccia, tuff-breccia, tuff, subordinate flows, minor black tuffaceous slate, and crinoidal limestone." D'Allura (1977, p. 86) suggested that from southeast of Lake Almanor to the Lakes Basin area the Taylor ranges from less than 1,000 meters (<3,000 feet) to approximately 3,000 meters (~10,000 feet). However, the exposed thickness of the Taylor as mapped by D'Allura (1977, Plate I) within the area of this report's Plate I ranges from less than 30 meters (<100 feet) to approximately 365 meters (~1,200 feet).

IV.B.5.c. Age

Durrell and D'Allura (1977, p. 847-848) reported that while "...McMath (1966) placed (the Taylor) in the Mississippian...Thus far, no fossils have been found in the Taylor" and "…the Taylor Formation is bracketed by the Late Devonian age of the Elwell Formation and the Early Mississippian age of the Peale Formation." However, D'Allura (1977, p. 113) grouped the Taylor with the Elwell and Sierra Buttes Formations as Devonian, but acknowledged that a Late Devonian age for the Taylor is both tentative and assumed.

IV.C. Superjacent Rocks

IV.C.1. Introduction

The important investigations of the Tertiary rocks that relate to the study area are those conducted previously by Durrell (1959a, 1959b, 1966, 1987) and more recently by Wagner and Saucedo (1990); Unruh (1991); Wagner et al. (2000); Grose (2000); Wakabayashi and Sawyer (2000); Garside et al. (2005); Garrison et al. (2008); Street (2009); and Cassel et al. (2012).

Durrell published three important articles dealing with Tertiary volcanic, volcaniclastic, and sedimentary formations in the northern Sierra Nevada (1959a, 1959b, 1966) for use within the Blairsden 15’ Quadrangle, with broader application well beyond. Durrell (1959a, p. 165) defined the following ascending succession, ranging from Middle Eocene to Upper Pliocene: Auriferous gravels; Lovejoy, Ingalls, Delleker, Bonta, and Penman formations; Warner basalt; and Mohawk Lake beds. This sequence was based on a combination of correlations with similar rocks in the Sierra Nevada, various fossil leaf evidence, and perceived stratigraphic relationships observed at exposures both within and outside the Blairsden Quadrangle:

- Auriferous gravels are Middle Eocene, based on correlation;
- Lovejoy is Middle or Upper Eocene, based on its relationship with the Auriferous gravels and the fossiliferous tuff bed at La Porte;

- Ingalls is inferred to be Oligocene, based on it apparently resting unconformably on the Lovejoy and beneath the Delleker at the Ingalls type locality along Red Clover Creek.
- The Delleker is inferred to be "probably Middle or Lower Miocene, possibly Oligocene" based on it apparently being below the Bonta;
- Bonta is upper Miocene based on fossil leaves within its basal portion (citing Turner, 1891, 1894a; Axelrod, 1957);
- Penman is "Lower Pliocene, or possibly Middle Pliocene" since it apparently rests unconformably on the Bonta and below the Warner basalt. Durrell (1959a, p. 175-176) subdivided the Penman into "lower," "middle," and "upper" members where recognizable, mainly within the east-central portions of the Blairsden Quadrangle, and "Elsewhere the formation is like the upper member." Durrell also described a "Penman Undifferentiated" that "applies to the upper Penman and with equal force to all of the Penman where the lower and middle members are not present."
- Warner ("including innumerable plugs and dikes") is tentatively Upper Pliocene; "...the age is not determined in the Blairsden quadrangle, nor is it accurately determined elsewhere," but inferred from its possible correlation with the Tuscan formation that is Upper Pliocene (citing Anderson, 1933);

- Durrell assigned an Upper Pliocene age to the lowermost portion of the Mohawk Lake beds, recognized the difficulty in doing so, and stated "It is thought...that the upper part of the Mohawk Lake beds are Quaternary. The lower part is probably Quaternary also, but there remains a possibility that some of it is Pliocene, and that the Pliocene-Pleistocene boundary lies within the section."

This stratigraphic succession was the foundational framework for nearly 50 years, but was controversial and ultimately challenged (at least in print) by Dalrymple (1964) and Creely (1965) based on prior potassium-argon radiometric age-dating techniques used by Dalrymple for (a) andesite mudflow breccia found beneath the "older basalt" (the Lovejoy) at Oroville South Table Mountain that Durrell did not recognize and (b) the Delleker at Red Clover Creek (also the Lovejoy type locality). Dalrymple bracketed the Lovejoy between 22.2 to 23.8 Ma (also in Creely, 1965; Wagner et al., 2000); placing it in the Early Miocene based on results obtained from plagioclase in the underlying breccia and sanidine in the Delleker.

The Lovejoy (referred to as the "Lovejoy Basalt" by Wagner et al., 2000, and "Lovejoy basalt" by Garrison et al., 2008) became a focus of subsequent investigators, including Wagner et al. (2000), Garside et al. (2005), Garrison (2004), Garrison et al. (2008), and Street (2009). These investigations were supported by improved radiometric-dating techniques, the accumulation of field evidence, and better understanding of the profound difficulties in working with volcanic deposits (Williams and McBirney, 1979); especially those in paleovalleys (Garside et al., 2005). Thus, the

Tertiary stratigraphy of Durrell is redefined as is necessitated by revisions in the unit ages and recognition of the considerable difficulty in effectively distinguishing between the Ingalls, Bonta, and Penman (and, possibly, the Warner). Indeed, Wagner et al. (2000), reported that with regard to the Ingalls, Bonta, and Penman in the mapping done by Grose (2000) in the Blairsden Quadrangle and with others in the Diamond Mountains (Grose, 1991), that Grose was "...unable to recognize Durrell's formations as mappable units."

Several additional important factors affected the understanding of the Tertiary stratigraphy as discussed by Durrell (1959a, p. 165 and 167):

- often confounding complexities resulting from depositional and erosional cycles involving volcanic rocks (Williams and McBirney, 1979);
- effects of high-angle block faulting on exposure patterns;
- presumptions that each of the inter-formational Tertiary depositional surfaces are unconformities that were eroded essentially flat and horizontal,
- all the formations are nearly horizontal;
- the Auriferous gravels were deposited only in "broad and shallow" river valleys;
- The Lovejoy was restricted to a different valley, nearly parallel to the one (or ones?) in which the Auriferous gravels were deposited, "...but it was an even shallower and broader one than that (or those?) in which the (Auriferous) gravels accumulated;" and,

- The succeeding "...five formations were deposited as sheets over large tracks of country."

However, Wagner et al. (2000, p. 158), argued that "...the andesites were emplaced over a pre-existing topography of significant relief" in agreement with Lindgren (1911, p. 37) and other investigators working in the central Sierra whom they cite. Additionally, Bateman and Wahrhaftig (1966, p. 128) state that "...these formations bury a topography with as much as 3,000 feet of local relief" in reference to the volcanic rocks of the northern Sierra Nevada that range from the Oligocene to the late Pliocene.

Wakabayashi and Sawyer (2000, p. 177) reported in apparent disagreement that uplift of the Sierra Nevada from Eocene to Miocene time was minor since "...the amount of incision of Miocene and Oligocene channels into the Eocene deposits is less than 60 m" (also citing Lindgren, 1911, and Yeend, 1974), thus indicating that the Sierra Nevada topographic relief "...had been reduced to fairly low levels by Eocene time in the central and northern Sierra."

Nevertheless, the Cenozoic stratigraphy of the portion of the northern Sierra Nevada extending from the Quincy area to that covered by the Blairsden Quadrangle and which has resulted from the age revisions is in the following ascending order:

- the Auriferous gravels are Lower Eocene (Henry et al., 2012).

- the Delleker rhyolite tuff is Late Oligocene[9] to Early Miocene; approximately 31 to 23 Ma (Grose, 2000; Garrison et al., 2008). The Delleker is not exposed in the study area of this thesis.
- the Lovejoy basalt is Middle Miocene; approximately 15 to 16 Ma, with 16 Ma the generally accepted age (Wagner et al., 2000; Garrison et al., 2008).
- the Ingalls, Bonta, and Penman formations; Grose (2000, with references therein) described these units as ranging from approximately 20 to 8 Ma, Early to Late Miocene, based on radiometric ages from samples collected at four locations within the Blairsden quadrangle. However, the overlap of the older end of this range of radiometric ages with the accepted 16 Ma age of the Lovejoy indicates a significant degree of uncertainty in the reported ages given that at least the Bonta among these three formations is younger than the Lovejoy as is demonstrated by the mapping in the study area for this thesis. Grose viewed these formations that were originally named and described by Durrell (1959a) as a "...heterogeneous volcanic pile (that) includes basalt flows, rhyolitic to basaltic tuffs, and lesser volcanogenic sandstones and conglomerates in complex facies and thickness variations difficult to decipher

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[9] Busby and Putirka (2009, p. 687) made the following observation regarding Oligocene-early Miocene ignimbrites in the northern Sierra (presumed to include the Delleker): "These ignimbrites erupted from calderas situated in central Nevada... For these to have flowed from central Nevada to the Sacramento Valley of central California, surface elevations must have continuously decreased in that direction, and the region could not have yet been disrupted by normal fault."

because of forest cover" and combined these lithologic units within an informally-named "Andesitic tuff breccias and flows."

- the Warner basalt (Durrell, 1959a); Grose (2000) assigned to the informally-named "Mafic andesite and basalt flows" the rocks mapped in the Blairsden quadrangle that are considered "...equivalent to Durrell's 'Warner Basalt.'" Grose did not provide an age for the unit. However, based on the age reported for the Warner-like intrusive (discussed next), the Warner basalt may be Late Miocene, but is no younger than uppermost Miocene. Nevertheless, the mapping for this thesis demonstrates that the Warner is younger than the Bonta.
- the Warner intrusive; Grose (2000) shows rocks grouped under the informal name "Mafic andesite intrusion" intruding rocks described as "equivalent" to the Warner basalt of Durrell (1959a). Grose reported a K-Ar date of 4.7 ±0.1 Ma for a sample of that intrusive material collected in the "...summit area of Mt. Ingalls..." Thus, these intrusive rocks are indicated to be uppermost Miocene or lowermost Pliocene. However, Saucedo et al. (in Wagner et al., 2000, p. 161) reportedly obtained a "...radiometric date of 11.4 ±0.7 Ma, or Late Miocene, for the rocks mapped as intrusive Warner Basalt near Red Cover Creek." This earlier radiometric age reported by Saucedo et al. (2000) for what is described as intrusive Warner is another example of an overlapping age that calls into question the reliability of the dating result and/or the correlation of these exposures with the Warner reported by Grose and Saucedo et al. (see below for further discussion of the Warner).

- the Mohawk Lake beds.; Redwine et al. (2015) reported that the ages of the lake bed sediments deposited in Mohawk Valley range "…from ~740 to ~7 ka…," based on a series of tephras and tephra beds. Thus, the Mohawk Lake beds range from at least the upper Pleistocene to the Holocene.

IV.C.2. Lovejoy basalt

IV.C.2.a. Definition

Turner (1894a, 1896, 1897) originally referred to the rocks that are now called Lovejoy basalt (Garrison et al., 2008) as the "older basalt." Durrell initially applied the name "Lovejoy basalt" (Wilhelms, 1958, p. 33), subsequently "Lovejoy formation" (1959a, 1959b, 1965, 1966), then "Lovejoy Formation" (1987), to basalt flows at sixteen principle locations in northern California. Occurrences of the Lovejoy basalt extend from the crest of the Honey Lake fault scarp (eastern Lassen County) southeast to Putnam Peak, near Vacaville, in the Sacramento Valley (Durrell, 1959b, p. 196-197; Wakabayashi and Sawyer, 2000; Garrison et al., 2008; Street, 2009). The formation is named for Lovejoy Creek which is adjacent to one of the principle occurrences within the Blairsden 15' quadrangle. The type section of the Lovejoy basalt is located on Red Clover Creek; in Sections 30 and 31, T25N, R12E.

IV.C.2.b. Distribution

The Lovejoy basalt crops out in three relatively limited areas within the limits of Plate I: (1) Lee Summit (Sections 5, 6, 7, and 8, T23N, R11E); (2) west of Fells Flat (Sections 10 and 11, T23N, R10E); and (3) in a somewhat narrow east-northeast- to west-southwest-trending belt from the Quincy-La Porte Road to Bachs Creek Ridge (Sections 32, 33, and 34, T24N, R10E to Sections 4, 5, 6, and 8, T23N, R10E). These exposures are part of considerably more extensive, yet discontinuously-exposed, northeast-to-southwest-trending and northeast-to-west-trending bifurcated belts (Garside et al., 2005, p. 226) within northern California that are part of the trans-Sierran distribution of the Lovejoy basalt (Durrell, 1959b, p. 196-197; Street, 2009). Grose (2000) states that the Lovejoy is confined to the same paleochannels cut into the Sierran basement wherein the Eocene(?) "Auriferous gravels" are preserved.

The mapping for the present study revealed that the Lovejoy rests unconformably on Shoo Fly Complex rocks and is, in turn, overlain unconformably by the Bonta formation, which is overlain unconformably by the Warner basalt. The best locations that demonstrate these relationships are in Section 6, T23N, R10E, on a northeast-facing flank of Bachs Creek Ridge. Lovejoy depositional contacts are generally approximated as sharp and horizontal, but some relief is also present (Figure 7). The Lovejoy is bounded elsewhere within the study area either partially or completely by high-angle faults (Plate I).

Gravels associated with the Lovejoy were not observed either within the formation or at its upper or lower contacts. This is in contrast to exposures reported in areas adjacent to that of Plate I (Durrell, 1959a, 1959b; D'Allura, 1977). However, the lack of exposed gravels below the Lovejoy does not preclude the possible existence at depth that is either obscured by faulting or hidden by younger Tertiary and/or Quaternary cover.

The exposed Lovejoy thickness observed during this study varies from approximately 6 to 73 meters (20 to 240 feet); in contrast to the up to 500-foot thickness described by Durrell (1959b, p. 202) for exposures in the Red Clover Creek area or the "…maximum exposed thickness of ~245 m (~800 feet) at Stony Ridge, located south of Thompson Peak in the Diamond Mountains…" reported by Garrison et al. (2008, p. 2).

IV.C.2.c. Lithology

Evidence for separate flows of Lovejoy basalt was not found within the study area. Such evidence is common in other areas in northern California and mark successive flows (see, for example, Durrell, 1959b). Rather, the Lovejoy forms relatively smooth slopes that are typically strewn with its distinctive blocky talus. This aspect may be either the result of multiple flows (if present) being poorly-developed and easily hidden by talus or that erosion accounts for the absence of more than one flow. Occasionally, the larger outcrops protrude from hillsides up to 2 meters high (6.5 feet). Outcrop surfaces (Figure 29) show the intersecting joint pattern and concoidal fractures which are responsible for forming the roughly equidimensional blocks that are characteristic of all such occurrences (Durrell, 1959b, p. 199). The basalt is vesicular to vuggy, with vugs up to 2 or 3 centimeters (1 inch) and vesicles that are generally 1 centimeter or less, roughly spherical, and may be lined with what is probably a zeolite. Scoriaceous portions of the Lovejoy were not found. In some instances, quartz xenocrysts or xenoliths of the country rock are recognizable in hand specimen.

The Lovejoy is a tholeiitic basalt (Garrison et al., 2008, p. 16). It is dark grey to black on fresh surfaces and weathers to dark chocolate brown. Durrell (1959b, p. 199) indicated that the color variations of fresh surfaces may result from the state of aggregation of magnetite and that flows with the coarsest magnetite are of the grey-colored variety. The soil developed from the Lovejoy is a distinctive deep chocolate-brown and contains chips of the weathered basalt.

In thin section, the Lovejoy is composed of microlitic to felty plagioclase with intersertal olivine, pyroxene, and opaque glass (Figures 30a and 30b). Plagioclase occurs as euhedral, lath-shaped, twinned crystals that range from 0.1 to 0.3 mm long, are rarely up to 0.5 mm long, and may show flow alignment. Durrell (1959b, p. 200) described the plagioclase as being of "intermediate composition." Hietanen (1973, p. 58) reported Lovejoy plagioclase composition as "An50." Plagioclase forms approximately 35 to 40 percent of the rock and, on occasion, displays a radial growth texture. Olivine and pyroxene rarely occur as microphenocrysts up to the size of those of plagioclase, but in general the pyroxene forms subhedral crystals up to 0.1 mm. Examples of truly ophitic plagioclase and pyroxene are rare. Clustering of olivine and pyroxene was not observed. Together, plagioclase, olivine, and pyroxene comprise approximately 70 to 80 percent of the rock. The remaining 20 to 30 percent is composed of glass, possibly made opaque by finely-disseminated magnetite, which would be consistent with the descriptions reported by Durrell (1959b, p. 201).

IV.C.2.d. Age and Correlation

Prior reports involving the age of the Lovejoy basalt resulted in controversy. Durrell (1959b, p. 214-216) dated the Lovejoy Formation to be Eocene, although it was thought to be either latest Eocene or lowest Oligocene on the basis of its stratigraphic relationship to the various Tertiary rocks throughout its range of exposures. Durrell (1959b, p. 216) found what he considered to be reworked Lovejoy embedded within lacustrine clays at Upper Dutch Diggings near La Porte (southwest Plumas County). The lacustrine clays are deposited between the Eocene Auriferous gravels and the La Porte tuff. The fossiliferous La Porte tuff is dated Eocene or lowest Oligocene (Potbury [1935] in Durrell, 1959a) on the basis of the La Porte flora. Thus, Durrell (1959b, p. 216) concluded that "...the Lovejoy is older than Upper Eocene or Lower Oligocene, and younger than the Middle Eocene Capay formation" upon which the Lovejoy rests in the Sacramento Valley. Durrell cited possible further restriction to "...very high in the Eocene, or possibly lowest Oligocene" if the Putnam Peak basalt, resting on the Upper Eocene Markley formation (Weaver [1949] in Durrell, 1959b, p. 197, 216), "...is properly correlated with the Lovejoy."

Creely (1965, p. 61) conditionally considered the Lovejoy (the "older basalt") to be possibly upper Miocene to lower Pliocene, despite such evidence, but no older than early Oligocene on the basis of somewhat tentative stratigraphy. However, in a footnote, Creely (1965) references the earlier work by Durrell (1959a, 1959b) and radiometric dating work done by Dalrymple (1964). The radiometric dating by Dalrymple of various Lovejoy basalt samples yielded an Early Miocene age (1964, p. 13-15). Moreover, Dalrymple considered that having not found Lovejoy clasts within the lacustrine clay at La Porte and the reported stratigraphic relationship of the Lovejoy to earlier rocks at Oroville South Table Mountain were corroboration of the early Miocene radiometric age. Since Durrell (1959b, p. 209) was not able to substantiate the stratigraphic evidence at Oroville Table Mountain cited by Dalrymple (1964), it is interesting to note that neither worker could find one of the key pieces of evidence for the other's argument for the age of the Lovejoy basalt.

The age of the Lovejoy basalt has taken on added interest in recent years, along with studies involving its chemistry and distribution for the implications about North American plume dynamics (Garrison et al., 2008) and the paleogeography of northern California and northwestern Nevada and the northern Sierra Nevada (Wagner et al., 2000; Garside et al., 2005; Street, 2009; Busby and Putirka, 2009).

Improved radiometric age-dating techniques have resulted in placing the Lovejoy within the Early to Middle Miocene; at about 16 Ma (Wagner et al., 2000, and references cited therein). Garrison et al. (2008, p. 14-16), reported that Ar40/Ar39 step-heating analytical results indicated estimates between 15.12 ± 4.64 Ma and 15.6 ± 1.0 MA and state that "The accepted age for the Lovejoy is now 15-16 Ma…unequivocally mid-Miocene…and broadly coeval with the main phase of the Columbia River Basalt Group." Additionally, Coe et al. (2005, p. 699), on the basis of paleomagnetic data, concluded that the Lovejoy was erupted "…probably within a few centuries to at most a few thousand years."

Thus, the Lovejoy is the basal unit within the Superjacent succession in the study area and forms the key stratigraphic marker against which the reported isotopically-derived ages of the younger Superjacent volcanics are to be compared.

IV.C.3 Ingalls formation

IV.C.3.a. Definition

Durrell (1959a, p. 167-170) applied the name "Ingalls Formation" to the pyroxene andesite described by Turner (1897, Folio 37) that overlies the "older basalt" (i.e., the Lovejoy). Durrell stated (1959a, p. 167) that some of the best Ingalls exposures are along Red Clover Creek where it is in contact with the Lovejoy basalt at the Lovejoy type locality. However, the Ingalls has no type locality because of its variability in composition and thickness throughout the Blairsden quadrangle. D'Allura (1977) did not recognize the Ingalls in the area of this report's Plate I. Strand (1972) mapped what was thought to be "Ingalls" to the north and northeast of Nelson Point (Sections 9, 10, 15, and 16, T23N, R10E) in both fault and depositional contact with the Shoo Fly, which was mapped by Strand as "Calaveras formation." Strand defined the "Ingalls" to also include a 20- to 25-foot thick basal conglomerate and showed it partially overlain by a flow mapped as Warner basalt. The "Ingalls" mapped by Strand is reinterpreted here to be the Bonta formation and the basal conglomerate to be the Bonta gravel. That Strand mistook the Bonta for the Ingalls is understandable because the two formations are similar in appearance and composition, including a basal conglomerate that Durrell (1959a, p. 169) described in the Blairsden quadrangle. However, the basalt that Strand mapped overlying the “Ingalls” is unmistakably the Lovejoy which is in fault, not depositional, contact with the Bonta in that portion of Plate I.

IV.C.3.b. Distribution

Rocks mapped by Durrell (1976) as Ingalls formation are exposed in a single, limited area (southwest quarter of Section 9, T23N, R11E) on the north side of the Middle Fork of the Feather River[10]. The mapping on Plate I is reproduced from Durrell. This exposure is at least 73 meters (240 feet) thick. The base of the Ingalls is hidden beneath alluvium, but it presumably rests on the Shoo Fly because the latter is exposed directly across the Middle Fork and the Ingalls is not found south of the river. In addition, Durrell mapped rocks of the Bonta formation also resting on the Shoo Fly and in fault contact with the Ingalls that is immediately to the east (Plate I).

IV.C.3.c. Lithology

Durrell (1959a, p. 169) interpreted the Ingalls as predominantly pyroxene andesite mudflow breccias that “...are devoid of recognizable bedding surfaces, are very well indurated...” and may be associated with a basal volcanic conglomerate and an intervening bedded andesite tuff. The Ingalls shown on Plate I varies from a volcanic conglomerate to a volcanic breccia, weathers dark brown or black, and has craggy outcrops with surrounding areas that support little or no vegetation. Durrell

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[10] Observation and sampling of the exposure was done in 1976 during a field area visit with Durrell and DeVay.

considered the craggy outcrops to be "...the most characteristic feature of the formation." A property of the Ingalls breccia that contrasts with that of the Bonta is that it breaks across the embedded clasts rather than around them. The Ingalls may be either an epiclastic deposit or a reworked pyroclastic deposit or both. It is composed of unbedded vesicular to scoriacious pyroxene andesite clasts set in a matrix that varies from sand to clay. The andesite clasts are angular to subangular and range from 1 to 2 mm to blocks greater than 30 centimeters. The individual clasts vary from dark grey to a reddish grey-brown and the matrix is grey. The soil that develops on the Ingalls is generally grey-brown and is strewn with fragments and clasts of the parent material. No basal conglomerate or tuff beds are associated with the Ingalls shown on Plate I.

Microscopically, the Ingalls andesite is composed of euhedral to subhedral plagioclase and euhedral to anhedral augite phenocrysts set in a brown groundmass that is composed predominantly of felty microlites of plagioclase, with subordinate augite, glass, and possibly magnetite (Figure 31). The plagioclase exhibits albite and Carlsbad twinning and is generally strongly zoned. The plagioclase phenocrysts may contain inclusions of glass, augite, magnetite(?), plagioclase, or some combination of these. The plagioclase is of intermediate composition, approximately An54 determined by optical method, while the microlites are more sodic, approximately An34 also by optical method. The plagioclase sizes range from 0.01 to 3 mm and may form aggregates with augite up to 4 mm in longest dimension. The plagioclase and augite phenocrysts compose from 50 to 60 percent of the total rock, with the proportion of plagioclase to augite at roughly 2 to 1. The augite is generally glomeroporphyritic and may display twinning. Flow-alignment of crystals was not observed.

IV.C.3.d. Age and Correlation

That the Ingalls might be Oligocene was originally inferred by Durrell (1959a, p. 170) based on its stratigraphic relationship to other volcanic formations within the Blairsden 15’ Quadrangle and its possible equivalence to the Oligocene Alta andesite of the Virginia City, Nevada, area and the Oligocene Wheatland Formation of the Sacramento Valley. However, Dalrymple (1964, p. 11-13, 15) argued that the Ingalls is Early Miocene based, in part, on radiometric age dates for samples of the Delleker formation which was presumed to overly the Ingalls. Because Dalrymple dated the Lovejoy as Early Miocene, the Ingalls then became constrained to no older than Early Miocene. Indeed, Wagner et al. (2000. p. 161) stated the following: “Radiometric dating by Siegel (1988) shows that andesite assigned to the Ingalls Formation at Red Clover Creek is mid-Miocene...This is the reverse of Durrell’s sequence.”

IV.C.4 Bonta gravels

IV.C.4.a. Definition

The basal gravels of the Bonta formation are subrounded to well-rounded, cobble to boulder, channel conglomerate beds (Figure 32). These sediments are so restricted that they are found in place only between the Bonta and the Shoo Fly and at three principal locations within the area of Plate I (discussed below). Thus, they are assigned to the Bonta and herein informally named the “Bonta gravels.” The gravels were mined to varying degrees for gold.

IV.C.4.b. Distribution

The three principal occurrences of the Bonta gravels are located in: (1) the northwest quarter of Section 15, T23N, R10E, to the northwest of Nelson Point on the north side of the Middle Fork of the Feather River (Figure 33); (2) the northwest quarter of Section 15, T23N, R10E, on the west side of the Quincy-La Porte road; and (3) the southeast quarter of Section 10, T23N, R10E, on the south side of the river. Bonta gravels within the study area are exposed in the Canyon of the Middle Fork of the Feather River, but this does not preclude the possible existence of other deposits of these gravels that may be hidden elsewhere beneath the Bonta.

Evidence for possible additional exposures of the Bonta gravels is in at least three places within the north half of Section 16, T23N, R10E. These other exposures are in the form of either thin veneers or gravel debris and are associated with both the volcaniclastic Bonta and exposed pre-Bonta (i.e., Shoo Fly) erosion surfaces. Each of these exposures is evidently disturbed by mining efforts. At least one such effort (northeast quarter of Section 16) took the form of hydraulic mining.

IV.C.4.c. Lithology

The Bonta gravels are distinct from the “Auriferous gravels” in that they are not rich in the quartz clasts that characterize the latter (Durrell, 1965, p. 2-3). Rather, they may resemble the “quartz-poor gravels” of Durrell (1965, p. 3) and, possibly, the “Cascade gravels” of D’Allura (1977, p. 195-196) in that they contain metavolcanic, meta-sedimentary, and granitic clasts of basement rocks and andesitic clasts presumably derived, at least in part, from local or nearly-local sources. Notably, the Bonta gravels do not contain clasts of Lovejoy basalt.

The Bonta gravels are generally thickly-bedded, predominantly matrix-supported, poorly-sorted, and poorly-indurated fluvial conglomerates. The bedding is usually poorly expressed and varies from horizontal to slightly inclined at shallow angles. The conglomerate clasts range from pebbles to boulders, with sand being the dominant matrix component. Overall, the matrix fraction comprises approximately 20 to 40 percent. Most clasts are well rounded to subangular. Clasts of the foliated rock types may retain some tabular or planar aspects. Clasts derived from the Shoo Fly are concentrated within an individual bed in at least one location; on the west side of the Quincy-La Porte road, in the northwest quarter of Section 15, T23N, R10E. This foliated-clast-rich cobble bed is approximately 0.6 meters (2 feet) thick and appears to mark the termination of the deposition of the larger-sized clasts since, above the bed, the Bonta grades into pebble conglomerate and sandstone beds that, in turn, are overlain by the volcaniclastic Bonta. Overall, the Bonta gravels vary from approximately 12 to 36 meters (40 to 120 feet) thick.

IV.C.4.d. Age

The Bonta gravels have no definitive age because they are without fossils. However, the gravels are bracketed by the underlying unconformity developed on the rocks of the Shoo Fly Complex that separates the Subjacent and Superjacent series and the overlying Bonta volcaniclastics. Strictly speaking, the age of the gravels is no more definitive than Middle Miocene; younger than the Lovejoy and older than the overlying Bonta.

IV.C.5 Bonta formation

IV.C.5.a. Definition

Durrell (1959a, p. 172) named the Bonta formation for Bonta Creek in the south-central part of the Blairsden 15’ Quadrangle, but without a type locality. Within the Blairsden Quadrangle, the formation varies from 30 to 230 meters thick (100 to 750 feet), but owing to unconformities, the original thickness is not known.

The evidence for the Bonta includes bedding; the presence of Delleker tuff, granitic, and other exotic clasts; color; soil characteristics; and a general relative paucity of hornblende in soil. Durrell (1959a, p. 173 and 176) cites the relative lack of hornblende in soil and the presence of Delleker debris (“biotite rhyolite tuff”) as characteristics that help to distinguish the Bonta from the Penman. However, the Penman cannot be entirely ruled out as overlying the Bonta in some of the areas that are shown underlain by the Bonta on Plate I. It is important to also note that Durrell (1976) and D’Allura (1977) mapped the Penman within the areas covered, respectively, by the southeast corner and northeast portion of Plate I.

IV.C.5.b. Distribution

The Bonta crops out within the area of Plate I in a continuous east-west trending belt across the middle of the study area that defines a paleovalley (discussed below). The belt narrows gradually from approximately 6 kilometers (3.8 miles) wide, at the east edge of Plate I, to 1.8 kilometers (1.1 miles) wide, near the west edge of the map. The belt is delineated by both faults and depositional contacts. The Bonta varies in thickness from perhaps several meters or less, in the case of small fault slivers or erosional remnants(?), to approximately 200 meters (656 feet), near the east edge of Plate I. The description of the Bonta reported by Durrell (1959a, p. 172) indicates that its thickness "...ranges from 100 to 750 feet" in the Blairsden Quadrangle, but that erosion precludes knowledge of the original thickness.

The most important of the depositional contacts are those between the Bonta and the underlying Shoo Fly, which are observable for the most part within the limits of the canyon of the Middle Fork of the Feather River, and the underlying Lovejoy. The Bonta is in depositional contact with the Shoo Fly in relatively few places beyond the river canyon (e.g., northwest quarter of Section 9, T23N, R10E). The Bonta is in depositional contact with both the underlying Lovejoy and the overlying Warner near the west edge of Plate I. Depositional contacts that are reasonably certain are essentially planar and horizontal. The only noteworthy examples of relief on the contact between the Bonta and another unit are present in various roadcuts along the Quincy-La Porte road. One such instance is on the south side of the road, in the southeast quarter of Section 33, T24N, R10E, where the Bonta is in contact with the Lovejoy basalt (Figure 7). Another example is on the west side of the road, in the southwest quarter of Section 10, T23N, R10E, where the Bonta is in contact with the Shoo Fly. In both cases, faulting obscures the full extent of the contacts and total relief is at least 12 meters (40 feet). Twelve meters is probably no less than one half to a third of the full magnitude of the relief at these locations, judging from the nature of the contacts elsewhere within the area of Plate I. Whether the relatively small exposures of the Bonta are evidence for faulting or erosional remnants, they demonstrate the extent to which the Bonta was distributed within the study area.

The Bonta does not crop out in either the northwest corner of Plate I or along the extreme west edge of the map. However, the Chico sheet of the Geologic Atlas of California (Burnett and Jennings, 1962) shows volcanic rocks, "equivalent" to the rocks exposed within the area of Plate I. Those exposures are shown as Pliocene pyroclastics in at least two locations within the Sierran block. One of these exposures is to the northwest of the study area; north of Meadow Valley in T24 and 25N, R8E. The other location is principally northeast of Bear Creek, in T23N, R8E, west and southwest of the study area. Hietanen (1973, p. 57) briefly referred specifically to both of these occurrences of andesite. Hietanen described the andesite exposures north of Meadow Valley as darker than the Penman formation of the Blairsden 15' Quadrangle and that it "...weathers to a rusty-brown soil that contains boulders of andesite." Hietanen described the andesite exposures east of Bear Creek as "...mostly medium-grey with sparse black hornblende that weathers to a gray soil that contains hornblende." These descriptions suggest that exposures of rocks with at least some lithologic equivalence to the Bonta may extend farther to the northwest of the study area, beyond the crest of the Sierra Nevada.

IV.C.5.c. Lithology

Durrell (1959a; 1966) interpreted the Bonta formation to be predominantly volcanic conglomerate inter1ayered with andesite mudf1ow breccia and volcanic fanglomerate. Berry (1979) described the Bonta farther to the east in the Portola area (within the Reconnaissance Peak 7.5' Quadrangle) as varying in composition from hornblende andesite to olivine and pyroxene basaltic andesite and includes previously unrecognized lava flows, tuffs, and obsidian. The lithological and sedimentological characteristics of the Bonta are best displayed in road cuts.

Distinguishing the Bonta from either the Ingalls or Penman formations is difficult because of similar composition and reworking. An important aspect of the Bonta is the presence of clasts of Delleker tuff, or ignimbrite. Under the original Durrell stratigraphy (1959a), the presence of Delleker tuff in the Bonta would have precluded its identification as the Ingalls formation. Other characteristics must also be used to distinguish it from the Ingalls and Penman. The Bonta often displays evidence of bedding (Figure 34a), in contrast to the Ingalls, and is probably both an epiclastic and a reworked pyroclastic deposit. Overall, the Bonta contains less hornblende and is darker in color than the Penman.

The Bonta within the study area is predominantly heterolithic andesite volcanic breccias and includes poorly- to moderately-well sorted volcanic and fluvial conglomerates and interbedded tuffaceous sandstones; in decreasing order of abundance. The breccias are generally internally unstratified, but they may serve to mark larger-scale stratification (Figure 34b). The degree of induration of the Bonta is highly variable. The Bonta ranges from soil-like to moderately-well indurated, depending on the degree of weathering and the nature of the deposit. In the latter case, breccia matrix breaks around the larger clasts, but usually breaks across the smaller clasts set within the matrix (Figure 35). The relatively fresh exposures of the volcanic breccia, such as those in roadcuts, weather to a range of pastel colors, including light brown, brown, pink, yellow, yellow-orange, and cream or buff, and display a type of color banding formed by iron-oxide staining that is concentrated along cracks or fractures. The breccias are generally characterized by clast-supporting, sandy matrices that contain scoriaceous and ashy, or tuffaceous, fragments. The matrix material may show enhanced vesicularity from the weathering-out of crystalline phases, such as feldspar or hornblende, as evidenced by lath-shaped voids or depressions arranged in a felty manner. The variability of the rock types that form the clasts contained within the Bonta makes impractical the collection of a truly representative sample[11]. Certain distinctive rock types, both cognate and exotic, characterize the Bonta, including both pyroxene and hornblende andesites and non-andesitic rock types.

However, the Bonta is dominantly of hornblende andesite composition. The andesite clasts range from angular to subrounded and from approximately 1 mm up to about 80 to

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[11] Durrell (pers. comm., 1976) very memorably remarked that a railcar would be needed in order to collect a representative sample from the Bonta.

90 centimeters (about 3 feet). They are mainly porphyritic and display a variety of pastel colors that include greyish blue, greyish purple, greyish green, buff, and brown. The foreign clast rock types include metavolcanic rocks, evidently derived from the Taylor and Sierra Buttes Formations; Shoo Fly Complex; Lovejoy basalt; Delleker tuff; quartz diorite; and rare fragments of opalized wood. The Lovejoy and quartz diorite clasts range from cobbles to boulders up to 6 meters (20 feet) long. Boulders of Lovejoy basalt were found in the Bonta in the northeast quarter of Section 9, T23N, R10E (south of Egbert Meadow) and quartz diorite boulders were found in the northwest quarter of Section 15, T23N, R10E (above and to the west of the Quincy-La Porte road). In one instance, a “mega-clast” of Taylor meta-andesite breccia, approximately 7.5 to 9 meters (25 to 30 feet) in diameter, was found in the northwest quarter of Section 14, T23N, R10E, near the 4,790-foot mark. Large boulders and a “mega-clast” of the Taylor Formation meta-andesite breccia are exposed near the southeast corner of Section 18, T23N, R11E (Figures 36a and 36b). The presence of these very large clasts attests to the transportive power of Bonta material on the move. The quartz diorite clasts usually have relatively unweathered surfaces, but may also show advanced stages of weathering. In such cases these clasts are set within matrix, are exposed in cross-section by either road cut or slope wash, and easily disintegrate into grus.

The interbedded conglomerates and sandstones within the Bonta constitute what appears to be a minor portion of the formation. Roadcut exposures of the Bonta indicate that the sandstones and conglomerates may make up 1 or 2 percent, certainly less than 5 percent, of the formation and the sandstones appear to be in roughly equal proportion to conglomerate.

The best exposures of the Bonta sandstones and conglomerates are located on either side of the Quincy-La Porte road, in both the southeast quarter of Section 10 and the northwest quarter of Section 15, T23N, R10E. The conglomerates are moderately-well sorted, display graded bedding and some imbrication, and weather like the sandstones from brown to either light grey-brown or buff. Both the sandstones and conglomerates are stained by iron oxide. Individual clasts in the conglomerates are typically pebble-sized, averaging approximately 5 centimeters (2 inches) across. The maximum size of the clasts is approximately 15 centimeters (6 inches) across. The clasts are well-rounded to sub-rounded. The rock types that make up the clasts typically include all of the types previously mentioned as both exotic and cognate to the Bonta breccias.

Tuffaceous sandstone, similar to the sandstone interbeds, forms the matrix material of the conglomerates. Bedding is enhanced by iron-oxide staining at the contacts between individual beds. The beds are generally lenticular and range from approximately 0.6- to 2-meters (2- to 6-feet) thick. The sandstone beds are well sorted, fine- to coarse-grained, and may display cross-bedding. The sandstones may display fractures or cracks and differential weathering that produces knobby surfaces that resemble concretions. The sandstones are tuffaceous, are in part clay-cemented, and contain grains of milky and glassy quartz, some biotite and hornblende, and some sand-sized rock fragments of basement rock types.

Soils developed on the Bonta are generally brown to dark-brown and contain crystalline debris derived from the rock types that make up the Bonta. The crystals include milky quartz, biotite, and hornblende (granitic debris); glassy quartz, sanidine, and biotite (Delleker debris); and hornblende and pyroxene (andesitic debris). A relatively crusty soil is apparently characteristic of the unforested Bonta (Durrell, 1959a, p. 173). The Bonta generally supports well-established forest vegetation and a concomitant, loose, richly organic, and thick surface soil zone.

The samples of the Bonta collected for hand-specimen examination and thin-section study include both hornblende andesite breccia clasts and matrix. In hand specimen, the clasts range from light greyish purple or pink, mottled with reddish-brown hornblende, to greenish grey, mottled with white feldspars, to dark grey, mottled with black hornblende. In thin section, the clasts are similar in composition and textural features with the following: trachitic to felty plagioclase and hornblende in a brown groundmass composed of trachitic to felty, microcrystalline plagioclase; subordinate hornblende; magnetite(?) and/or iron oxide after hornblende; and glass (Figure 37). The plagioclase phenocrysts generally display albite, Carlsbad, and pericline twinning and may be zoned. The euhedral to subhedral plagioclase ranges from groundmass microlites of 0.01 mm up to phenocrysts 3.0 mm long. The plagioclase phenocrysts are of optically-determined intermediate composition, averaging approximately An_{50} (An_{54} to An_{46}). The groundmass plagioclase is more sodic, with an approximate composition of An_{30} to An_{40} (also optically-determined).

The euhedral to anhedral hornblende ranges from approximately 0.1 mm up to 1 centimeter. However, hornblende phenocrysts are generally no larger than 2 to 4 mm in longest dimension. The hornblende is generally altered, at least in part, to iron oxide which forms reaction rims, embayments, inclusions, and comb-like terminations. Iron oxide also forms pseudomorphs after hornblende. Hornblende that is poikilitic with plagioclase is also present. The plagioclase and hornblende phenocrysts make up approximately 50 to 60 percent of the rock. The proportion of plagioclase to hornblende is approximately 2 to 1. The remaining approximately 40 to 50 percent of the rock is comprised of magnetite(?) and/or iron oxide (5 to 10 percent) and groundmass plagioclase plus glass (40 to 45 percent).

The samples of andesite breccia matrix material that were examined (Figure 35) are composed of a groundmass of opaque ash and clay into which are set anhedral to euhedral crystals of plagioclase, hornblende, and augite. The crystals occur both singly and in aggregates, with a size range up to 4 mm long. The hornblende is generally less than or equal to 2 mm long. The crystals display no preferred orientation, and the plagioclase is generally zoned. The plagioclase estimated An composition was not obtainable. Also present in the vesicular matrix are rock fragments of both hornblende and pyroxene andesite up to 4 centimeters in longest dimension.

IV.C.5.d. Age and Correlation

Durrell (1959a, p. 173) briefly mentioned the finding near Clio (Figure 3) by Turner (1891) of the “...Mohawk flora...at the very base of the Bonta...” and that the age of the

Mohawk flora was "...refined to Upper Miocene by Axelrod (1957)." However, Wagner et al. (2000, p. 160; citing Page et al., 1995), reported that rocks considered to be Bonta are 11 to 19.7 Ma on the basis of radiometric dating; placing the Bonta in the Early to lower Late Miocene.

As indicated above in the introduction to the Superjacent rocks, Grose (2000) reported, also on the basis of radiometric dates, that the age of the andesitic volcanics exposed in the Blairsden Quadrangle, that include the Bonta, or its "equivalent," ranges from the Middle to Late Miocene (20 to 8 Ma). However, Grose also states that "…the bulk of the effusives is believed to have been emplaced about 11 to 14 Ma ago as evidenced by the regional volcanic history." This qualification by Grose that points to the regional volcanic history for the apparent younger age range of the Bonta, as opposed to the isotopically-derived range, is in keeping with the results of this study that demonstrate that the Bonta unconformably overlies the 16 Ma old Lovejoy basalt. Thus, the Middle Miocene seems to be a reasonable age for the Bonta.

IV.C.6. Penman formation

IV.C.6.a. Definition

Durrell (1959a, p. 174-176) described the "Penman formation" as andesitic deposits that consist of three members, "lower," "middle," and "upper," and that "Natural outcrops of the Penman formation are very rare…" The name is taken from Penman Peak in the Blairsden Quadrangle. Like the Ingalls, the Penman has no designated type locality because of its "...incompleteness of section, and variability of the unit." The lower and middle members are distinctive, but the upper member is relatively indistinct and is quite similar in its gross aspects to the Bonta Formation. Where the lower and middle members are not present, the Penman is presumably a mix of the upper member with either the lower members or with rock types which are exotic to the Penman.

Wilhelms mapped the Penman within the area of this report's Plate I as the "Estray andesite" (1958, p. 36-45) presumably because he was not able to recognize whether the deposits belonged to either the Penman or Bonta formations. However, D'Allura (1977) mapped these same exposures as Penman, evidently recognizing similarities to the deposits of Penman that he mapped a short distance to the northeast in Sections 29 and 30, T24N, R11E.

IV.C.6.b. Distribution

The andesitic deposits mapped by D'Allura (1977) as Penman are within the northeastern portion of Plate I. The Penman is mapped either in partially fault-bounded blocks or as deposits that unconformably overlie the Shoo Fly Complex, Sierra Buttes, Elwell, or Taylor formations. An exception to this is in the northeast quarter of Section 35, T24N, R10E, where the Penman is mapped capping a small hilltop in depositional contact with the underlying Shoo Fly. All the depositional contacts between the Penman and underlying Subjacent units are essentially horizontal and planar. The thickness of the various deposits ranges from approximately 12 meters (40 feet) to 104 meters (340 feet).

IV.C.6.c. Lithology

The Penman that crops out to the west and northwest of the Williams Loop (Section 25, T25N, R10E) is poorly exposed within forest and is similar to the Bonta in that it is difficult to tell whether the parent material is either volcanic breccia, fanglomerate, agglomerate, or fluvial conglomerate and sandstone. To the east of the Williams Loop, recognition of the parent material is aided by roadcuts and relatively sparse vegetation. The Penman that underlies the southwest quarter of Section 30, T24N, R11E, and the center of Section 25, T24N, R10E, crops out on hillsides in a manner that is consistent with the interbedded conglomerate and sandstone parent material exposed in the roadcut due east of the Williams Loop. This exposure affords a view of the sedimentologic and lithologic characteristics of the unit. The interbedded conglomerates and sandstones display typical fluvial features that include scour-and-fill, clast imbrication, graded bedding, and lenticular geometry. The clasts within the conglomerate beds range in size from pebble to cobble. Rounding is generally well developed and sorting is better than in the Bonta gravels.

The hillside exposures of the Penman include zones of float that alternate from pebble-rich to pebble-poor. These zones evidently mark the intersection of the conglomerate and sandstone beds with the hillside surfaces. The clasts in the conglomerates include well-rounded pebbles to cobbles of hornblende-poor andesite, brown basalt that may be Lovejoy, and basement rocks that include some granitics, the Shoo Fly meta-sediments, and Sierra Buttes Formation. Also present is float of serpentinite that may be derived from nearby exposures. The soil that develops on the gravel beds is light yellow-brown to grey, sandy, and contains debris of the same rock types represented by the larger clasts mentioned above. In addition, the soil contains some hornblende, feldspar, and milky plus clear quartz, but little or no biotite. The gravel beds are poorly indurated and the individual clasts may be easily loosened. The soil that develops on the sandstone, or ashy, beds is grey and contains many grey to buff-colored and well-rounded pebbles of tuff and tuffaceous sandstone. The soil also contains medium to coarse sand-sized chips of the basement rock types, crystals of milky and glassy quartz, minor amounts of hornblende, and both weathered and relatively fresh biotite. The fresher biotite forms “books” of crystal plates. The Penman was not examined in thin-section.

IV.C.6.d. Age and Correlation

The available evidence suggests that the Penman is no younger than Late Miocene. Durrell (1966, p. 191), speculated that the age of the Penman may be either Lower or Middle Pliocene or both. Wagner et al. (2000, p. 160), reported “...radiometric dates from localities designated by Durrell as characteristic (of the)…Penman” at 13.6±0.7 Ma and 6.8±0.7 Ma; thus, Middle to Late Miocene. As discussed above, Grose (2000) mapped “andesitic tuff breccias and flows” in the Blairsden 15’ Quadrangle that he considered “generally equivalent” to the Ingalls, Bonta, and Penman formations, with radiometric ages that ranged from 19.7 to 6.8 Ma. Thus, Grose reported that the Penman-like rocks are no younger than Late Miocene.

IV.C.7. Intrusive Andesite

IV.C.7.a. Definition

The informal lithologic term "intrusive andesite" is here applied to the single in-place exposure of intruded andesitic rocks within the limits of Plate I that was mapped in the initial reconnaissance field inspections for this thesis. The andesite is similar in many respects and may be equivalent to the "andesite breccia dikes" described by Durrell (1944) near the hamlet of Blairsden, California (Figure 3). D'Allura (1977) did not show this body separately. Instead, D'Allura mapped the area underlain by the "intrusive andesite" simply as Penman and without the roughly semi-circular cross-sectional outline in plan view that appears to define its exposed extent.

IV.C.7.b. Distribution

The intrusive body, or plug, is formed by a complex of dikes that is located approximately 1.4 kilometers (0.9 miles) southeast of the Williams Loop, in the northwest quarter of Section 31, T24N, R11E. The complex is partially hidden by alluvium. The construction of the Feather River Highway is chiefly responsible for the exposure of the complex and its wall rocks. The resulting road cut (Figure 38) greatly facilitates the recognition of the intrusive and brecciated nature of the complex. Similar brecciated intrusive andesites are particularly difficult to distinguish from the surficial andesitic deposits that may host them unless unmasked by relatively sparse vegetation. Furthermore, it is possible that other plugs and/or dikes of similar age and character exist within the study area, but were not observed.

IV.C.7.c. Lithology

The rocks that form the dike complex are brownish-yellow to greenish-grey. These colors contrast markedly with those of the host rocks that are poorly-stratified breccias and poorly-sorted, matrix-supported volcanic conglomerates that weather from a light greyish-pink to a light pinkish-brown. The contacts between the intrusive and host rocks are relatively sharp and marked by a thin, dark brown band, or rind, that is generally about 5 centimeters (2 inches) wide. Such rinds, and apparent baked zones up to 1 meter (3 feet) wide in the wall rocks, have been accentuated by weathering to a darker color than that of the adjacent intrusive material. The thicknesses of the dikes range from 1 meter and less up to 11 meters (35 feet). The dike rocks are intrusion breccias (Fisher, 1961, p. 1412) that display varying degrees of brecciation. Fresh surfaces of samples taken from the largest and least brecciated of the dikes are grey and mottled with abundant white euhedral feldspar phenocrysts that range from 1 to 4 mm in length. Also present are anhedral phenocrysts of black hornblende that are poikilitic with feldspar. Like the feldspar, the hornblende phenocrysts range from 1 to 4 mm, but are less numerous and constitute no more than 5 percent of the rock. The feldspar phenocrysts make up approximately 30 percent of the rock. The aphanitic groundmass contains abundant feldspar microlites that display a crude flow-alignment (Figure 39).

IV.C.7.d. Age and Correlation

The intrusive andesite is presumed to be no older than Middle Miocene because it intrudes rocks that are reinterpreted here to be the Bonta, rather than the Penman as were mapped by D'Allura (1977). As discussed above, the Bonta is presumed to be Middle Miocene.

However, if the intrusive andesite proves to be related, possibly a feeder, to the Penman mapped by D'Allura elsewhere within the outline of Plate I, then its age would be no younger than Late Miocene.

IV.C.8. Warner basalt

IV.C.8.a. Definition

Durrell (1959a, p. 178-180) adopted the name "Warner basalt" from Russell (1928), based on the former's examination of the Warner in the Warner Mountains and being convinced of the validity in correlating those rocks with exposures of platy-jointed, light-gray olivine basalt in the Blairsden Quadrangle.

However, Wagner et al. (2000, p. 160-161; citing Hannah, 1977), cautioned that "Warner basalt" is a "...collective term for similar looking basalts throughout northeastern California and does not imply contemporaneity." Nevertheless, the name Warner basalt is retained for this thesis, rather than the cumbersome "Warner-like basalt" or "Warner-equivalent basalt," on the basis of the similarity of certain physical and compositional characteristics (discussed below) with those described by Durrell (1959a).

IV.C.8.b. Distribution

The Warner basalt underlies and forms several knobs near the western (Sections 5 and 6, T23N, R10E) and eastern (Sections 8 and 9, T23N, R11E) edges of Plate I. These eastern exposures were mapped by Durrell (1976). D'Allura (1977) mapped the Warner in the area covered by northeast corner of this report's Plate I. In that area, the Warner either rests on rocks mapped as Penman or is in both fault and unconformable depositional contact with the underlying Taylor Formation. Elsewhere within the study area, especially in the western half of Plate I, the Warner is in fault and/or unconformable depositional contact with either the Shoo Fly or the Bonta. It is rarely in fault contact with the Lovejoy. Durrell (1959a, p. 179) described similar relationships between the Warner and underlying older units in the Blairsden Quadrangle as evidence that the base of the Warner is an unconformity.

Most Warner rocks cap the Bonta within the previously-mentioned, east-west belt across the middle of the study area. Thus, the Warner crops out at successively higher, step-like elevations that ascend from approximately 1,340 to 1,400 meters (4,400 to 4,600 feet) above msl, near the eastern edge of Plate I (also see Plate II), to about 1,890 meters (6,200 feet) above msl on Bachs Creek Ridge at the west edge of the map. The lowest elevation where the Warner crops out within Plate I, at roughly 1,097 meters (3,600 feet) above msl, is near the south end of Thompson Valley, in the northeast corner of Section 28, T24N, R10E.

Interestingly, exposures of the Warner in Sections 3 and 4, T23N, R10E (northwest of Fells Flat) occur at roughly the same 1,400-meters (4,590 feet) elevation as those near the east edge of Plate I; the intervening distance being approximately 8.7 kilometers (5.4 miles). Durrell (1976) mapped the Warner in the southwest quarter of Section 9, T23N, R11E, where it is exposed in hillsides above its contact with the underlying Bonta;

approximately 183 meters (600 feet) southwest of elevation 4605. This outcrop is one of the best places to examine both the platy jointing and the character of the fresh rock (Figure 40). However, the steeply-dipping to vertical jointing indicates that this exposure may be of intrusive origin rather than extrusive as it is shown on Plate I. An old logging road in the northwest quarter of Section 11, T23N, R10E, serves to expose the characteristic horizontal platy jointing of the Warner in shallow road cuts of 1 meter (3 feet) and less in height.

IV.C.8.c. Lithology

The Warner is an olivine-pyroxene basalt. The characteristically olivine-bearing Warner basalts were deposited as flows and subsequently formed by the intrusion of plugs and dikes of similar composition (Wilhelms, 1958, p. 45-49; Durrell, 1959a, p. 178-180; Durrell, 1966, p. 192; Strand, 1969, p. 62-64; D'Allura, 1977, p. 212-214; Berry, 1979, p. 49-52).

The outcrop evidence that distinguishes the Warner from the Lovejoy (Figure 29) includes color and soil characteristics, but the distinctive platy nature of both exposed in-place rocks (Figure 40) and weathered-out debris that also forms float is particularly diagnostic. This platy aspect differs markedly from the blocky nature of Lovejoy outcrops that is caused by the intersections of ubiquitous joints and fractures. Weathered surfaces of the in-place Warner are typically brownish-gray to grayish brown, whereas the Lovejoy is a distinctive chocolate brown.

Outcrops of in-place Warner basalt within the study area are relatively rare and, like the Lovejoy basalt, the Warner is particularly susceptible to weathering. In general, soils that are underlain by the Warner are dark red-brown to brownish-red and contain sand- to boulder-sized pieces of the parent material. In some cases, notably in the south half of Section 30 and in the east half of Section 31, T24N, R10E, the Warner is deeply weathered to a very dark brownish-red soil. The Warner weathers into roughly rounded boulders that may have angular to sharp, fracture-produced edges. Weathered blocks and pieces, or float, of the parent material that retain the platy aspect of the original jointing are also distinctive. These characteristics were among the bases for distinguishing the not-in-place Warner from the Bonta while mapping.

The Warner basalt in hand specimen is dense, hard, predominat1y light-grey to dark grey, with golden-yellow olivine visible both as phenocrysts up to 2 mm across and as a finer component of the groundmass. Thin, white, euhedral feldspar laths are conspicuous, are up to 2 mm long, and display a felty texture. The basalt contains sparse quartz and/or slate xenoliths. Some clinopyroxene is green, typically forms about 15 to 20 percent of the rock, but it may form up to 35 to 40 percent, and may occur in aggregates up to about 4 mm in longest dimension. The olivine is less abundant; typically approximately 10 percent.

In thin section (Figures 41a and 41b), the Warner groundmass is sucrosic, aphanitic, microporphyritic, and contains the pyroxenes and interstitial glass or fine magnetite(?). The groundmass is also mottled by white plagioclase crystals that are less than 1 mm long. The plagioclase is typically trachytic, with an optically-estimated average composition of An58 to An71. Both olivine and pyroxene are intergranular and may be zoned. Much of the olivine is altering to iddingsite. In the case of non-porphyritic (intrusive?) Warner, feldspar is a component of an aphanitic groundmass that is difficult to recognize except in thin section. The microscopic differences between the Lovejoy and Warner basalts may be appreciated by comparing, respectively, the images shown on Figures 30a and 30b with those on Figures 41a and 41b, where the contrasting textures of the groundmass between the two basalts is readily apparent.

IV.C.8.d. Age and Correlation

The Warner basalt is presumed to be the youngest of the extrusive volcanic rocks exposed within the study area, including the "intrusive andesite" discussed above based on the similarity of composition between the latter and its host rocks. Grose (2000) indicated that exposures of intrusive mafic andesite near the summit of Mt. Ingalls in the Blairsden 15' Quadrangle are feeder material to the "mafic andesite and basalt flows" that are described as being equivalent to the Warner basalt of Durrell (1959a). Additionally, a sample of the intrusive andesite from Mt. Ingalls yielded a K-Ar date of 4.7 ±0.1 Ma. On that basis, the Warner may be no younger than uppermost Late Miocene or lowermost Pliocene. However, a radiometric date of 11.4 ±0.7 Ma reported by Saucedo et al. (1992; in Wagner et al., 2000), for "...rocks mapped as intrusive Warner Basalt near Red Cover Creek," may suggest that the

Warner is at least upper Middle to lower Late Miocene.

IV.C.9. Warner intrusive

IV.C.9.a. Definition

The intrusive bodies that are exposed within the study area and may have served as localized sources for the Warner basalt are here informally referred to as "Warner intrusive." The exposures are important in helping to delineate faults that are interpreted to have been exploited by these rocks.

IV.C.9.b. Distribution

Rocks mapped as Warner intrusive are limited to five separate exposures within the area of Plate I. These include: a larger circular (in plan view) plug within the southwest and northwest corners, respectively, of Sections 6 and 7, T23N, R10E (Figure 42); a small circular plug in the northeast quarter of Section 31, T24N, R10E; and three elongate exposures associated with faults in the northeast quarter of Section 1, T23N, R10E. Wilhelms (1958; p. 46) mapped these three elongate exposures as "Warner basalt intrusion," but only the eastern-most of the three is shown in association with a fault. Additionally, D'Allura (1977) mapped three separate Warner plugs as intrusions into the Taylor Formation; in the southern and northern halves of Sections 20 and 29, T24N, R11E, respectively.

IV.C.9.c. Lithology

The plug on Bachs Creek Ridge (Figure 42) is typical of the Warner intrusive rocks. Talus from the plug shows the rock to be light-grey to grey, with some surfaces weathering to a light pinkish color (Figure 43). The rock is aphanitic basalt, with some columnar jointing that is best displayed on the southeast flank of the plug (Figure 44). The basalt contains hornblende plus quartz xenocrysts; quartzose (Shoo Fly?) and volcanic (Bonta? pyroxene andesite) xenoliths that likely represent the host rocks; and white feldspars, some of which may also be xenocrysts. The quartz xenocrysts display some rounding and embayments. These constituents are up to 4 centimeters in longest dimension, with the larger crystals showing some flow alignment. Radially-fibroidal materials, possibly zeolites or silica, are present in some cavities that appear to be formed from the weathering out of altered hornblende.

Thin-sections show the rock includes hornblende, altering possibly to pyroxene[12]; some opaque (magnetite?) pseudomorphs after hornblende; and olivine, with some altering to iddingsite. Figures 45a and 45b show pyroxene and feldspar phenocrysts in reaction with the groundmass; the latter is indicated by irregular (fuzzy), rounded rims and some embayments. The groundmass contains trachytic feldspar microlites, that show some flow alignment, plus microcrystalline olivine and pyroxene, opaques, and glass.

IV.C.9.d. Age and Correlation

If the Warner intrusive rocks are coeval with the Warner basalt of this thesis, then they may range from the Middle Miocene to Pliocene.

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[12] Augite phenocrysts were reported to occur in various samples of the extrusive Warner basalt by Durrell (1959a, p. 178) and D’A1lura (1977, p. 213).

Grose (2000) described the intrusive andesite(s) at Mt. Ingalls as possibly uppermost Late Miocene or lowermost Pliocene. Wagner et al. (2000, p. , with references therein) also suggest that the Warner intrusive rocks may range in age from Middle to Late Miocene, possibly to Pliocene.

IV.C.10. Quaternary Deposits

Quaternary (i.e., 2 Ma to the present) alluvial deposits in the study area are valley-floor sediments, alluvial fans, gravel bars and terraces, stream overbank deposits, talus, and landslides. Some perched stream-terrace deposits may be older than Quaternary. These older deposits may include those that are exposed deeper within the canyon of the Middle Fork in the north half of Section 15 and east half of Section 16, T23N, R10E. These possibly older deposits may instead belong to the Bonta gravels, with the overlying volcanic material having been eroded away.

Associated with a number of these questionably older gravels are exposed erosion surfaces developed on Shoo Fly rocks. Nevertheless, all the exposed gravel bar and terrace deposits are reworked by the search for gold. The largest of these reworked deposits are at Fells Flat and English Bar (Figure 46), in Sections 11 and 12, T23N, R10E, where at least one private mining claim remained active in 2015, albeit with what amount to casual efforts focused on small-scale dredging in the Middle Fork.

Perhaps the most important alluvial deposits are those that form the floors of the American and Thompson Valleys (northwest corner of Plate I) and a relatively shallow topographic depression south of Lee Summit near the east edge of Plate I (Section 8 and western half of Section 9, T23N, R11E). The importance of these features is the areal extent and evidence for the development of the landscape (Durrell, 1987, Ch. 7). The American and Thompson Valleys (Figure 47) mark the northern end of the Plumas Trench, the name given by Durrell (1959a) to the complex graben that separates the northern Sierra Nevada (sensu stricto) from Grizzly Ridge. Durrell speculated with reason that an ancient lake occupied American Valley and its eastern arm, Thompson Valley, and that the lake resulted from fault-related damming of Spanish Creek. In addition, Durrell (1976) mapped the depression south of Lee Summit as underlain, also speculatively, by deposits of the extinct Long Valley Lake which extend about 7.5 kilometers (~4.7 miles) to the southeast through Long Valley (north and east of the Middle Fork) to the northeast quarter of Section 19, T23N, R12E.

IV.D. Discussion

Based on the mapping for this thesis and that of Durrell (1976) and D'A1lura (1977), the ascending stratigraphic succession of the Superjacent units described above and shown on Plate I is the Lovejoy, Ingalls, Bonta gravels, Bonta, Penman, intrusive andesite, Warner, Warner intrusive, and Quaternary alluvium. Except for the Delleker formation, which is not exposed in the study area, this succession is not a significant departure from that of Durrell (1959a, p. 165). However, the important differences between the two organizations are as follows: (a) the present stratigraphy contains several units (i.e., Bonta gravels, intrusive andesite, Warner intrusive) that were not specifically included by

Durrell, but their presence was alluded to in the descriptions of the major units of the Blairsden Quadrangle; (b) had the Delleker been fortuitously present in the area covered by Plate I, it should be beneath the Lovejoy, which is a significant departure from Durrell and is in keeping with the reinterpretation of the Blairsden stratigraphy as discussed by Wagner et al. (2000, p. 167); and (c) the ages of the units are redefined, with the most significant among them being that of the Lovejoy basalt (Garside et al., 2005, p. 214-215).

As mentioned previously, the overlapping ranges of the radiometric ages reported by the various workers cited above do not comport with the evidence found in the field and demonstrate levels of uncertainty beyond the associated error bars. The allowance by Grose (2000) in considering "regional volcanic history" is of particular relevance here.

Relatively recent publications added to the broader interest in the Lovejoy basalt that includes its implications for the paleogeography of the northern Sierra Nevada. Page et al. (1995), and Wakabayashi and Sawyer (2000) recognized the importance of the Lovejoy as a distinctive stratigraphic marker because of its "...resistance to erosion and its position at the base of the ancestral valley of the Feather River" and that it "...makes an excellent strain gauge to identify and quantify late-Cenozoic tectonic deformation of the region since its deposition 16 million years ago..." (Page et al., 1995, p. 1-2). Durrell (1959a) described the Lovejoy as being restricted to a valley and later (1959b; 1987) as a broad, shallow valley, with distribution to the southwest from its source near the Honey Lake escarpment (see Wagner et al., 2000; Garrison et al., 2008), across the Blairsden Quadrangle, and then to the northwest and southwest into the Sacramento Valley. Thus, the Lovejoy flowed

“...along one or more Eocene Auriferous Gravel channels, because (it) overlies Auriferous Gravels in a paloevalley at several locations” (Garside et al., 2005). However, the Auriferous gravels do not underlie the Lovejoy in the study area. Page et al. (1995, p. 6), also interpreted the Lovejoy as indicating that it filled valleys or canyons (“a few kilometers wide”), that it “…extended southwest from the Honey Lake area across the ancestral Sierra Nevada between the present South Fork and Middle Forks Feather River into the Central Valley,” and that “…in places the flows backfilled into tributary drainages and overtopped low drainage divides.” An important observation made by Street (2009, p. 10) is that during the last 14 million years, “...erosive events have removed or covered the majority of the original Lovejoy Basalt, leaving an array of discontinuous outcrops throughout the northern Sierra Nevada...”

The Lovejoy in the study area is exposed only to the north of the Middle Fork of the Feather River where it invariably rests on Shoo Fly Complex rocks. The elevation of the lowest exposed Lovejoy base is approximately 4,520 feet (~ 1,378 meters) above msl (Section 11, T23N, R10E). The elevation of the highest exposed base is approximately 5,720 feet (~ 1,743 meters) above msl (Section 6, T23N, R10E). This 365-meter difference represents a portion of the approximately 600- to 1,000-meter late Cenozoic vertical separation reported by Wakabayashi and Sawyer (2000, p. 193) for the Lovejoy “... across faults of the Frontal Fault system in the northernmost Sierra (Feather River drainage).” However, Page et al. (1995, p. 8), indicate that, where the Lovejoy crosses the Plumas trench at the divide between the Mohawk Valley and the American Valley, it “...is down approximately 1,000 to 1,200 m over (the) 18-km-wide graben."

Most of the exposures of the Tertiary volcaniclastics within the study area crop out to the north of the Middle Fork, in both number and areal extent. With very few exceptions, these exposures are bounded by combinations of faults and/or depositional contacts. The east-west belt across the study area formed by the volcanic and volcaniclastic units (Plate I) suggests that they collectively occupied a relatively narrow paleocanyon, with the Lovejoy forming the basal unit. Indeed, the depiction by Garside et al. (2005, p. 226, Fig. 8), indicates that the belt forms part of the route of a paleochannel through which the Lovejoy flowed from its source and into what is now the Central Valley.

The apparent lateral dimensions of the paleocanyon may have been about one and one-half kilometers wide (~1 mile), but faulting and erosion make this estimate uncertain. A range for the possible minimum depth of the paleocanyon may be indicated by the two apparently thickest occurrences of the Lovejoy: (1) approximately 170 meters (560 feet) in Sections 5 and 6, T23N, R10E, and (2) approximately 128 meters (420 feet) in Section 10, T23N, R10E. If the unbroken succession of the Bonta and Warner above the Lovejoy that is exposed in Section 32, T24N, R10E, and Section 5, T23N, R10E, is representative, then the combined approximately 183-meter (600 feet) thickness may indicate that the paleocanyon depth ranged from about 310 to 350 meters (about 1,020 to 1,160 feet). Further speculation is that the Lovejoy only partially filled its paleocanyon and that the succeeding units, Bonta and Warner, completed the filling and then spread out laterally relatively short distances to the north, toward what is now East Quincy, and south, as represented by the exposures within the canyon of the Middle Fork.

The belt and the possible dimensions indicated above may suggest a palogeography that is more detailed, with tributary channels, than the concept of the Lovejoy depositional environment expressed by Durrell (1959b). Garside et al. (2005, p. 226 and 230, and Fig. 8), interpreted the distribution of the Lovejoy within the area of Plate I, based in part on the mapping for this thesis (Sheeks, 1977), as indicating that the Lovejoy was not confined to a single paleochannel. Although they named the inferred paleochannel the “Tertiary Buckeye-Bean Hill Channel,” Garside et al., described the paleochannel as consisting of a main course that extended from Thompson Peak to near Spring Garden where it diverged into two channels that extended west and southwest toward the Central Valley. The westerly of these two channels is indicated by the Lovejoy exposures that extend toward and onto Bachs Creek Ridge; on the north side and in the center of the mapped belt. This westerly channel extends to at least the isolated exposure of Lovejoy located west of Bachs Creek Ridge (Saucedo and Wagner, 1992; Wakabayashi and Sawyer, 2000, p. 181). The southwesterly channel includes the exposures west of what is now Fells Flat (Section 10, T23N, R10E) and crosses the present course of the Middle Fork to connect with Lovejoy exposures that are well beyond the west edge of Plate I, including those northwest of the former Richmond Hill settlement and Little Grass Valley Reservoir in southwestern Plumas County (Garside et al., 2005, p. 226; Saucedo and Wagner, 1992). Upstream from the divergence at Spring Garden, the main route of the associated paleochannel served as the conduit wherein the Lovejoy flowed south and southwest from its source at Thompson

Peak (Garrison et al., 2008, p. 9) and through the type locality at Red Clover Creek (Durrell, 1959b). This route is significant in that it demonstrates that there was "...no Sierran escarpment to impede the basalt flow" (Wakabayashi and Sawyer, 2000, p. 203).

The courses taken by the Lovejoy were further addressed by Garside et al. (2005, p. 227), with the observation that the Lovejoy flowed "...along one or more Eocene Auriferous Gravel channels, because the Lovejoy overlies Auriferous Gravels in a paleovalley at several locations." Garside et al. (2005, Fig. 8), showed the inferred course of the Buckeye-Bean Hill Channel crossing, near Lee Summit, the inferred course of the northern branch of the Tertiary Yuba River, an "Eocene-Oligocene paleovalley," that extended from what is now Franks Valley, south of Taylor Lake, to near La Porte. It is significant that the canyon of the Middle Fork of the Feather River is positioned along a different route than either of the two Lovejoy channels that were inferred by Garside et al. (2005). The discussion by Durrell (1987, p. 230-234) of the "Old Erosion Surface" (on Shoo Fly Complex rocks) and the course of Middle Fork on that surface includes the interpretation that the course is antecedent and that at least some of the faulting shown on Plate I (Durrell referred to the mapping for this thesis) facilitated the river maintaining its course prior to and during the uplift of the Sierra Nevada. Schweickert (2015, p. 330) alluded to this interpretation involving the course of the Middle Fork by observing that the river "...cuts across the Sierra crest and flows along the Mohawk Valley, attesting to the importance of normal faults in that area."

If the interpretation of the river's course by Durrell (1987) is correct, then the following may result: (a) some of the faulting that helped the river maintain its course was reactivated during the Cenozoic to help form the current fault pattern, (2) the course was situated within the paleocanyon that also contained the Lovejoy, and (3) following the deposition of the Lovejoy and possibly the younger units, enough of the paleotopography remained to allow the Middle Fork to resume its down-cutting whereupon the Lovejoy was removed from that portion of the paleocanyon. Such a scenario would be consistent with the inferred southwesterly channel that crosses the Middle Fork. That paleochannel connects the Lovejoy west of Fells Flat with the exposures north of Richmond Hill, with no Lovejoy exposures in between; the intervening region along that paleochannel is within the current canyon of the Middle Fork.

The results of a recent study reported by Mix et al. (2015) that involves stable-isotope paleoaltimetry provides evidence to support "...high topography and a warm climate in the Sierra Nevada during the early Eocene" and concludes that "...paleoaltimetry estimates support geomorphic models calling for a trellised drainage network and conflict with tectonic models calling for significant uplift of the northern Sierra Nevada during the late Cenozoic." The evidence provides a link between the paleoclimate and paleogeography during the Eocene that resulted in the development of the fluvial systems in the northern Sierra Nevada and the subsequent distribution within those systems of the Tertiary clastic, volcanic, and volcaniclastic deposits discussed above.

V. SHOO FLY SANDSTONE PROVENANCE

V.A. Introduction and Methods of Analysis

The information and data resulting from this study's petrologic examinations and chemical analyses of the Shoo Fly metasandstone samples are discussed in this section and support inferences for provenance and tectonic depositional settings using the graphical-statistical tools published by Dickinson (1985), McLennan (1989), and Verma and Armstrong-Altrin (2013). It is recognized that the available dataset used in this study is small, the resulting inferences for Shoo Fly provenance and tectonic settings are necessarily tentative, and additional data are needed to provide for more robust assessments.

The analytical approach of Cox and Lowe (1996) was adopted for this thesis because all the respective matrix percentages determined by point counting the "SF 1" Shoo Fly quartzose metasandstone samples exceeded 10 percent (Table 2a) and is here interpreted as "pseudomatrix" (Dickinson, 1970, p. 702-703). That approach includes combining point-count and whole-rock geochemical data, for which sufficient sample volume was also available for laboratory needs, to permit constructing "approximate original framework grain compositions" and leads to using the provenance discrimination QFL diagram of Dickinson (1985, p. 340) and the "high silica" discriminant-function, multi-dimensional tectonic-setting diagram of Verma and Armstrong-Altrin (2013, p. 125).

Using the tectonic-setting diagram of Verma and Armstrong-Altrin addresses concerns regarding the limitations of ternary diagrams as expressed by Verma (2010; 2012) in favor of log-ratio-transformed discrimination diagrams and provides for comparing depositional inferences made by other workers (for example, Bond and DeVay, 1980; Hannah, 1980).

It is a general rule that sandstones contain the most valuable information for use in assessing sediment sources. Blatt (1967, p. 1031) expressed the essence of this statement by stating that: “The importance of petrogenetic investigations of sandstones is clear: such studies are our only method of obtaining quantitative data about the nature and distribution of the rocks which existed upstream at the time a sediment was being deposited lower in the drainage basin.” Dickinson and Suczek (1979) provided a related expression: “Sandstone compositions are influenced by the character of the sedimentary provenance, the nature of the sedimentary processes within the depositional basin, and the kind of dispersal paths that link provenance to basin. The key relations between provenance and basin are governed by plate tectonics, which thus ultimately controls the distribution of different types of sandstones.”

Yet the information to be gained from sandstones is potentially complicated by the presence of matrix material; especially when some or most of that material is derived either from the “breakdown products of labile mineral grains and rock fragments” (Cox and Lowe, 1996) or the introduction of fluids with concomitant recrystallization. Standlee (1978, p. 33) acknowledged the inherent difficulty in recognizing true matrix versus pseudomatrix or “secondary matrix” (Cox and Lowe, 1996, p. 552) in assessing the Shoo Fly sediments. Cox and Lowe echoed this same concern: “…when the proportion of pseudomatrix in a sandstone exceeds 10%[13], standard petrographic analysis can lead to incorrect provenance interpretation." And, "…where secondary matrix constitutes a significant portion of the rock, and petrographic analysis cannot satisfactorily resolve the original framework components, bulk chemical analysis may be essential for accurate provenance determination." Thus, the 10-percent limit is the essential criterion by which to determine whether or not to combine petrographic with whole-rock chemical data in assessing original modal compositions and for inferring provenance. However, Cox and Lowe discuss important caveats (1996, p. 552-553) for using that approach. A key caveat is that it is "valid only if there has been no large-scale mass transfer of material during creation of the pseudomatrix."

One way to assess whether such mass transfer has occurred is through petrologic examination. The presence of "stylolites or oversized pore spaces" provides textural evidence of the mass transfer of material. Another way is to calculate values for the "Index of Compositional Variability" (ICV), which is the ratio of summed concentrations of select major oxides to that of Al2O3. "Low values (<0.5)...imply…(the) loss of soluble species from primary silicate minerals." Table 7 lists the ICV values calculated for this study's sandstone samples and defines the ICV formula. These values range from 0.96 to 1.25 and suggest that the mass transfer of materials did not affect the

[13] Dickinson and Suczek (1979) used 25 percent as the basis for excluding from consideration of provenance rocks that contain more matrix or cement than that percentage.

sandstones that were analyzed for this thesis. It is important to note, however, that DeVay (1981, p. 20, 25, 41, 46) described features interpreted as stylolites in the Shoo Fly sandstones.

Bond and DeVay (1980) acknowledged that “Considering the deformation in the (Shoo Fly) sandstones, some recrystallized unstable grains may be indistinguishable from matrix and point counting may not give the original sandstone composition. This could account for the average of 16% matrix in the quartzose sandstones…compared with 5% to 10% matrix or interstitial material in many relatively undeformed sandstones.”

D’Allura (1977, p. 24) discussed the matter of matrix in the Shoo Fly of the “Quincy district” and observed that “...there was apparently little matrix in the original sediment” and that “...metamorphism has largely modified the textures” of the sandstones such that original sorting and angularity are difficult to interpret, with angularity having been “...enhanced by “pressure solution.””

V.B. Analyses

Modal analysis of the samples represented by the thin sections prepared at U. C. Davis, was by point-counting alone because of the lack of sufficient available field-sample volume needed for the geochemical analyses. The remaining samples were analyzed for major oxides and rare-earth elements (REE) by, respectively, x-ray fluorescence (XRF) and inductively-coupled plasma-mass spectrometer and inductively-coupled plasma-optical emission spectrometer (ICP-MS/ICP-OES) methods (see Appendix A).

Table 3 summarizes the major oxide results. The original, full suite of REE data for the samples is provided in Appendix B. Table 4 summarizes the REE analytical results for the typically-used suite of selected REE constituents (for example, see Girty et al., 1996a; 1996b) that were then normalized (Table 5) using the chondrite-normalization factors published by Taylor and McLennan (1985) and McLennan (1989). The results were then plotted (Figure 48) on a REE-chondrite-normalized distribution diagram.

Calculated from these XRF and REE data are the following ratios (see Table 6): aluminum oxide/titanium oxide (Al2O3/TiO2); thorium/scandium (Th/Sc); "europium (Eu) anomaly" (represented by "Eu/Eu*" per McLennan, 1989, p. 176); and thorium/uranium (Th/U). Also calculated are values for the "chemical index of alteration" (CIA) using the formula reported by Taylor and McLennan (1985) and McLennan (1993, p. 297). These ratios and the CIA are discussed by Girty et al. (1996b, p. 7 and 8) in terms of the characteristics being associated with certain provenance types. Lawrence (1996) also provided useful summaries on the importance and applications of the Al2O3/TiO2, Th/U, and Eu/Eu* ratios; CIA values; and REE distribution patterns.

The values for Th/U and CIA provide an approximate gauge on the degree of weathering that may have affected the source rocks from which the Shoo Fly metasandstones were derived. "Relatively high Th/U ratios (generally > 3.8; a "well-established elemental ratio for crustal rocks" per McLennan, 1989, p. 185) may indicate that uranium was lost in its more soluble form (U^{+6}) during repeated cycles of weathering and erosion" and "CIA values of about 45-55 indicate virtually no weathering, whereas values of 100 indicate intense weathering (particularly of feldspars) with complete removal of the alkali and alkaline earth elements (McLennan, 1989)" (Girty et al., 1996b, p. 7-8).

Similarly chondrite-normalized values for post-Archean Australian shale (PAAS), using PAAS REE data published by Taylor and McLennan (1985, p. 30), were also plotted on Figure 48 for comparison along with values derived from argillite samples described by Garrison et al. (1997, p. 127) from the "Lang sequence" (i.e., "SF 1") within the aureole of the Emigrant Gap composite pluton (also see Girty et al., 1996b, p. 12). The plotted PAAS values and the resulting patterns provide bases for comparing sediments with what is taken to be the "the average REE pattern of the upper continental crust." Sediments with REE patterns that differ from that of the PAAS may be the result of recycling processes that are less efficient, such as within "volcanically active tectonic settings," than are those for terrigenous sediments where the assumption is that there is "…efficient mixing of source lithologies…" (McLennan, 1989, p. 185). Sediments deposited in passive continental margin settings have REE patterns similar to PAAS, whereas the REE patterns for sediments deposited in active continental margin settings (e.g., island or continental arcs) have lower REE and may not have negative Eu anomalies. Yet, REE patterns for active continental margin sediments may still be similar, if not identical, to PAAS and have "...negative Eu anomalies, with Eu/Eu* in the range 0.60-1.00" (McLennan, 1989, p. 170, 185-187).

Taylor and McLennan (1985, p. 42) summarize the significance of Eu anomalies in sedimentary rocks by stating that "…virtually all post-Archean sedimentary rocks (sandstones, mudstones, carbonates) are characterized by Eu depletion of approximately comparable magnitude. The only important sedimentary rock types which do not have Eu depletion are some of the first cycle volcanogenic sediments deposited in fore-arc basins of island-arcs and derived mainly from andesites which, not unnaturally, reflect the parent rock patterns." And, Eu depletion in sedimentary rocks (and the upper continental crust) is attributed to "…chemical fractionation within the continental crust, related to production of K-rich granitic rocks which typically possess negative Eu anomalies."

V.C. Results

Table 2a lists the point-counted results from the "SF 1" Shoo Fly metasandstone samples. The normalized percentages for total monocrystalline quartz (Qm) and total polycrystalline quartz (Qp) derived from the point-count data are summarized in Table 2b. The matrix in these samples ranged from 33 to 58 percent of the total counts; averaging 42 percent. Also shown in Table 2a are the framework-component percentages (normalized to total 100 for each sample) for quartz (Q), feldspar (F), and lithic fragments (L); ranging as follows: Q = 77 to 100, F = 0 to 4.5, and L = 0 to 21.5. The approximate averages of these percentages are: Q = 95, F = 1, and L = 4.

Standlee (1978), Varga (1980), and Bond and DeVay (1980) observed the same apparent quartz-rich nature of the Shoo Fly sandstones; each having collected from the portion of the northern Sierra Nevada wherein the present study area is also situated.

DeVay (1981, p. 27; 80-81) inferred that the Shoo Fly quartzose sandstones are "exceptionally mature," based on "...using quartz content as an indicator of compositional maturity…"

Table 7 summarizes the calculated "weight percent" component results for the sandstone samples that were analyzed for bulk-rock geochemistry using the procedures published by Cox and Lowe (1996) that combine the petrographic and chemical data to derive the values that are then plotted (Figure 49) using the Dickinson (1985) QFL diagram. The resulting respective average compositions are: Qt (total quartz) = 89, F = 8; and L = 6. Plotting these QFL results yielded inferred "Craton Interior" and "Recycled Orogen" provenances, with the numerical average plotting within the "Recycled Orogen" field.

The major-oxide data that are summarized in Table 9, adjusted to be volatile-free (subscript "adj"), were used in calculating the discriminant-function values listed in Table 8 using the equations of Verma and Armstrong-Altrin (2013, p. 126). The calculated discriminant-function values were then used to plot the respective sample data points on a "high-silica" (i.e., $SiO_{2(adj)}$ = 63 to 95 percent) multi-dimensional tectonic-setting diagram shown on Figure 8.

The calculated Al_2O_3/TiO_2 values ranged from approximately 10.3 to 19.3; averaging approximately 14.6. The Th/Sc values range from approximately 1.3 to 2.4; averaging approximately 1.6. The Eu/Eu* values range from 0.54 to 0.75; averaging 0.62. The Th/U values range from approximately 5.6 to 8.1; averaging approximately 6.8. The CIA values range from approximately 64 to 76; averaging approximately 70.9. Table 6 lists the derived values from these ratios and provides respective comparisons with the values reported by Girty et al. (1996b, p. 7) for “Old Differentiated Upper Continental Crust,” “Magmatic Arc undifferentiated,” and “Magmatic Arc differentiated.”

V.D. Shoo Fly Provenance Inferences Previously Reported

Standlee (1978), Bond and DeVay (1980), Hannah (1980), along with D’Allura (1977), DeVay (1981), Girty and Wardlaw (1984, 1985), Girty and Pardini (1987), Mount (1990), Lawrence (1996), and Girty and Lawrence (2000), provided inferences on the provenance of Shoo Fly Complex sandstones based on point-counting and/or geochemical data. Among these, only Standlee, Bond and DeVay, and DeVay provided data and resulting provenance inferences for sandstones in the portion of the Shoo Fly studied for this thesis; mapped as “SF 1” by D’Allura et al. (1977), or the “Lang sequence” by Harwood (1992). Girty and Wardlaw, Pardini, Girty and Pardini, and Mount reported data and provenance inferences for rocks collected within the portions of the Shoo Fly that are interpreted to be structurally higher within the Complex that is exposed in the Lakes Basin and Bowman Lake areas, including the Duncan Peak and Culbertson Lake allochthons and the Sierra City melange. Pardini (1986) and Girty and Pardini (1987) excluded samples with matrix content greater than 25 percent from analysis; presumably following Dickinson and Suczek (1979, p. 2173).

Girty and Wardlaw (1985) followed the point-counting methods recommended by Dickinson (1970) and ignored entirely the matrix component (<0.03 mm) of the

Culbertson Lake allochthon sandstones (ranging from 3.3 to 36.5 percent)[14]. Instead, Girty and Wardlaw used the framework QFL percentages in forming inferences on provenance; also per the diagrams of Dickinson and Suczek (1979).

Standlee (1978, p. 43) derived modal analytical data from Shoo Fly sandstones collected along the Middle Fork of the Feather River, on Bachs Creek Ridge, and near Limestone Point. Standlee described the sandstones as, respectively, quartz arenite, subarkosic arenite, and black quartz arenite, while acknowledging that "Although the sedimentary origin is readily apparent, application of strict sedimentological methods to the epiclastic rocks of the Shoo Fly Formation is perhaps impractical, due to the strong post-depositional modifications" (1978, p. 32-34). Standlee estimated the range of matrix amounts within these sandstones to be from 0 to 15 percent of the total rock, but did not report the application of a consistent size definition for the matrix observed in thin section[15]; generally described as a "...fine-grained mixture of recrystallized quartz+a1bite." Standlee (1978, p. 167) concluded from data and overall petrologic findings that the "...lower Shoo Fly Formation consists of a thick sequence of extremely siliceous epiclastic rocks... " that "...can best be interpreted as a combination of two

[14] Forty-three of the 63 sandstone samples point-counted by Girty and Wardlaw contained matrix in amounts greater than 10 percent.

[15] Standlee (1978, p. 41) defined matrix as "less than 0.05 mm" specifically for the black quartz conglomerate that he sampled north of Limestone Point.

distinct lithologies of different provenances” (1978, p. 38): “...(1) a terrane composed of plutonic (cratonic) rocks and pure quartz sandstone, and (2) an intermediate to mafic volcanic/plutonic arc” terrane (Standlee, 1978, p. 57). The depositional model proposed by Standlee (1978, p. 58) includes a deep-water basin, bordered by these two sources on opposite flanks, wherein these rock types become mixed and/or inter-fingered, with the former terrane becoming increasingly distal with time and the latter being relatively proximal to the site(s) of deposition.

The analyses by Bond and DeVay (1980) and DeVay (1981) of quartz types in the Shoo Fly sandstones indicated a source in a predominantly plutonic/metamorphic terrane, based on quartz grain modal compositions, mono- and poly-crystallinities, and inclusions. Bond and DeVay concluded that the quartzose sandstones and interbedded phyllites (part of the “quartzose flysch”) appear to have been deposited on oceanic crust, with the sandstones probably derived from a Precambrian basement in a nearby continental block that may have included a mixture of massive plutonic, gneissic, and sedimentary terranes and “The most likely tectonic setting that would account for all of these features is the outer or oceanic part of a sedimentary wedge that was deposited along a passive continental margin.” Thus, the provenance inference discussed by Bond and DeVay does not include an arc provenance. In fact, Bond and DeVay (1980, p. 295-296) state that “It is highly unlikely that a terrane with abundant volcanic rocks, such as a magmatic arc,…was the source of the quartzose flysch” and “…sediments derived from magmatic arcs rarely contain more than 50% quartz in the total framework population and commonly have framework compositions in which quartz ranges from only 0% to 15%" (with citations thereto). DeVay (1981, p. 98) subsequently concluded that the source area(s) from which the Shoo Fly quartzose sandstones in the "SF 1" were derived was a massive plutonic and gneissic terrane and that "Evidence for a volcanic source terrane from which sediment could have been supplied to the Shoo Fly quartz is lacking."

Girty and Wardlaw (1984, p. 340) inferred that feldspathic sandstones in the Sierra City melange exposed in the Bowman Lake area were derived from a volcanic-plutonic terrane that may have been the Alexander terrane of southeastern Alaska. The reporting by Girty and Wardlaw is particularly noteworthy in that no K-feldspar was found in those sandstones and the petrographic data "...suggest that framework components of compositionally immature feldspathic sandstones in the Shoo Fly melange probably represent detritus derived during a *single cycle* (their emphasis) of erosion of a volcanic-plutonic provenance." Girty and Wardlaw (1985) subsequently reported on sandstones in the Poison Canyon and Red Hill components of the Culbertson Lake allochthon. Girty and Wardlaw inferred that the depositional basin in which the sandstones accumulated was "...floored by oceanic lithosphere and was close enough to some continental landmass to have received sand-sized detritus derived from it. The continental landmass may have been located in western North America, but there is nothing in the data presented here (by Girty and Wardlaw) that precludes the possibility that it was located on some foreign continent." The reporting for the Red Hill sandstones included the observation that relict syntaxial overgrowths were observed on "some" monocrystalline quartz fragments and staining for K-spar showed it to be rare.

The sandstone samples from the Sierra City melange that were judged suitable for point-counting analysis by Girty and Pardini (1987) were subdivided into plagioclase-poor and plagioclase-rich sandstones. The inferences resulting from the data were a recycled-orogen provenance for plagioclase-poor sandstones that included meta-sedimentary, sedimentary, and volcanic rocks, whereas the source for the plagioclase-rich sandstones was a dissected magmatic-arc that included volcanic and plutonic rocks. Girty and Pardini suggested that the two sandstone types "...may have been derived from compositionally different parts of the same terrane" and that the Sierra City melange "...may have formed as a result of a submarine slide or slides in an evolving Paleozoic subduction complex." Additionally, "The source of volcanic and feldspathic detritus in the Sierra City melange is problematical. It may be an unknown, and as yet unidentified, magmatic-arc terrane that is located somewhere along the Pacific rim."

Hannah (1980, p. 20-21) discussed the Shoo Fly interpretations reported by D'Allura (1977) that included several lines of evidence regarding the depositional setting for several rock types that help to form the Complex: (1) the shales (now slates) indicate a deep-water setting with little to no addition of coarser detritus; (2) the obviously shallow-water carbonates were deposited near a landmass; (3) phosphatic sediments, also reported by Varga (1980, p. 158-160), indicate adjacency to a continental shelf within low to middle latitudes ("40°N to 40°S") similar to modern-day analogues where upwelling currents concentrate phosphate (Varga, 1980, p. 177-185); and (4) the quartz sandstones indicate a continental plutono-metamorphic terrane (citing Bond and DeVay, 1980). Hannah thus concluded that the Shoo Fly most likely was deposited on a continental rise or slope, near the mouth of a submarine canyon. Noteworthy in the discussions by Hannah and Varga are the mentions that most of the areas where modern phosphates are found are situated on the "…west coasts of continents…" (Varga, 1980, p. 177). Varga added the following: "The phosphate nodules and layers and associated sediments within the upper(?) portions of the Shoo Fly Formation in the northern Sierra Nevada are similar to deposits formed in areas of divergence upwelling…" and "If this correlation is valid, it may be concluded that at least the upper(?) portion of the Shoo Fly Formation was deposited in relatively shallow water (<300 m) along the west-facing coast of a relatively large continental mass or, possibly, a narrow east-west seaway between two continents…" Additionally, "The present position of phosphates within the Shoo Fly Formation near the western edge of the Cordillera is consistent with the paleogeography of the North American continent during Ordovician-Silurian time." The calculated average CIA value of about 70.9, indicating moderate weathering of the source(s) of the sandstones studied for this thesis, appears to be consistent with such a suggestion.

Mount (1990, p. 46-55) also did not take fully into account the presence of matrix (ranging from 17 to 35 percent) in (a) reporting the results from studying what was interpreted to be the Sierra City melange in the Lakes Basin area, (b) assessing sediment compositional maturity, and (c) inferring provenance. None of the sandstone samples collected by Mount were excluded from consideration by point-counting. The inferences discussed by Mount included both continental block and recycled-orogen contributions in melange sandstones, with additional contributions in melange conglomerates from a volcanic source. Mount acknowledged, however, the presence of pseudomatrix as likely the result of the decomposition of sedimentary or volcanic lithic fragments and allowed for adjustments in the respective positions in QFL space of the sample data if matrix is factored in; thus suggesting alternative inferences for provenance than those that that were mainly reported. It appears that matrix-related adjustments to the Mount data would move the provenance inferences toward magmatic arc sources even without the benefit of geochemical results.

Lawrence (1996) and Girty and Lawrence (2000) examined the question of whether the source of siliciclastic detritus in the Shoo Fly Complex was situated within the continental interior of western North America. The examination involved the statistical treatment and comparisons of averaged values for thorium/uranium, rubidium/strontium, and Al2O3/TiO2 ratios; CIA; Eu/Eu*; and REE distributions derived from samples of Shoo Fly mudstones and sandstones with samples of southwestern Cordillera miogeoclinal sediments. The Shoo Fly sediments were represented by samples collected from the Poison Canyon and Red Hill units in the Culbertson Lake allocthon; at and near Bowman Lake. The miogeoclinal sediments were represented by samples collected from Precambrian and lower Cambrian rocks exposed in eastern California and western Nevada, including the “Inyo facies” and “Death Valley facies.” Several initial premises were key to the examination. First, the graphing of log-based ratios of major oxides according to Herron (1988) provided a reasonable assurance that similar rock types were being compared. Second, if the sediments from both these areas were derived from the same source, they should have similar compositions as reflected by the statistical comparisons of the respective averaged values. Third, “...the sources of sediment dispersed from within the western North American interior during the latest Precambrian and early Paleozoic can be subdivided into southern and northern segments;” based on the cited works of Gehrels and Dickinson (1995) and Gehrels et al. (1996), involving single-crystal detrital zircon U-Pb geochronology.

The conclusions reported by Girty and Lawrence were that the Shoo Fly and miogeoclinal samples (a) “...did not share the same source,” (b) single-crystal U-Pb detrital zircon ages from the Shoo Fly Complex are similar to those derived from miogeoclinal strata whose source “...was located in northwestern North America,” and (c) that the data “...are consistent with the idea that the source of the voluminous siliciclastic detritus in the Shoo Fly Complex was probably located in northwestern rather than southwestern North America.” Additionally, the source of clastic material in the Inyo and Death Valley facies is located “...somewhere in the adjacent southwestern interior of North America,” based on “stratigraphic trends and paleocurrent data.”

Gehrels et al. (2000, p. 138), reported that detrital zircon data indicate an outboard magmatic arc provided only minor detrital input to lower Paleozoic strata of northern

California, including the Shoo Fly Complex, and that the dominant source of the more mature Shoo Fly sandstones "...consisted of >1.8 Ga basement rocks and overlying platformal strata in the Peace River Arch region of northwestern Canada" (also see Lawrence, 1996, p. 90). However, Cant (1988, p. 294-295) acknowledged that problems remain in "...interpreting the history and origin of the Arch." For the Arch region to have been the source of the Shoo Fly sediments would require that it was exposed at least as early as the Ordovician through unroofing and dissection associated with its uplift rather than by rifting since "...the first period of active normal faulting (in the region occurred) in the Devonian (380 Ma)."

Thus, each of the Shoo Fly investigators previously cited and/or quoted in this report describe the Complex being formed by a variety of lithologies, including: clastic, chemical, and volcaniclastic sediments; subaqueous basalt deposits (Girty et al., 1990, p. 45); plus ultramafic, basic, and felsic intrusives. Where these rock types are found, either singly or in some combination, depends on what location or area within the expanse of the Complex is being examined. Moving beyond that general consensus on lithologies is when the reported interpretations on provenance diverge.

The foregoing hypotheses serve as examples for the observation made by Varga (1980, p. 194) that "...copious tectonic models (have been) suggested by many previous authors..." for the evolution of the western Cordillera. That observation applies equally to the many syntheses (also see the "Geologic Setting" section above for other examples) that involve the participation of the Shoo Fly Complex in that evolution and that were published since the 1969 Penrose Conference was held at Asilomar, California, where "…the Sierra Nevada became a prime example of an Andean-style continental margin" (Moores, 2011).

V.E. Shoo Fly Provenance Inferences of this Thesis

The available information and graphical analyses reported here suggest that the Shoo Fly Complex sandstones exposed in the study area are a mixture of components from at least two source terranes: continental plutonic and sedimentary. A continental metamorphic source terrane remains a third possibility, but is equivocal because of the lack of definitive evidence. The percentages for total quartz that result by applying the approach of Cox and Lowe (1996), including petrographic and geochemical analyses, range from approximately 72 to 98 percent; averaging about 89 percent (Table 7). The range for feldspar is approximately 1 to 28, averaging about 8, and for lithics is from zero to 11 percent, averaging about 6. Consequently, a "Recycled Orogen" provenance (Dickinson, 1983; 1985) is inferred (Figure 49), based on these averaged results.

Dickinson (1985, p. 338-342; 347-351) discussed the series of provenance types proposed as distinguishable through proportions of detrital framework components in sandstones and describes sediments that are derived from the "Craton Interior" and "Recycled Orogen" provenances. Summarizing Dickinson, debris that are derived from craton interiors (or "stable" cratons) yield quartz-rich sands with "high Qm/Qp and K/P ratios," whereas "Recycled Orogen" provenances (or "subduction complexes") yield

“...quartzolithic sands low in F and Lv with variable Qm/Qp and Qp/Ls ratios.” The main sources of sediments that form quartzose sands are “...low-lying granitic and gneissic exposures, supplemented by recycling of associated flat-lying platform sediments.” Dickinson emphasizes the importance of “...intense weathering for concentrating quartz in relation to feldspar and/or lithic fragments” through the “...combined effects of climate and relief on the production of quartzose sands” and the “...possibility of appreciable weathering during temporary storage on low-lying floodplains along the continental dispersal path.” Additionally, the main sources of the sediments that form quartzolithic sands include terranes “...where stratified rocks are deformed, uplifted, and eroded.” These settings include subduction complexes, backarc thrustbelts, and suture belts. The resulting sediments are compositionally variable, reflecting “...cratonic, arkosic, or volcaniclastic sources...” that may be “...modified in part by metamorphic processes...” or by diagenesis or both.

The Shoo Fly quartzose samples studied for this thesis appear to have more in common with sediments derived from “Recycled Orogen” provenance(s) than from craton interiors, based on the compositional ratios used by Dickinson (1985) as indicated above and suggested by the averaged QFL values plotted on Figure 49. Only one sample listed in Table 2b has a Qm/Qp value greater than 1 and the use of the K/P ratio is meaningless since no Kspar was identified in these samples. Even so, the samples are demonstrably low in feldspar and lithic framework components.

Yet, the provenance characterization ratio values reported by Girty et al. (1996b, p. 7), do not provide for a strong case to be made that a source of the Shoo Fly represented by the quartzose sandstone samples listed in Table 6 is either “differentiated old upper continental crust,” magmatic arc, or “exotic types.” The ratio results from the samples suggest that both continental crust and magmatic arc sources may have provided material to form the Shoo Fly sediments. However, there remain the factors that are discussed by McLennan (1989, p. 170, 185-187) and which are shared by each of the Shoo Fly samples: the negative Eu/Eu* anomaly and Th/U values listed in Table 6 and the REE fractionation patterns shown on Figure 48. These factors lend weight to the inference that the provenance of the “SF 1” Shoo Fly is continental rather than arc-related.

It is worth noting that the characteristics reported by Girty et al. (1996b, p. 7), for sandstones from the Red Hill and Poison Canyon units in the Culbertson Lake allochthon may be comparable with this study’s samples per the following: the “…highly quartzose nature,…presence of abraded syntaxial quartz overgrowths on some framework grains, and a relatively high average chemical index of alteration…”

A hypothetical model for the portion of the Shoo Fly that is exposed in the study area and accounts for the inferred sources discussed above includes a basin wherein the varied clastic and chemical lithologies were deposited, in part, as coalescing submarine fans, with material possibly “...channeled within a subduction-related trench offshore from the (Cordillera) continental margin” (Gehrels et al., 2000, p. 143). The model proposed by Standlee (1978, p. 58) included such a basin, but flanked on opposite sides by a "plutonic crystalline" basement, capped by quartz arenite, and a "volcanic/plutonic arc." Although that model included a progressively opening basin, it is limited in that it does not effectively place the Shoo Fly in a plate-tectonic context and appears mainly designed to simply link the sediment types with possible sources.

Moores (1970, p. 838, Fig.3b) proposed a different hypothesis for the development of the North American Cordillera that involved the collision of subduction-zone and continental-margin terranes, with two oppositely-dipping subduction zones beneath oceanic crust that is being compressed and that this system was "...affected three times by major 'orogeny':" the Devonian Antler, Permian Sonoma, and Jurassic Nevadan orogenies. The subduction zones may have operated either essentially simultaneously or sequentially. The Moores hypothesis may also help to explain the mafic and ultramafic (i.e., ophiolitic) rocks found elsewhere in the Shoo Fly Complex (Colpron and Nelson, 2009, p. 291).

A continental margin source is indicated by the plutonic detritus found in the Shoo Fly metasandstone samples; the inclusion-containing quartz and detrital zircons. Metamorphic detritus, if such were to be confirmed, would add significantly to this interpretation. The mature, recycled (e.g., syntaxial overgrowths on quartz) sedimentary detritus is likely to be from a distal source, such as a continental interior, that resulted in the observed rarity of these grains.

Dickinson (1977, p. 143-145) provided a classic “ocean basin closure” model where a wide ocean basin separates a continental margin from a distal island arc formed above a west-facing subduction zone, with the basin gradually closing[16]. That model provides a mechanism for the accretion of the Shoo Fly onto the continental margin. The approach of an island arc in the Moores and Dickinson models may also account for the distinctly volcaniclastic sediments (including breccias) that occur in the uppermost Shoo Fly (DeVay, pers. comm., 2015) on its present eastern flank in the Jamison Creek-Florentine Canyon area near the Plumas Eureka State Park.

At least one difficulty with the Dickinson model is that the envisioned obducted sedimentary package is a stack of east-verging, thrusted wedges with the sediments facing away from the continental margin. This is not the case with the Shoo Fly, which faces east toward the continent and would require subsequent rotation of the obducted stack.

Colpron and Nelson (2009, p. 292) discussed the assembly of the Shoo Fly Complex within the northwestern Laurentian margin, whereby the lower allochthons were tectonically juxtaposed with the Sierra City melange, and make the following

[16] Dickinson (1977) also stated that the scenario involving the “...development of a residual marginal basin as a remnant of a once larger ocean that shrank in size as an intra-oceanic island arc approached the continent by subducting the intervening ocean floor...” was “...favored initially by Moores (1970) for the Antler and Sonoma events...” and “...remains a viable alternative...,” but “...has been discounted by most recent authors.”

observation: “In the Shoo Fly Complex, the most exotic component now lies structurally inboard of less far-travelled rocks. However, if after Silurian-Devonian time the amalgamated fragment has been transported thousands of kilometres to the south, an accompanying rotation up to 180^{o} is unsurprising.” Colpron and Nelson suggested that such movement of the Shoo Fly Complex would “...require passage...from a site of collision with northwestern Laurentia to a location nearer southwestern Laurentia...” The “Geodynamic model” discussed by Colpron and Nelson (2009, p. 295) envisions a complex translocation of “Caledonian-derived elements of the Eastern Klamath, Northern Sierra and perhaps Okanagan terranes...into contact with their northwestern Laurentian counterparts...and later (migration) southward along western Laurentia as composite terranes...” Additionally, “This southward transport of terranes most probably occurred along a sinistral transform fault system that developed along the western edge of Laurentia in Middle Devonian time” and resulted in the emplacement of the Shoo Fly Complex in its present geographic position relative to the western United States by the “Late Permian to Early Triassic (c. 250 Ma)” (Colpron and Nelson, 2009, p. 293-300, also see Figs. 11-16).

The “Geodynamic model” may also provide an explanation for the continental-rift and/or arc chemical signature indicated by the discriminant-function approach of Verma and Armstrong-Altrin (2013). Colpron and Nelson also state that

"...westward travel around northern Laurentia…developed along eastern Laurentia and western Baltica in mid-Paleozoic time" and that "Initial rifting and rapid westward migration of a narrow subduction zone led to dispersion of the crustal fragments that once lay between Baltica, Siberia and northeastern Laurentia."

VI. STRUCTURAL GEOLOGY

VI.A. Introduction

This section is a generalized discussion of the dominant structural features that have affected and continue to affect the rocks in the region of the northern Sierra Nevada wherein the study area is situated. D'Allura (1977), Durrell and D'Allura (1977), D'Allura et al. (1977), Standlee (1978), Hannah (1980), Varga (1980), and Varga and Moores (1981), provide important, well-documented details about the structural elements that are expressed at the micro, macro, and regional scales in this same region of the northern Sierra, including the Lakes Basin area. These works focused primarily on structural elements in the Subjacent Units, including the Shoo Fly, while several also address pre-Tertiary and Cenozoic faulting. Girty and Schweickert (1983a, 1984), Taylor (1986), Richards (1990), and Girty et al. (1990) reported details about structural elements in Shoo Fly Complex rocks exposed to the south in the Bowman Lake and Lake Spaulding areas.

VI.B. Pre-Cenozoic Structures

The pre-Cenozoic structures that are the subject of this section are those that are wholly within the Subjacent units; particularly within the Shoo Fly Complex rocks that are exposed in the area of Plate I. Those structures include: (a) the major angular unconformity that separates the Shoo Fly rocks from the overlying Devonian age Sierra Buttes Formation, which resulted from a first period of regional deformation; (b) two generations of "local" (per Varga, 1980, p. 187) folds; (c) the pervasive foliation that parallels the area's northwest-southeast-trending tectonic grain; and (d) "...major faults affecting (the) subjacent units..." (D'Allura, 1977, p. 252-262).

The major pre-Devonian unconformity has long been recognized. For example, Durrell and Proctor (1948, p. 170, 175) observed this "...profound unconformity..." near Wades Lake (Lakes Basin area) and described the contrast in folding between the underlying "Calaveras" (i.e., Shoo Fly) and overlying "meta-rhyolite series" (i.e., Sierra Buttes) as evidence for it. Varga and Moores (1981, p. 512-513) also described evidence for the unconformity and its importance for the following reasons: (1) the contrast between the Shoo Fly and overlying Devonian age rocks demonstrates the marked change in sources and depositional environments ("...continental slope-rise sedimentation...to island-arc volcanism..."); (2) the "…pre-Nevadan (pre-Late Jurassic) folding…" in the Shoo Fly Complex "…did not affect the younger volcanic arc sequences..." above the unconformity; and (3) "…microfossils recovered from both sides of the unconformity bracket the early deformation between (the) Late Devonian and Ordovician-Silurian." Although the unconformity, including its folded sections, is well exposed in the Lakes Basin area, it is not exposed within the present study area. However, D'Allura (1977) mapped the unconformity in one small area within the outline of Plate I; in the northeast quarter of Section 30, T24N, R11E, where the Shoo Fly is in contact with the Sierra Buttes Formation.

Varga (1980, p. 52) reported that "...the pre-Nevadan discordance between the Shoo Fly and Sierra Buttes Formations was approximately 35^{o}," based on detailed mapping and structural analyses. Such an acute angle may be consistent with deformation of the Shoo Fly by imbricate thrusting prior to the erosion that produced the unconformity and some degree of folding would be expected to attend deformation associated with such thrusting. Alternative explanations for this acute discordant angle at the unconformity might also include down-warping or fault-block rotation during rifting. However, extrapolating these alternative hypotheses to cover the length of the Shoo Fly seems untenable considering its approximately 113 kilometer (70-mile) distance from the Lake Almanor area to at least the North Fork of the American River (D'Allura et al., 1977, p. 395 and 399) or even the approximately 177 kilometers (110 miles) from the Lake Almanor area to near Placerville (Clark, 1962, p. B-17; McMath, 1966, p. 173). Varga and Moores (1981, p. 187) did not recognize pre-Nevadan folds north of the Lakes Basin area[17] "...possibly because intense Late Jurassic deformation obliterated them."

Varga (1979; 1980) documented the two generations of folds in the Shoo Fly,

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[17] Varga (1980, p. 186) also stated: "Absolutely no trace of early structures was found along (the Middle Fork) traverse…"

locally designated “F1” and “F2,” in traverses along the Middle Fork of the Feather River and the west and east branches of the North Fork of the Feather River. The “F1” of Varga is the second period of regional deformation (Varga, 1980, p. 186), is of “Nevadan” age (Late Jurassic), and is associated with tight to isoclinal folding and a regional steeply dipping, NNW-striking foliation (penetrative slaty cleavage). The “F2” is possibly(?) “Late Nevadan” and involves kink folding of the regional foliation that is best developed in the pelitc sediments. The Sierra Buttes also exhibits these “F1” and “F2” structures. The first period of regional deformation also resulted in structures that are only locally developed, have highly variable orientations, no associated foliation, and did not affect the overlying late Devonian Sierra Buttes Formation. Varga (1980) reported direct evidence for this first regional period only along the North Fork of the Yuba River and in the Lakes Basin region, differentiated from the succeeding events by: (a) “Post-Ordovician-Silurian, Pre-Late Devonian” age folding; (b) lack of discernible axial plane cleavage; and (c) the development of the major unconformity. The evidence shown on Figure 50 supports the finding of Varga in the Feather River drainages. At the outcrop shown on this figure, the structures involve “F1” folds and superposed “F2” folds. The “F1” folds have highly-appressed limbs and relatively thickened hinge zones that are likely the result of the rock types involved in this outcrop (i.e., interlayered chert and slate) in addition to the intensity of deformation and/or elevated temperatures (Varga, 1980, p. 192).

Standlee (1978, p. 19 and 74) referred to the foliation in the Shoo Fly as "the major structural element" and associated its formation as axial planar to the isoclinal folding of sedimentary bedding during "F1" folding. The foliation observed in the present study area (Plate I) is consistent with the findings of Standlee; trends generally northwest-southeast, is steeply dipping (either east or west) to vertical, and is best displayed in the slates (see the photo following this report's title page and Figure 15).

Thin-sections provide the best evidence of the foliation in the Shoo Fly sandstones and siltstones (Figures 17, 21-23). Foliation is not displayed in outcrops of either the rocks intrusive to the Shoo Fly (described above) or the limestone at Little Volcano-Limestone Point. However, thin-sections (Figure 28) from samples collected from the outer surfaces of the quartz porphyry dike (26a and 26b) show that the rock is slightly foliated. Varga (1980, p. 92) also reported that the margins of the Buckhorn Mine stock are slightly foliated.

The area encompassed by Plate I is situated in the central portion of the "Hough Block," (D'Allura, 1977, p. 15 and 251a). The "Hough," "Genesee," and "Kettle Rock" Blocks help to form the major pre-Cenozoic structural architecture of the region of the northern Sierra Nevada between Lake Almanor and the Lakes Basin area. D'Allura (1977, p. 262) speculated that the age of the complex faulting that defines the blocks is "…somewhere between late Jurassic and Eocene and may conceivably be related to the late stages of the Nevadan orogeny." The serpentinite exposures east and southeast of Thompson Valley (Massack area) are bounded by northwest-southeast-trending faults that are consistent with the region's major pre-Cenozoic faults. D'Allura (1977, p. 191) interpreted them as "...pre-dating the deposition of the Sierra Buttes Formation."

D'Allura (1977) also mapped within the area of Plate I (in Section 25, T24N, R10E) the trace (albeit limited in length) of an anticline in the Shoo Fly. D'Allura interpreted in cross-section (1977, C-C') this anticline as forming the western limb of a complexly-folded sequence, cut by faults, that also involves the Sierra Buttes, Elwell, and Taylor Formations and, as such, is an important component of the structure of the Hough Block (D'Allura et al., 1977, p. 397). D'Allura (pers. comm., 2016) confirmed that recognizing this fold in the Shoo Fly was based on discernible sedimentary facing in opposing dip directions. However, not found in the study area for this thesis was unequivocal evidence that would support either the finding or interpretation of this major, map-scale structure extending into the Shoo Fly. Thus, the folding shown by D'Allura is not extended (Plate II, cross-section C-C') into the study area, but it is recognized that it cannot be ruled out as a possibility.

VI.C. Cenozoic Structures

The Cenozoic structures mapped within the study area are the high-angle faults that affect all the rock units other than alluvium that are represented on Plate I. Recognition of the faults that offset and juxtapose the Superjacent units is predicated on the acceptance of the stratigraphy of this thesis. Mapping the faults may be extended with some confidence into the adjacent basement rocks. The pattern of this block faulting is consistent with that shown by Durrell (1976) and D'Allura (1977) which is also based on the offsetting relationships between the units of the Devonian series; the Sierra Buttes, Elwell, and Taylor Formations. D'Allura (1977, p. 251) expressed the following pertinent observation: "There is no reason to suspect that the areas dominated by subjacent units are less intensely faulted than areas where superjacent units dominate." Hannah (1980, p. 89) made a similar observation by stating that the Cenozoic normal faults "…must occur with comparable density in areas stripped of (the) Cenozoic cover." In some cases, plugs and/or dikes of basalt indicate reasonable fault demarcations or extensions. A number of springs in the study area may also provide some additional evidence for faults, but these features may have also formed where contrasting lithologies are juxtaposed.

Except for a few exposures, outcrops of the Warner basalt in the study area are bounded by combinations of depositional contacts and faults. These exceptions are located in adjacent Sections 32 (T24N, R10E) and 5 (T23N, R10E) where erosional remnants of the Warner cap knobs located slightly northeast of Bachs Creek Ridge. All the outcrops of Warner basalt mapped by Durrell (1976) and D'Allura (1977) within the outline of Plate I are similarly bounded by depositional contacts and faults. Thus, a significant number of the faults are post-Warner, which were formed after the presumed age of the Warner; uppermost Late Miocene or lowermost Pliocene. Durrell (1959a, p. 179) stated what is applicable to the present study area: "...the Warner basalt... in the Blairdsden quadrangle was erupted before the period of faulting that produced the scarps."

The several plugs of intrusive Warner, near the west edge (Section 31, T24N, R10E, and Section 7, T23N, R10E) and center (Section 1, T23N, R10E) of Plate I and in the area mapped by D'Allura (1977), exploited the faults associated with them. If these plugs were feeders of Warner basalt, then the resulting deposits would be succeeding flows that appear to be almost entirely absent from the area, probably removed by erosion. The caps of remnant Warner basalt mentioned above may be remaining evidence of that removal.

Additional possibilities for the age of the faulting within the area of Plate I were suggested by D'Allura (1977, p. 25) in describing the "Massack fault" (or "Massack fault system") in Sections 22, 23, 25, T24N, R10E, which "...juxtaposed and at the same time eliminated parts of the Shoo Fly and younger volcanic formations." The age of the Massack fault is at least post-Bonta and may be post-Penman if the Penman proves to be as D'Allura mapped it. The Massack fault also juxtaposes along its mapped trace the serpentinite of the Massack area against Shoo Fly rocks (Plate II; cross-section B-B'). The Massack fault does not involve either the extrusive or intrusive Warner basalt. Additionally, the Massack fault "...marks the northeastern boundary of the Plumas Trench..." and "...through a series of offsets, joins the boundary faults in Long and Mohawk Valleys" (Figure 3; and D'Allura, 1977, p. 257-258). D'Allura (pers. comm., 2016) did not map the trace of the Massack fault to the southeast beyond Squirrel Creek (Section 25, T24N, R10E) because of the lack of supporting evidence.

Durrell (1987, p. 209 and 212) interpreted the Cenozoic faulting in the northern Sierra Nevada as resulting from "Six episodes of faulting...during the Tertiary period." Each episode was interpreted to have followed the respective deposition of the volcanic formations that form the Blairsden stratigraphy discussed above.

The primary, dominant trend of all faults shown on Plate I is northwest-southeast, This trend is shared by faults beyond the area of Plate I that are interpreted by D'Allura (1977) to be pre-Cenozoic. A later, secondary set of faults that trends mainly northeast-southwest, also nearly east-west, intersects and offsets the primary set (D'Allura, 1977, p. 258). As with the primary set of faults, the secondary set involves the Cenozoic and Paleozoic rocks. An important example of the secondary set that involves the Lovejoy is located in Sections 10 and 11, T23N, R10E, where the exposure in bounded entirely by faults that juxtapose the basalt with rocks of the Shoo Fly, Bonta, and Warner. the Lovejoy is juxtaposed against the Bonta and the Warner along the trace of the fault that bounds this block on its north side. The Lovejoy is juxtaposed against Bonta and Shoo Fly rocks along the trace of the fault that bounds this block to the south.

The resulting block-faulting described above led to the formation of the complex graben that is the Plumas Trench and the series of separate alluviated valleys that extend south from American Valley through Mohawk Valley and into Sierra Valley (Figure 3). The faulting that separated the valleys gave rise to the occupation by ancient lakes; although Durrell (1987, p. 269) suggested that Long Valley may have been an exception because of the lack of compelling evidence. Mapping also by Wilhelms (1957), Durrell (1959a, 1976, 1987), Strand (1972), D'Allura et al. (1977), Berry (1979), and Hannah (1980), showed that this pattern of faulting is widespread and extends from the crest of the Sierra Nevada east to the Diamond Mountains (Durrell, 1987, p. 213). Thus, this region of the northern Sierra Nevada and northeastern California is situated within the Basin and Range geomorphic, or structural, province (D'Allura, 1977, p. 262; Hannah, 1980).

Earthquake epicenter data, available on line from the Northern California Earthquake Data Center, demonstrate that the region remains highly active seismically, albeit with relatively low-magnitude events. Epicenter locations were downloaded using search criteria that included the corner coordinates of this report's Plate I and the somewhat arbitrary time frame from 1984 to 2015. The resulting dataset shows that the majority of the seismic events are clustered within the portion of the Plumas Trench that is within the outline of Plate I (Figure 5). These events may tend to confirm the faults shown on Plate I. However, it is recognized that the apparent correspondence of the locations between the mapped faults and epicenters may, to some degree, be strictly coincidental. The data represented by the epicenters that are within the outline of Plate I also show that the event depths range from very shallow (0.02 km; 0.01 mile) to relatively deep (approximately 38 km; 23.6 miles). Nevertheless, both the mapped faults and epicenters indicate that the Basin and Range structure is continuing to develop westward into the northern Sierra Nevada.

Wakabayashi and Sawyer (2000, p. 194-199) also discussed this westward structural development, although the interpretation is based on the distribution of the Tertiary deposits and the suggestion that "…the Sierra Nevada-Basin and Range boundary and associated Frontal faulting have migrated westward in the late Cenozoic" having probably begun "…in the Feather River area…sometime after 6.8 Ma." As discussed previously, the reported age of the Warner intrusive may range from Middle Miocene to Pliocene. If this range is correct and may be applied to the area of Plate I where the Warner intrusive is associated with faults, then at least some of the faulting may pre-date the upper Late Miocene age interpretation made by Wakabayashi and Sawyer.

VII. CONCLUSIONS

VII.A. Shoo Fly Complex

The "SF 1"of D'Allura et al. (1977), is the member of the Shoo Fly Complex that is exposed in the study area for this thesis. It is apparent from the descriptions and mapping by Harwood (1992) that the "Lang" sequence is the "SF 1" of D'Allura et al. by another name. However, the extrapolations of the Lang in west-verging thrust contact with the overlying Sierra City melange by Harwood, then Girty et al. (1993a), north of the Lakes Basin area and across the present study area are without conclusive evidence, do not comport with the observations described in this thesis and reported separately by Varga (1980), and appear to be, to a large degree, literature-based; at least for Harwood[18]. Moreover, the evidence reported by Varga (1980), shared by DeVay (pers. comm., 2014-2015), and observed for this thesis support the interpretation that within the present study area the “SF 2”of D’Allura et al. (1977) is the “SF 1.”

The sediments that formed the metasandstones in the “SF 1” were derived from continental crust, including plutonic and sedimentary sources. This conclusion is demonstrated by the nature of the framework quartz observed in thin section and the REE distribution patterns based on this study’s ICP-MS/ICP-OES analytical results.

A “Recycled Orogen” provenance for the metasandstones is inferred from the numerical average of the QFL data derived from point-counting and major-oxide analytical results by XRF. This inferred provenance is in substantial agreement with that reported by Bond and DeVay (1980) and DeVay (1981) whose studies also involved petrographic analysis of “SF 1” metasandstones. However, no conclusive evidence of a metamorphic source terrane was found in this study; in contrast with the suggestions made by Bond and DeVay (1980) and DeVay (1981).

The pre-Cambrian Peace River Arch region of Canada may have been the source of the clastic sediments that formed the metasandstones (Gehrels et al., 2000). This possibility is consistent with the conclusion of Lawrence (1996) that “...the

[18] As noted earlier, Harwood (1992, p. 3) stated that the mapping “relied heavily on the thesis maps and published reports” of those listed in acknowledgment and confirmed (pers. comm., 2013) that the Shoo Fly investigations were focused south of Interstate 80.

terrigenous detritus within the Shoo Fly Complex was derived from a mixture of Archean and post-Archean debris shed from the northern interior of western North America."

Alternatively, Colpron and Nelson (2009) proposed a "Geodynamic model" that is consistent with detrital zircon signatures indicating a northwestern Laurentian margin provenance and envisions a complex translocation of what became the Northern Sierra terrane from northern Laurentia southward along western Laurentia into its present geographic position relative to the western U.S. This postulated transport of thousands of kilometers began with "Initial rifting and rapid westward migration of a narrow subduction zone...," involved a "...sinistral transform fault system that developed along the western edge..." of the Laurentian craton, and helps to explain the position of the Sierra City melange ("the most exotic component" in the Shoo Fly Complex) being "...structurally inboard (east) of less far-travelled rocks." The Colpron and Nelson "Geodynamic model" may also provide an explanation for the continental-rift and/or arc chemical signature indicated by the discriminant-function approach of Verma and Armstrong-Altrin (2013). The Colpron and Nelson "Geodynamic model" appears to provide the better hypothesis involving the evidence from this study.

Additional petrographic and geochemical analyses are needed to address the tentative findings involving the rift-arc chemical signature and the significant amounts of pseudomatrix in this study's metasandstone samples. Additional study is also needed to determine the geographic extents of the various subdivisions of the Shoo Fly Complex that were described by other workers and discussed in this report. Such assessments should reveal additional details about the rocks that compose the Shoo Fly Complex and provide further evidence on which to base its provenance.

D'Allura (1977, p. 190) described mafic and ultramafic material in the Massack area as displaying no contact aureoles and interpreted these exposures as being "...'cooly' emplaced along faults." The nature of the meta-diabase in the southeast portion of the study area and how it was emplaced remain to be determined because no associated aureole was observed there.

VII.B. Cenozoic Units

The mapping for this thesis supports the stratigraphy of the successive Cenozoic units as described in this report. Consequently, it is also concluded that a significant degree of uncertainty is associated with the isotopically-derived overlapping age ranges reported by other geologists for the units that form that stratigraphy. The following are also evident:

- the Lovejoy basalt is the oldest of the Superjacent units exposed in the study area and it is against its age, 16 Ma, that the ages of the succeeding units are to be compared;
- the exposures of the Lovejoy basalt in the study area define two stems that diverged from the main paleochannel through which the Lovejoy flowed;

- the belt-like distribution of the Superjacent volcanic and volcaniclastic deposits within the study area help to delineate a paleovalley wherein they were deposited and through which these materials moved to the west and into the ancestral Sacramento Valley;
- the stratigraphy allows for the recognition of the block-faulting that affected all the Cenozoic units, other than alluvium, mapped for this thesis and that from Durrell (1976) and D'Allura (1977);
- the block-faulting defines a primary, mainly northwest-southeast- trending set and a secondary, generally southwest-northeast-trending set that offsets the primary set;
- the block-faulting has similarly affected the Subjacent units within the area of Plate I;
- a significant number of the mapped faults are post-Warner basalt;
- a number of exposed plugs and dikes of intrusive Warner exploited faults belonging to both sets, thus indicating that these materials may have resulted in later flows and which, with some exceptions, appear to have been eroded away; and,
- the faulting and available seismic data show that basin-and-range deformation is migrating westward into the Sierra Nevada.

Additional work is also needed to determine: (1) if the Bonta and Penman formations within the outline of Plate I are in fact separate units; (2) whether, as commented by Day (pers. comm., 2016), these units may "...simply (be) similar lithologies that recur(red) at various times during the Cenozoic history of volcanism. The unit names, then, are shorthand for similar lithologies but might have little stratigraphic significance;" and (3) if the Cenozoic volcanics and/or volcaniclastics described here exist in areas south of the Middle Fork of the Feather River, whether they define another paleovalley other than the one mapped for this thesis and which would add to interpretations about the pattern and timing of faulting in this region of the northern Sierra Nevada.

Thus, the history of the rocks that form this portion of the northern Sierra Nevada spans approximately 450 Ma and is still evolving. The vast majority of the rocks are migrants to the region. It is hypothesized that the source of the Shoo Fly Complex rocks was located in the region north of what is now Alaska and Canada and were assembled and transported south over the thousands of kilometers through complex crustal movements. During that process, the Shoo Fly was deformed and unconformably overlain by island arc and other sediments. Three succeeding major orogenies, Antler, Sonoma, and Nevadan, affected these rocks that became part of the North American Cordillera. Within the study area, a profound unconformity representing approximately 330 Ma forms the surface on which the Cenozoic volcanic and volcaniclastic units were deposited. The sources for most of these rocks were located in neighboring areas within the northern Sierra, but the oldest deposits that are found elsewhere in the region are postulated to have been transported from western Nevada. These volcanic deposits are important evidence for reconstructing the paleotopography of the region and in identifying faults.

While the information and data provided in this report answer the basic questions posed as the objectives for this thesis, it is my hope that other geologists will continue to investigate the rich geology of the northern Sierra Nevada, particularly the Shoo Fly Complex, and add to the impressive body of knowledge that is reported to date about the region’s rocks.

VIII. TABLES

Table 1. Shoo Fly Complex Subdivisions

Clark (1976)	D'Allura et al. (1977) Standlee (1978)	Girty and Schweickert (1979) - Bowman Lake area -	Schweickert et al. (1984)* Harwood (1992)*	Girty et al. (1996a; b)* and references therein
SBF	SBF	SBF	SBF	SBF
Upper Shoo Fly Formation	Upper Shoo Fly Formation ("SF 3")	Upper Shoo Fly Complex	Sierra City melange	Sierra City melange
	Middle Shoo Fly Formation ("SF 2")	Middle Shoo Fly Complex	(Indian Creek Unit**) Culberstson Lake allochthon: Bowman Lake area	Culberstson Lake allochthon
			(Paxton Unit**) Duncan Peak allochthon: Bowman Lake area	Duncan Peak chert or allochthon
Lower Shoo Fly Formation	Lower Shoo Fly Formation ("SF 1")	Lower Shoo Fly Complex (Assemblages: 'A' (lowest), 'B' (middle), 'C' (highest)	Lang (or "Lang-Halsted") Sequence	Black Oak Spring sequence**
				Lang sequence
---------MFZ-------	-----------MFZ----------	----------------MFZ---------------	----------------MFZ---------------	--------------MFZ------------
FRPB	FRPB	FRPB	FRPB	FRPB

Notes:

Diagram (not to scale) comparing certain published Shoo Fly Complex subdivisions. The preliminary scheme used by Girty and Schweickert (1979) applies to the Bowman Lake area where further Shoo Fly Complex subdivisions have been published by various workers, including Schweickert, Girty, Harwood, etc. (see citations in thesis text). Subdivision of the Shoo Fly is not used in this thesis for the exposures within the study area (see text and Plate I). SBF = Sierra Buttes Formation. MFZ = Melones Fault Zone. FRPB = Feather River Peridotite Belt.

*The subsequent scheme used by Schweickert et al. (1984), Harwood (1992), and Girty et al. (1996a, 1996b), was applied over the broad geographic expanse from south of Lake Almanor to south of Interstate 80.

**The names Indian Creek Unit and Paxton Unit were superseded, respectively, by the Culberstson Lake and Duncan Peak allochthons for exposures in the Bowman Lake area. The Black Oak Springs sequence stems from the work by Taylor (1986).

Table 2a. Point-Counting Results (modal percentages) from the Shoo Fly Complex Sandstone Samples

Sample / Parameter (%):	S/T/R	Q	F	L(+ch)	Qfine	Qcse	Matrix	Mqtz	Mphyllo	N
1-7	17/24/10	100	0	0	91	9	40	62	38	1,474
1-94	20/23/11	97.4	0	2.6	30	70	34	78	22	1,672
S15-7201	15/23/10	95.4	4.5	0.1	87	13	35	56	44	1,659
S15-7202	15/23/10	96	0.4	3.6	76	24	47	53	47	1,505
S15-7203	15/23/10	77.1	1.4	21.5	58	42	58	55	45	833
S15-7204	15/23/10	98.8	0.2	1	80	20	47	46	54	1,088
S15-9713	15/23/10	98.6	1.4	0	82	18	33	67	33	665

Notes:

S/T/R = Section/Township/Range
Q = total quartz
F = feldspar (entirely plagioclase; no K-spar observed)
L= lithic (chert and/or slate rock fragments; slate percentages of total counts range from 0 to 1.59)
ch = chert (percentages of total counts range from 0 to 9)
Qfine = fine-grained quartz (>0.04 and <0.8 mm)
Qcse = coarse-grained quartz defined (>0.8 mm
Mqtz = quartz matrix component
Mphyllo = phyllosilicate matrix component
N = total point counts, including matrix
Q, F, and L are normalized to sum to 100%
Qfine and Qcse are normalized to sum to 100%
Mqtz and Mphyllo are normalized to sum to 100%

All counts were made under 100x magnification, using 0.5-mm intervals.
Variations in counts (“N”) are because of specimen size and/or travel limits of the mechanical stage.

The five “S15” samples were also analyzed for whole-rock geochemistry by XRF (major oxides; Table 3) and ICP-MS/ICP-OES (REE; Appendix B). The point-count data from these five samples were used to derive "weight-percent” QFL results (see Table 7) using the procedures and calculations of Cox and Lowe (1996).

Table 2b. Point-Counting Results for Monocrystalline and Polycrystalline Quartz from the Shoo Fly Complex Sandstone Samples

Sample / Parameter:	Q	Qm%	Qp%	Qm/Qp
1-7	79	28	72	0.39
1-94	746	13	87	0.15
S15-7201	132	23	77	0.30
S15-7202	184	17	83	0.20
S15-7203	114	26	74	0.35
S15-7204	111	31	69	0.45
S15-9713	77	60	40	1.5

Notes:

Q = total point counts of quartz >0.8 mm
Qm% = normalized monocrystalline quartz >0.8 mm within Q (rounded to whole numbers)
Qp% = normalized polycrystalline quartz >0.8 mm within Q (rounded to whole numbers)

Table 3. Major Oxide Analytical Results: Shoo Fly Complex Sandstone Samples

Analyte / **Sample**:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	**REP-S15-7201**	Units	RL	MU
SiO2	89.6	78.9	75.2	92	88.3	89.9	%	0.01	2.1
Al2O3	4.35	9.02	11.2	3.48	4.21	4.38	%	0.01	4.2
Fe2O3	1.84	4.37	5.27	1.66	2.98	1.84	%	0.01	4.3 - 3.4
MgO	0.55	1.31	1.6	0.46	0.87	0.56	%	0.01	18 - 4.6
CaO	0.27	0.34	0.12	0.06	0.08	0.26	%	0.01	50 - 12
K2O	0.8	1.58	1.99	0.58	0.48	0.78	%	0.01	10 - 4
Na2O	0.75	1.13	1.31	0.41	0.46	0.77	%	0.01	85 - 4.3
TiO2	0.36	0.65	0.64	0.18	0.41	0.35	%	0.01	10 - 8.9
MnO	<0.01	0.02	0.05	<0.01	0.01	<0.01	%	0.01	85 - 10
P2O5	0.05	0.09	0.08	0.05	0.04	0.05	%	0.01	38 - 11
Cr2O3	0.01	<0.01	0.01	<0.01	0.01	<0.01	%	0.01	85
V2O5	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	%	0.01	85
LOI	1.22	2.11	2.37	0.888	1.2	1.15	%	-10	TBD - 10.6
Sum	99.8	99.6	99.8	99.7	99.1	100.1	%	---	---

Notes:

Major oxide analytical results by XRF (Appendix A) for Shoo Fly Complex metamorphosed quartzose sandstone samples collected in the study area. For calculation purposes, all values shown less than the RL (<0.01) were converted to the RL. However, the totals shown ("Sum") are as reported by the lab.
REP = replicate.
RL = laboratory reporting limit.
LOI = loss on ignition. TBD = To be determined, based on acquiring sufficient data to provide an estimated MU.
MU = Measurement uncertainty. See Appendix A for analyte-specific, concentration-based MU values.
The analyses were done by SGS Minerals Service, Lakefield, Ontario, Canada.

Table 4. Rare Earth Element Analytical Results:
Shoo Fly Complex Sandstone Samples

REE / **Sample**:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	PAAS	Units	RL	MU
Ce	41.6	51.2	54.1	25	37.7	79.6	ppm	0.1	18
Dy	1.57	2.38	2.9	0.98	1.72	4.68	ppm	0.05	27 - 14
Er	0.85	1.27	1.56	0.56	1.06	2.85	ppm	0.05	27 - 14
Eu	0.56	0.67	0.77	0.29	0.41	1.08	ppm	0.05	52 - 29
Gd	1.95	3.14	3.36	1.32	1.98	4.66	ppm	0.05	17
Ho	0.3	0.45	0.59	0.19	0.36	0.991	ppm	0.05	52 - 27
La	19.6	25	26.8	11.9	18.5	38.2	ppm	0.1	13
Lu	0.14	0.19	0.25	0.08	0.19	0.433	ppm	0.05	177 - 52
Nd	16.2	20.7	22.6	9.3	15.2	33.9	ppm	0.1	17
Pr	4.63	5.7	6.31	2.66	4.27	8.83	ppm	0.05	18 - 17
Sm	2.7	3.9	4	1.6	2.7	5.55	ppm	0.1	18
Tb	0.27	0.44	0.53	0.18	0.29	0.774	ppm	0.05	66 - 27
Tm	0.13	0.19	0.25	0.09	0.17	0.405	ppm	0.05	177 - 52
Yb	0.9	1.2	1.6	0.6	1.2	2.82	ppm	0.1	43 - 18
Eu/Eu*	0.75	0.59	0.64	0.61	0.54	0.65	---	---	---

Notes:

Analytical results for selected rare earth elements (REE) by ICP-MS/ICP-OES (Appendix A) for Shoo Fly Complex sandstone samples collected in the study area. Included are post-Archean Australian shale (PAAS) averaged values from McLennan (1989; also see Taylor and McLennan, 1985, p. 30).

For calculation purposes, all values shown less than the RL (e.g., <5) were converted to the RL.
The analyses were done by SGS Minerals Service, Lakefield, Ontario, Canada.
Also see Appendix B.

MU = Measurement uncertainty. See Appendix A for analyte-specific, concentration-based MU values.

Eu/Eu* = europium-anomaly values calculated per McLennan (1989).

RL = laboratory reporting limit.

Table 5. Selected Chondrite-Normalized Rare Earth Element Analytical Results Shoo Fly Complex Sandstone Samples

REE / **Sample**:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	PAAS	C-N Factor	Units
La	53.4	68.1	73.0	32.4	50.4	104.1	0.367	ppm
Ce	43.5	53.5	56.5	26.1	39.4	83.2	0.957	ppm
Pr	33.8	41.6	46.1	19.4	31.2	64.5	0.137	ppm
Nd	22.8	29.1	31.8	13.1	21.4	47.7	0.711	ppm
Sm	11.7	16.9	17.3	6.9	11.7	24.0	0.231	ppm
Eu	6.4	7.7	8.9	3.3	4.7	12.4	0.087	ppm
Gd	6.4	10.3	11.0	4.3	6.4	15.2	0.306	ppm
Tb	4.7	7.6	9.1	3.1	5.0	13.3	0.058	ppm
Dy	4.1	6.2	7.6	2.6	4.5	12.3	0.381	ppm
Ho	3.5	5.3	6.9	2.2	4.2	11.6	0.0851	ppm
Er	3.4	5.1	6.3	2.2	4.3	11.4	0.249	ppm
Tm	3.7	5.3	7.0	2.5	4.8	11.4	0.0356	ppm
Yb	3.6	4.8	6.5	2.4	4.8	11.4	0.248	ppm
Lu	3.7	5.0	6.6	2.1	5.0	11.4	0.0381	ppm
Eu/Eu*	0.75	0.59	0.64	0.61	0.54	0.65	1.00	---

Notes:

Chondrite-normalized values from selected rare earth element (REE) results (Table 4) by ICP-MS/ICP-OES analyses (Appendix A) for Shoo Fly Complex sandstone samples collected in the study area. The selected REE constituents are consistent with those used by McLennan (1989) and Girty, at al (1996a, 1996b).

The listed sample and PAAS values are plotted on Figure 48.

Included for comparison are chondrite-normalized values using post-Archean Australian shale (PAAS) averaged values reported by McLennan (1989, p. 172).

C-N factor = chondrite-normalization factors reported by McLennan (1989, p. 172).

Eu/Eu* = europium-anomaly values calculated following McLennan (1989, p. 176).

The average Eu/Eu* for the five Shoo Fly samples = 0.62.

ppm = parts-per-million.

Table 6. Provenance-Characterization Ratio Results

[1]Key Ratio/ **Sample**:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	Mean	Std. Dev. (S)	"ODUCC"	"MAu"	"MAd"
Al2O3/TiO2	12.08	13.88	17.50	19.33	10.27	15.25	4.02	~18 to ~24	<14/17-50	nsd
Th/Sc	1.5	1.39	1.30	1.26	2.36	1.56	0.46	~1.0	~1.0 - <0.01	nsd
La/Sm	4.57	4.03	4.22	4.68	4.31	4.36	0.26	4.2	<4.2	nsd
Eu/Eu*	0.75	0.59	0.64	0.61	0.54	0.63	0.08	~0.6 to 1.1	none	neg. anom.
Th/U	7.14	6.51	5.63	6.70	8.08	6.81	0.90	>3.8	<~3.0	nsd
CIA	63.9	69.4	72.2	72.8	76.2	70.90	4.60	---	---	---

Notes:

Provenance-characterization ratio results calculated for the Shoo Fly Complex sandstone samples collected in the study area using the XRF (Al2O3 and TiO2) and REE data listed, respectively, in Tables 3 and 4. Except for La/Sm and Eu/Eu*, the REE values used here are non-normalized. The Eu/Eu* values are those listed in Table 5.

CIA ("Chemical Index of Alteration"); per Taylor and McLennan (1985, p. 13) and McLennan (1993, p. 297; pers. comm., 2015).

[1]These ratios are discussed by Girty et al. (1996b, p. 7).

ODUCC = "Old Differentiated Upper Continental Crust." "MAu" = "Magmatic Arc undifferentiated." "MAd = Magmatic Arc differentiated."

For the listed MAu Al2O3/TiO2 values, the <14 (approx.) applies to basaltic sources, whereas the 17 to 50 (approx.) applies to andesitic through rhyolitic sources, or the plutonic equivalents, depending on which igneous rock type dominates in the provenance. These ranges and values are per McLennan (1989, p. 297) and/or Girty et al. (1996b).

"S" = Standard deviation ("sample")
"neg. anom." = Negative Eu/Eu* anomaly
"nsd" = No significant difference between MAd and MAu

Table 7. "Weight-Percent" Component Results Calculated for Shoo Fly Complex Sandstone Samples

Parameter / **Sample:**	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	Mean
Qt	72 (72.3)	87 (87.1)	97 (97.3)	98 (98.3)	92.5	89
F	28 (27.7)	2 (1.5)	3 (2.7)	1 (0.9)	7.5	8
L	0	11 (11.4)	0	1 (0.9)	0	6
total	100	100	100	100	100	103
ICV	1.05	1.04	0.98	0.96	1.25	---

Notes:

Qt = total quartz.
F = feldspar
L = lithics (rock fragments)

The listed samples were point-counted for constituent modal-percent data (Table 2a). The resulting data were used to derive the results listed in this table using the procedures of Cox and Lowe (1966). The plots of these data are shown on the provenance discrimination diagram of Dickinson (1985, p. 340). The values in parentheses are calculated using the approach of Cox and Lowe (1996). These values were rounded to those outside the parentheses in order to be able to plot them on the discrimination diagram shown on Figure 49.

ICV = "Index of Compositional Variability" (Cox et al., 1995; Cox and Lowe, 1996, p. 552) and is calculated as follows, using the LOI-adjusted major-oxide data by XRF analysis listed in Table 3:

$$(Fe2O3 + K2O + Na2O + CaO + MgO + MnO + TiO2)/Al2O3$$

ICV values less than 0.5 imply "large-scale mass transfer of material during the creation of the pseudomatrix" and render invalid the use of the provenance analysis approach of Cox and Lowe.

The use of mean values in point-count analyses and QFL plots is consistent with other workers (e.g., Girty and Wardlaw, 1985; and Girty and Pardini, 1987), but is contrary to the recommendation by Cox and Lowe (1996, p. 556) to use median values, especially with limited datasets. However, with this dataset, adjustments to the values are needed (i.e., totaling 100) in order to make them useable for plotting on the discrimination diagram (Figure 49).

Table 8. **Calculated Results Using the Two "High-Silica" Discriminant-Function Equations of Verma and Armstrong-Altrin**

Parameter / **Sample:**	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	Mean
Multi-dem DF1 equation	-1.63	-1.14	-0.57	-1.24	-0.99	-0.985
Multi-dem DF2 equation	-0.63	-0.14	0.93	0.32	0.63	0.222
(SiO2)adj	89.79	79.28	75.33	92.21	89.16	---

Notes:

The Verma and Armstrong-Altrin (2013, p. 126) Discriminant-function equations are as follows:

DF1(Arc–Rift–Col)$_{m1}$ = (−0.263 x ln(TiO_2/SiO_2)adj) + (0.604 x ln(Al_2O_3/SiO_2)adj) + (−1.725 x ln(Fe2O^t_3/SiO_2)adj) + (0.660 x ln(MnO/SiO_2)adj) + (2.191 x ln(MgO/SiO_2)adj) + (0.144 x ln(CaO/SiO_2)adj) + (−1.304 x ln(Na_2O/SiO_2)adj) + (0.054 x ln(K_2O/SiO_2)adj) + (−0.330 x ln(P_2O_5/SiO_2)adj) + 1.588

DF2(Arc–Rift–Col)$_{m1}$ = (−1.196 x ln(TiO_2/SiO_2)adj) + (1.064 x ln(Al_2O_3/SiO_2)adj) + (0.303 x ln($Fe_2O^t_3/SiO_2$)adj) + (0.436 x ln(MnO/SiO_2)adj) + (0.838 x ln(MgO/SiO_2)adj) + (−0.407 x ln(CaO/SiO_2)adj) + (1.021 x ln(Na_2O/SiO_2)adj) + (−1.706 x ln(K_2O/SiO_2)adj) + (−0.126 x ln(P_2O_5/SiO_2)adj) − 1.068

These values are plotted on the Verma and Armstrong-Altrin (2013) discriminant-function multi-dimensional diagram (Figure 8) for "high-silica" clastic sediments. "High-silica" is defined as (SiO2)adj = 63% – 95%.

"adj" = volatile-free adjustments per Table 9.

Table 9. **Major-oxide Values After Volatile-Free Adjustments**

Parameter / **Sample:**	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**
SiO_2	89.79	79.28	75.33	92.21	89.16
Al_2O_3	4.36	9.06	11.22	3.49	4.25
$Fe2O^t_3$	1.84	4.39	5.28	1.66	3.01
MgO	0.55	1.32	1.60	0.46	0.88
CaO	0.27	0.34	0.12	0.06	0.08
Na_2O	0.75	1.14	1.31	0.41	0.46
K_2O	0.80	1.59	1.99	0.58	0.48
TiO_2	0.36	0.65	0.64	0.18	0.41
MnO	0.00	0.02	0.05	0.00	0.01
P_2O_5	0.05	0.09	0.08	0.05	0.04
total	98.8	97.9	97.6	99.1	98.8

Notes:

The “adjustment” of these 10 major elements is to 100 weight percent, “with the prior conversion of Fe concentration (FeO or Fe_2O_3) as $Fe_2O^t_3$ (total Fe) from appropriate atomic or molecular weights...” (Verma and Armstrong-Altrin, 2013). These values were then used in the discriminant-function equations to derive the values in Table 8.

Where the original major oxide values from the XRF analyses were reported by the laboratory less than the respective reporting limits, they were set to the reporting limits for use in the above calculations.

IX. FIGURES

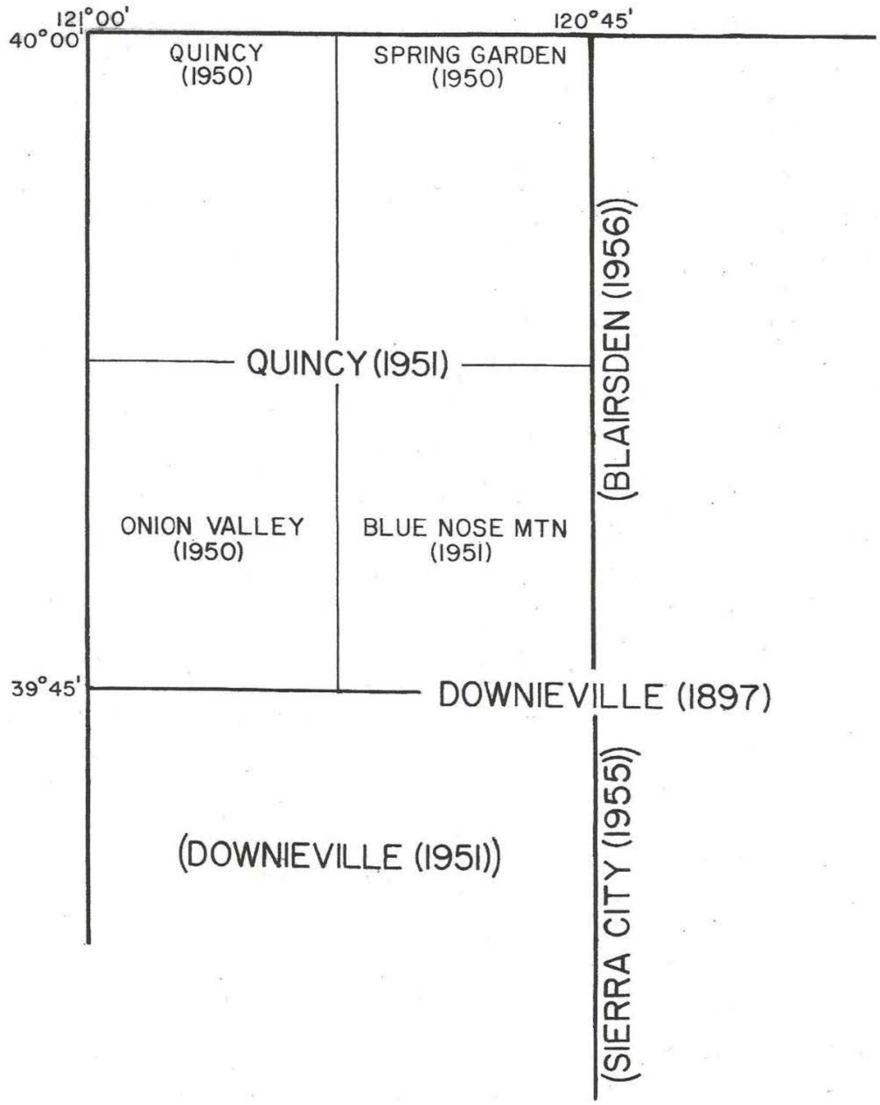


Figure 1. Index map of pertinent topographic quadrangles.

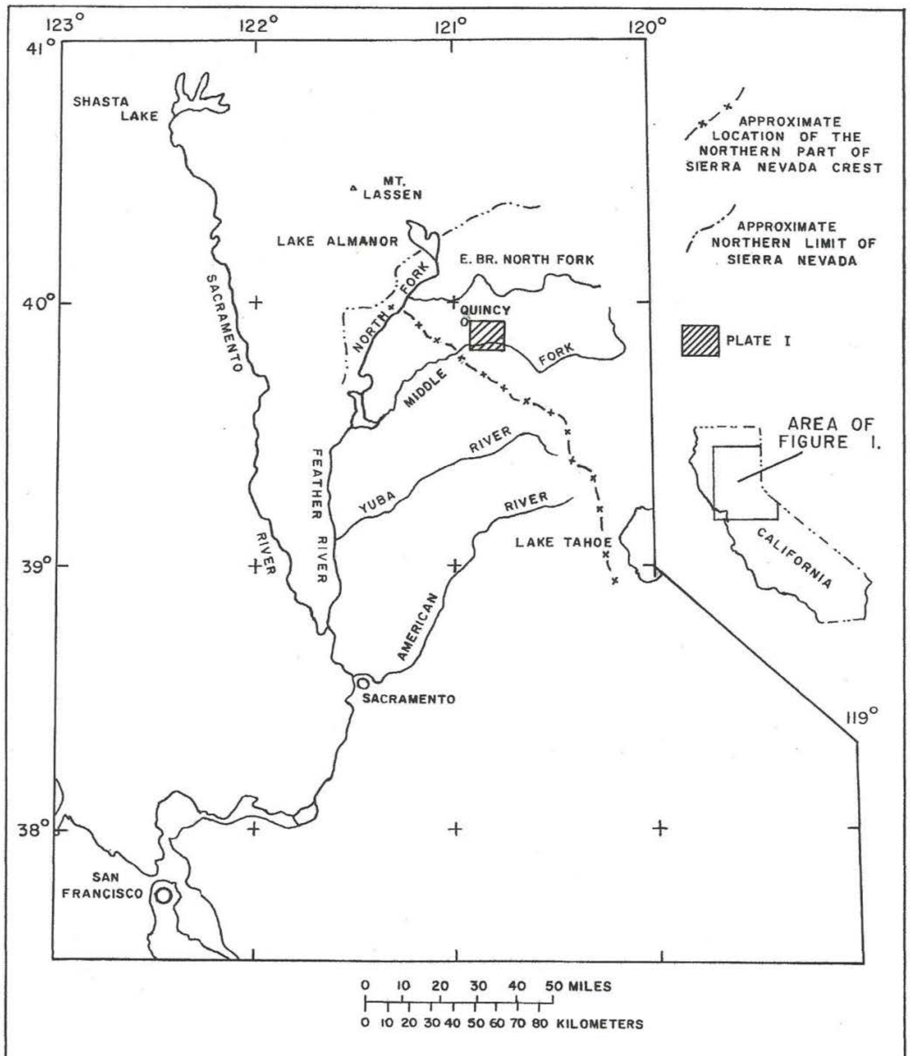


Figure 2. Index map showing the location of the study area in northern California (modified from Hietanen, 1976).

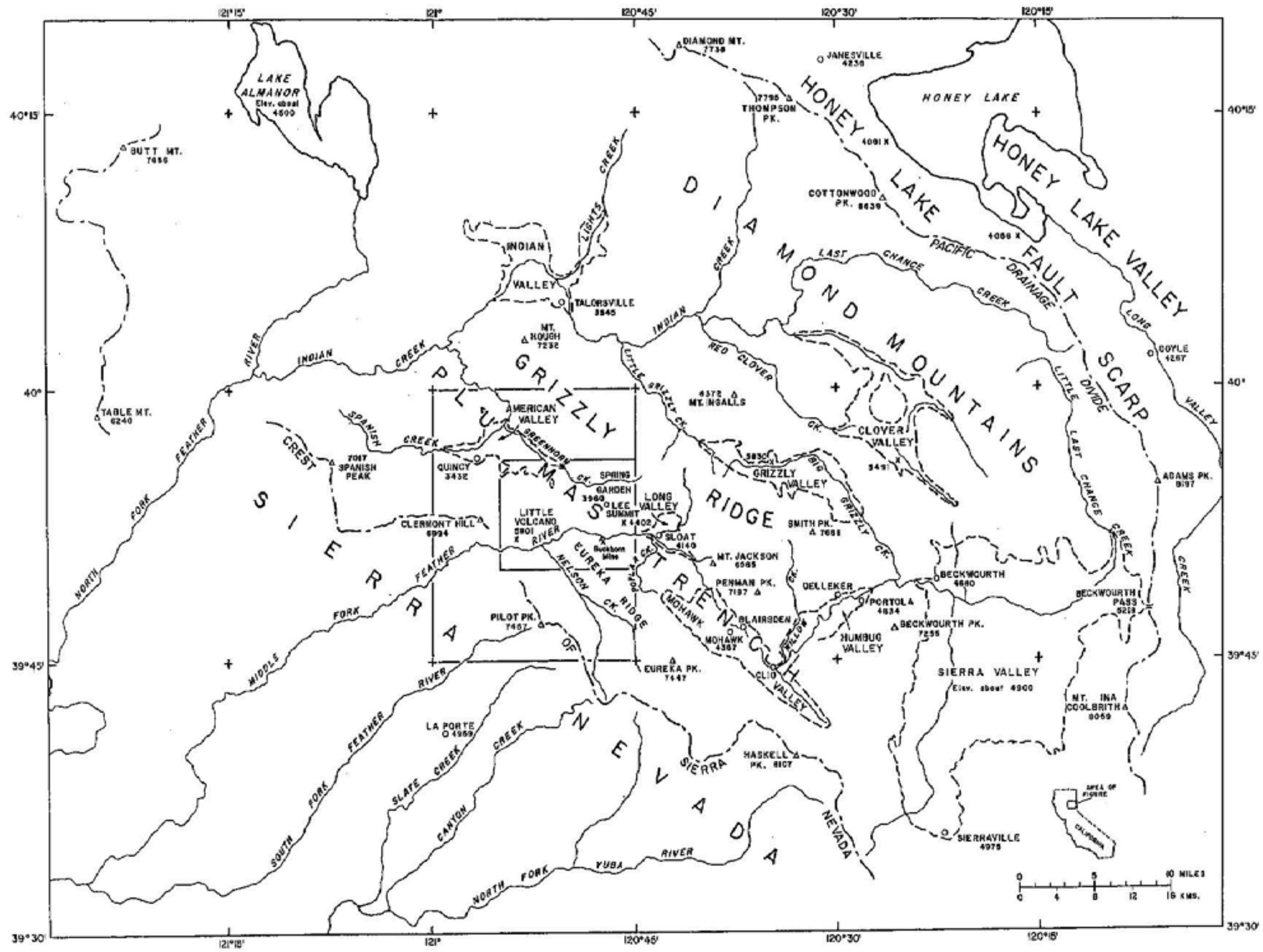


Figure **3**. Index map of the northern Sierra Nevada and adjacent regions, showing the Quincy 15' quadrangle and the enclosed outline of this report's geologic map (Plate I). Modified from Durrell (1959a).

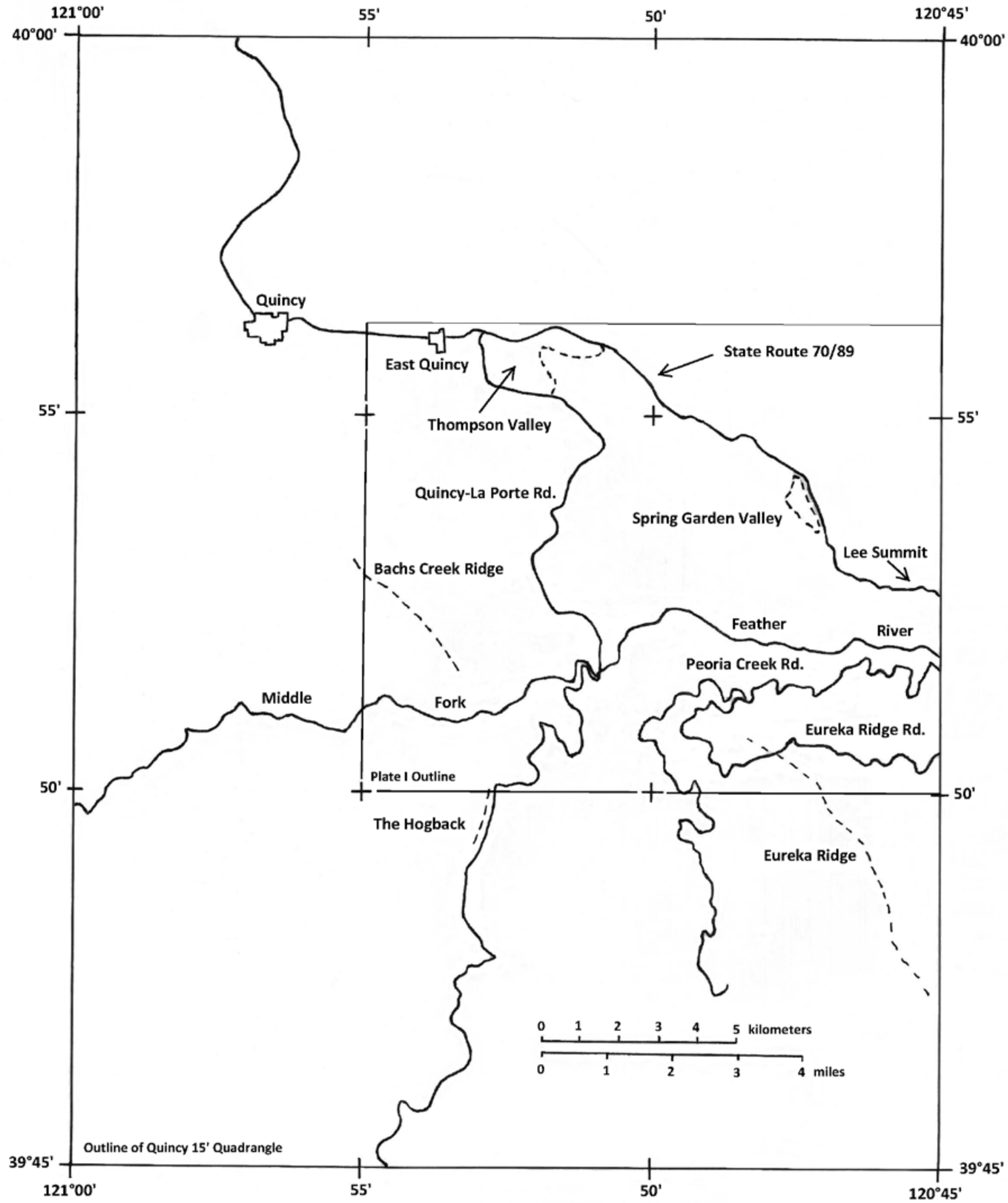


Figure 4. Main access routes across Plate I.

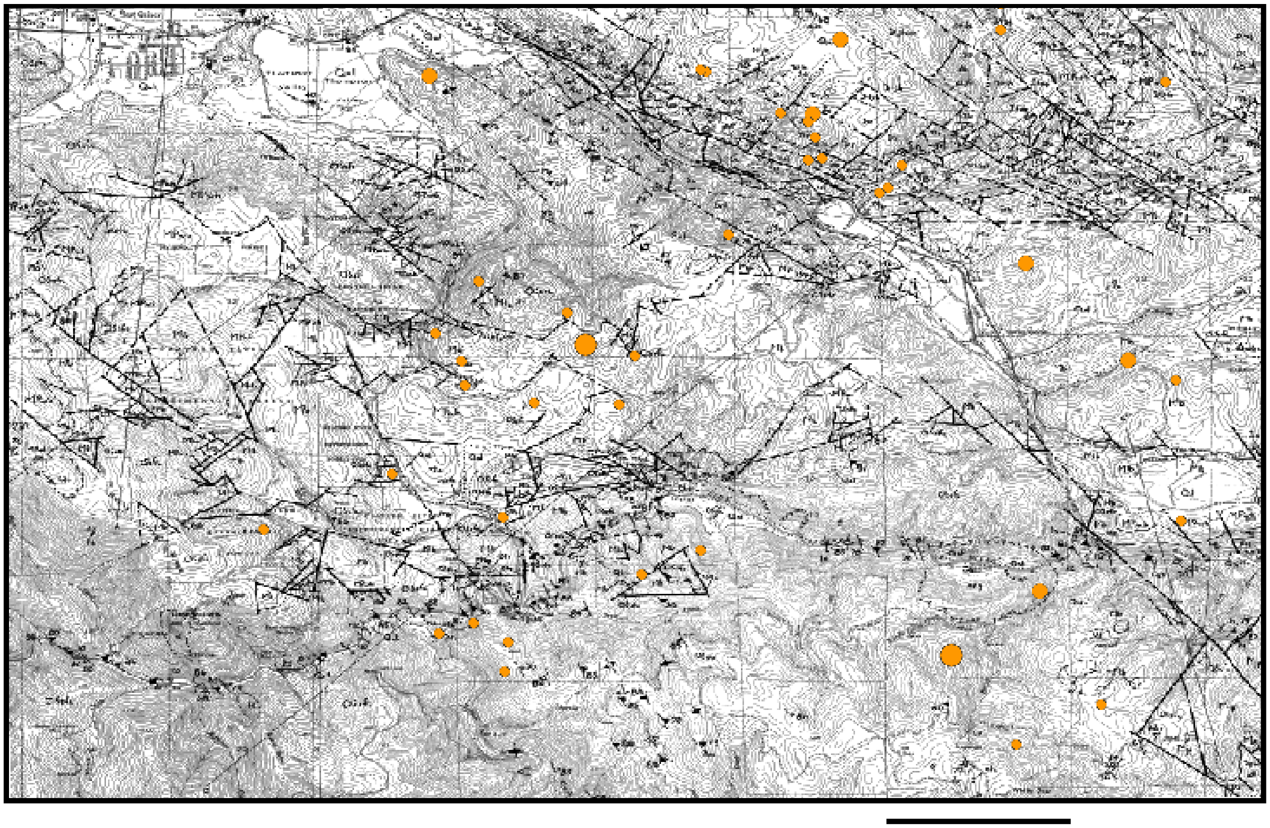


Figure 5. Earthquake epicenters superimposed on this study's geologic map (Plate I). The data for these locations were downloaded from the Northern California Earthquake Data Center (U. C. Berkeley Seismological Laboratory), then displayed using "Google Earth" and "ArcGIS" for this overlay. The Data Center input catalog is the corrected, "Double-Difference Catalog (1984 to Present)." The search criteria included events between January 1984 and August 2015, magnitudes between 0 and 8, depths between 0 and 50 km, and the map's corner coordinates. The search resulted in epicenters with event magnitudes ranging from 1.2 to 3.1. The depths for all the displayed events are less than 35 km (~22 miles). The sizes of the orange dots represent the range of magnitudes.

AGE	FORMATION	SYMBOL	THICKNESS (meters)	DESCRIPTION
Quaternary	Alluvium	Q	?	Valley alluvium and stream deposits (Qal); alluvial fan (Qaf); landslide deposits (Qls); talus (Qt); stream terrace (Qst); glacial lake deposits of extinct Long Valley Lake (Qll).
Miocene-Pliocene	Warner basalt & Warner intrusive	MPwb & MPwi	6 - 189	MPwb: light-grey olivine basalt, with distinctive platy jointing; deep red-brown soil. MPwi: light-grey trachytic olivine basalt, typically associated with faults; forms columnar-jointed plug on Bachs Creek Ridge.
Mid- to Late Miocene	Tertiary intrusive andesite	Tia	?	Tia: hornblende pyroxene andesite dike complex; weathers pastel pink, brown and yellow; single occurrence mapped on Plate I.
	Penman	Mp	12 - 104	Mp: volcanic breccia, fanglomerate, agglomerate, or fluvial conglomerate and sandstone; clasts include hornblende-poor andesite, brown basalt (Lovejoy?), granitics, Shoo Fly, and Sierra Buttes Formation. D'Allura's map symbol is "Pp."
Mid-Miocene	Bonta & Bonta gravels	Mb & Mbg	6 - 200+	Mb: heterolithic andesitic volcanic conglomerate, mudflow breccia, agglomerate, sand lenses, and tuffaceous sands; contains exotic clasts; dark to light red-brown soil contains crystal debris; some dark-grey to black craggy outcrops. Mbg: well-rounded to angular cobble conglomerates, (river channel deposits); clasts include Shoo Fly, vein quartz, quartz diorite, and chert; most deposits were mined for gold.
Mid-Miocene	Ingalls	Mi	73+	Mi: dark brown to black, craggy, volcanic conglomerate to volcanic breccia. Durrell's map symbol is "Øi."
Mid-Miocene	Lovejoy basalt	Mlb	6 - 73	Mlb: dark-grey to black olivine pyroxene basalt; occasionally weakly trachytic; distinctive irregular jointing and fractures produce blocky surfaces and talus; may contain quartz xenocrysts; occasionally vesicular to vuggy; deep chocolate-brown soil.
Late Devonian	Taylor	Dt	<30 - 365+	Dt: augite andesite breccia, tuff-breccia, tuff, subordinate flows, minor black tuffaceous slate, and crinoidal limestone. D'Allura divided the Taylor into the "Squirrel Creek" and "Johnson Hill" subunits.
Late Devonian	Elwell	De	30 - 60+	De: gray to black radiolarian chert, with streaks, lenses, and nodules of very fine-grained phosphate rock and locally present quartz keratophyre tuff. Durrell and D'Allura (1977) assigned the name Elwell and presumed the Devonian age based on the Dugan Pond fossils of Anderson et al. (1974).
Mid- to Late Devonian	Sierra Buttes	Ds	<30 - 400+	Ds: predominantly dacitic or rhyolitic intrusives, flows, breccia, and tuff, with minor chert, slate, argillite, and rare fossiliferous limestone.
Ordovician-Silurian	Shoo Fly Complex including sandstone, slate, chert, limestone, serpentinite, a quartz porphyry granite stock, meta-diabse, quartz porphyry dikes	OSsfc (ch) (ls) (us) (qpg) (md) (qpd)	>14,000 (structural thickness only) (base not seen)	OSsfc: lower-greenschist facies metamorphosed interfoliated (interbedded?) quartz-rich psammitic and pelitic rocks, with chert (ch); isoclinally folded; locally sheared; associated subordinate rocks include limestone (ls), serpentinite (us), metadiabase (md), a quartz porphyry granite stock (qpg), and quartz porphyry dikes (qpd). D'Allura divided the Shoo Fly in the Quincy area into the "Tollgate Creek" and "Spanish Creek" subunits.

Figure 6. Geologic column for the portion of the Quincy 15' quadrangle encompassed by Plate I. Also see D'Allura (1977) and Durrell (1959a, 1959b, 1987) for descriptions of the units mapped by them within Plate I. Not to scale.

Figure 7. Photograph of a depositional contact between the underlying Lovejoy basalt and overlying Bonta volcanic mudflow breccia. Based on observations made throughout the study area, the contact’s inclination is interpreted to be original. However, it remains possible that some rotation may be caused by block faulting in the area. The location of the photo is the road cut on the south side of the Quincy-La Porte Road in Section 33, T24N, R10E. For scale, the darker block of Lovejoy at lower right is approximately 0.3 meters (1 foot) wide.

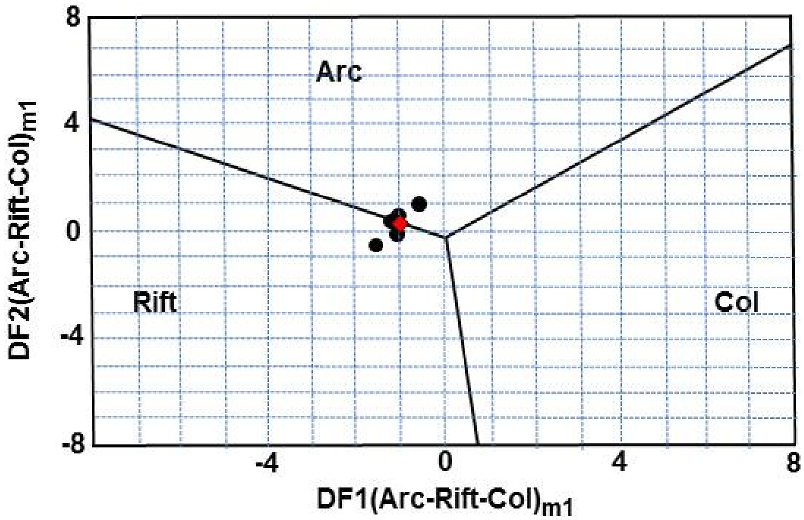
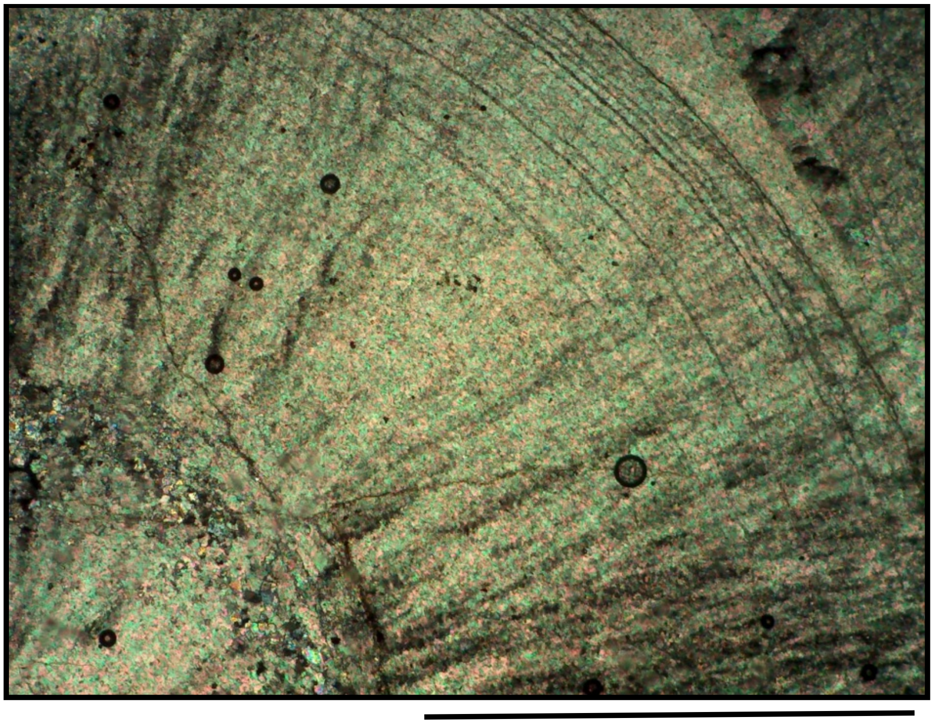


Figure 8. Discriminant-function multi-dimensional diagram of Verma and Armstrong-Altrin (2013) for "high-silica" clastic sediments showing plots of calculated values listed in Table 8 that were derived using XRF analytical results from the Shoo Fly Complex quartzose sandstone samples collected for this thesis. The "DF1" and "DF2" discriminant functions are defined in Table 8. "Col" = collision tectonic setting. "Rift" = continental rift tectonic setting. The diamond-shape symbol (red) represents the mean of the dataset.

Figures 9a and 9b. Photographs of an area underlain by serpentinite in the southwest quarter of Section 17, T23N, R11E. Both images are toward the west. Top image shows the typically sparse vegetation developed on the exposure. Bottom image is a close-up of the exposed material, with hammer for scale, taken in the background of the area shown in the top image, near the treeline.

Figures 10a and 10b. Photographs of metadiabase exposed near the southeast corner of Section 18, T23N, R11E. Top image is toward the northeast. Bottom image is the block shown in the foreground of the top photograph, with hammer for scale. Also see Figures 27a and 27b; photomicrographs of a sample collected from this block.

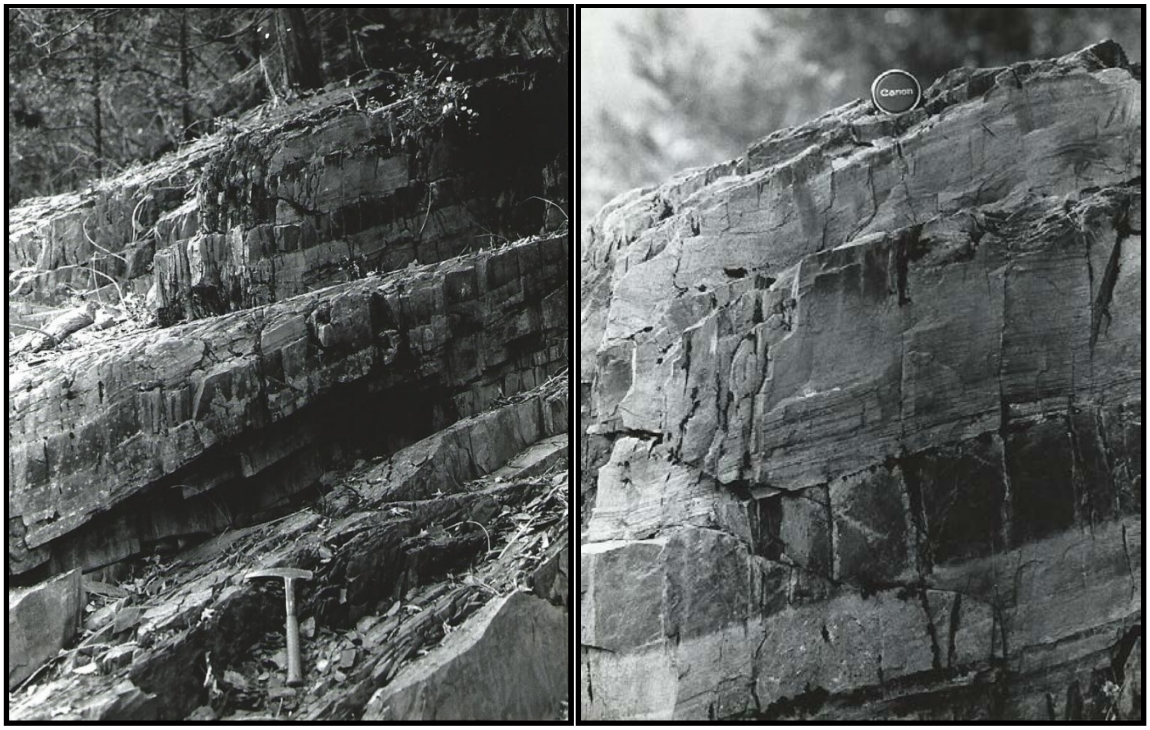


Scale bar = 0.8 mm

Figure 11. Photomicrograph (x-nicols) of an oolite, with successive growth rims, in a sample from the large dolomitic limestone block (Plate I) in the Shoo Fly at Little Volcano-Limestone Point (Section 17, T23N, R10E). The lack of deformation of the oolite is characteristic of the limestone (also see Standlee, 1978, p. 99-102; Varga, 1980, p. 111-113) and supports the interpretation that the block is an olistostrome.

Figures 12a and 12b. Photographs of Shoo Fly siltstone showing bedding laminations interpreted to represent the “Td” (“upper parallel laminae”) subdivision of the “Bouma Sequence” (Bouma, 1962). The photographs were taken on the north side of the Middle Fork of the Feather River; near the southwest corner of Section 7, T23N, R11E. The laminations are parallel to the northwest-striking, steeply east-dipping to vertical cleavage shown in the adjacent grey slate in the top photo. The sedimentary facing is interpreted to be to the east. Pencil for scale. Such evidence was very rarely observed; found at only two other locations (Figures 13, 14a, and 14b). A photomicrograph of a sample collected from this outcrop is shown on Figure 23.

Figure 13. Photograph of graded bedding in Shoo Fly metamorphosed siltstone. The siltstone is weathered to a reddish-orange which grades into a greenish-grey commensurate with the decrease in grain size. The bedding faces east and is overturned to the west; the siltstone strikes N30W and dips 70 degrees west. The photograph is toward the northwest and was taken at the south edge of the Middle Fork of the Feather River; in the southwest quarter of Section 7, T23N, R11E (Plate I). Such evidence was very rarely observed; found at only two other locations (Figures 12a, 12b, 14a, and 14b). Hammer in lower right for scale.



Figures 14a and 14b. Photographs of graded bedding in Shoo Fly metamorphosed interbedded siltstone and shale. The bedding shown in the right-hand photo is a close-up of the upper portion shown in the left-hand photo and is interpreted to represent a partial (“Ta”-absent) “Bouma Sequence” (Bouma, 1962), with the shale overlain by “Tb” and “Tc” subdivisions (note the wavy laminations at top). The photographs are looking west and were taken at the north edge of the Middle Fork of the Feather River; in the southeast quarter of Section 12, T23N, R10E. The beds strike N84W and dip 16 degrees south; parallel to the plunge of a small syncline that they define (Plate I). The fold contains an axial-plane cleavage that strikes N6W and dips 88 degrees west. Such evidence was very rarely observed; found at only two other locations (Figures 12a, 12b, and 13). Hammer and lens cap for scales.

Figure 15. Photograph of Shoo Fly rocks, with lensoid, grey-white chert in greenish-grey slate. Photograph is looking southeast and was taken on south side of the Middle Fork of the Feather River; near the southeast corner of Section 8, T23N, R11E. The cleavage in slate strikes northwest and is near vertical to vertical. Hammer at center for scale.

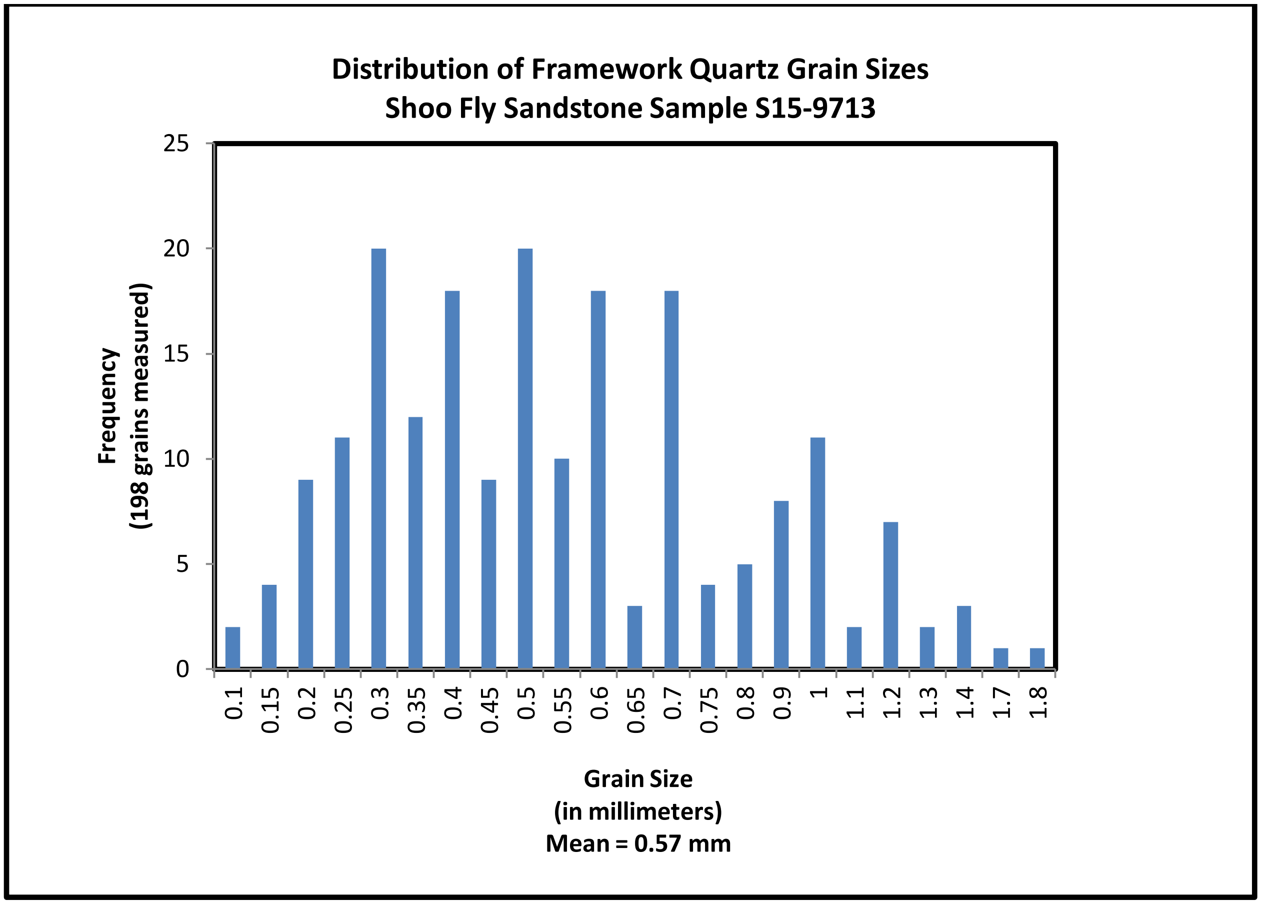


Figure 16. Grain-size distribution histogram of framework quartz in Shoo Fly quartzose sandstone sample S15-9713. The mode of these values is 0.30 mm. This pattern suggests that the distribution of grain sizes may be bi-modal, but is not conclusive. However, thin sections of the sandstones indicate that such a distribution is typical of the samples collected for this thesis. Similar findings were reported for the quartzose sandstones examined by DeVay (1981, p. 7).

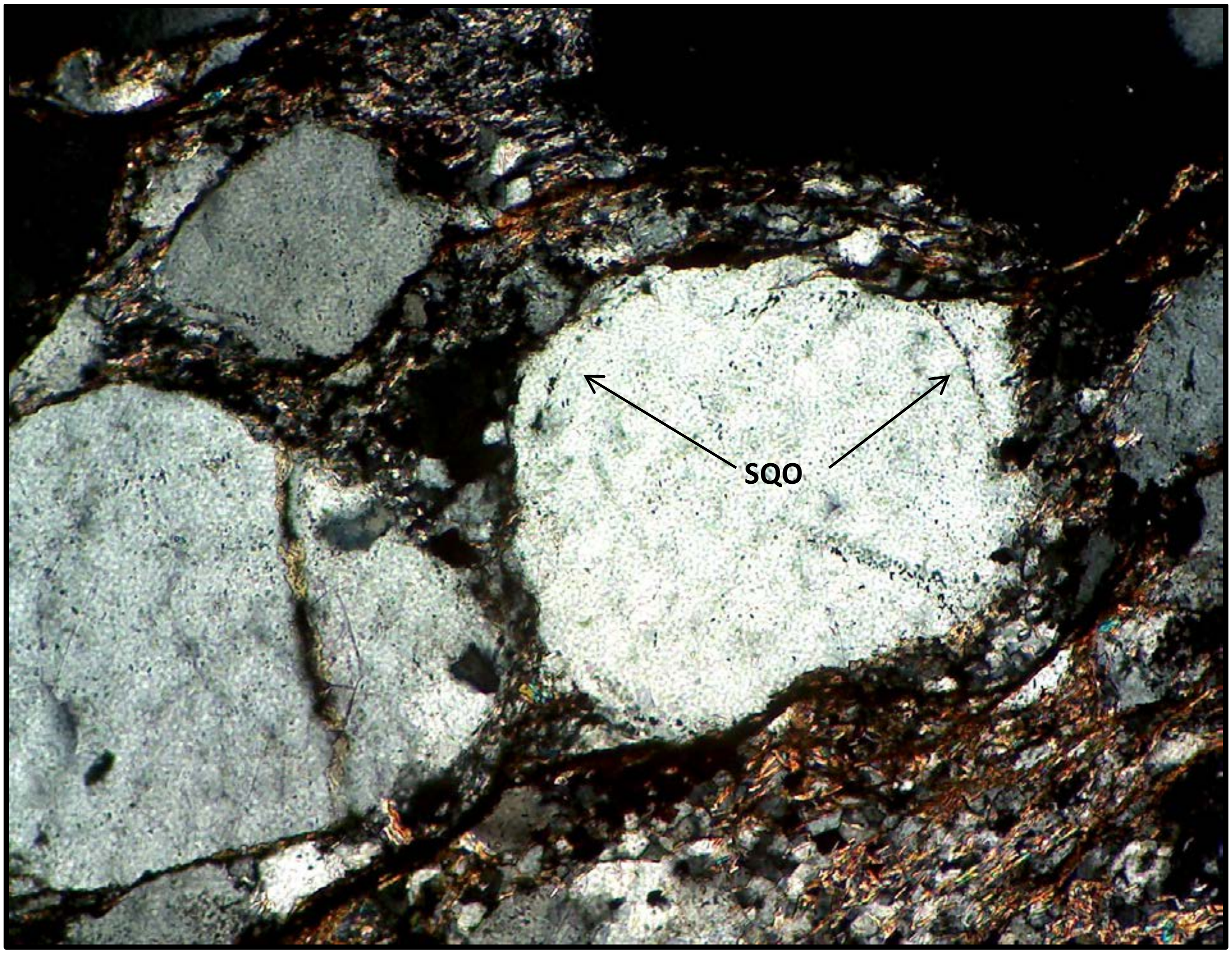


Figure 17. Photomicrograph (x-nicols) of Shoo Fly sandstone showing sub-rounded quartz framework grain with rare syntaxial quartz overgrowth (SQO). Foliation in this sample is mainly defined by the orientation of the quartz-phyllosilicate matrix. The quartz grain with the overgrowth is approximately 0.5mm wide.

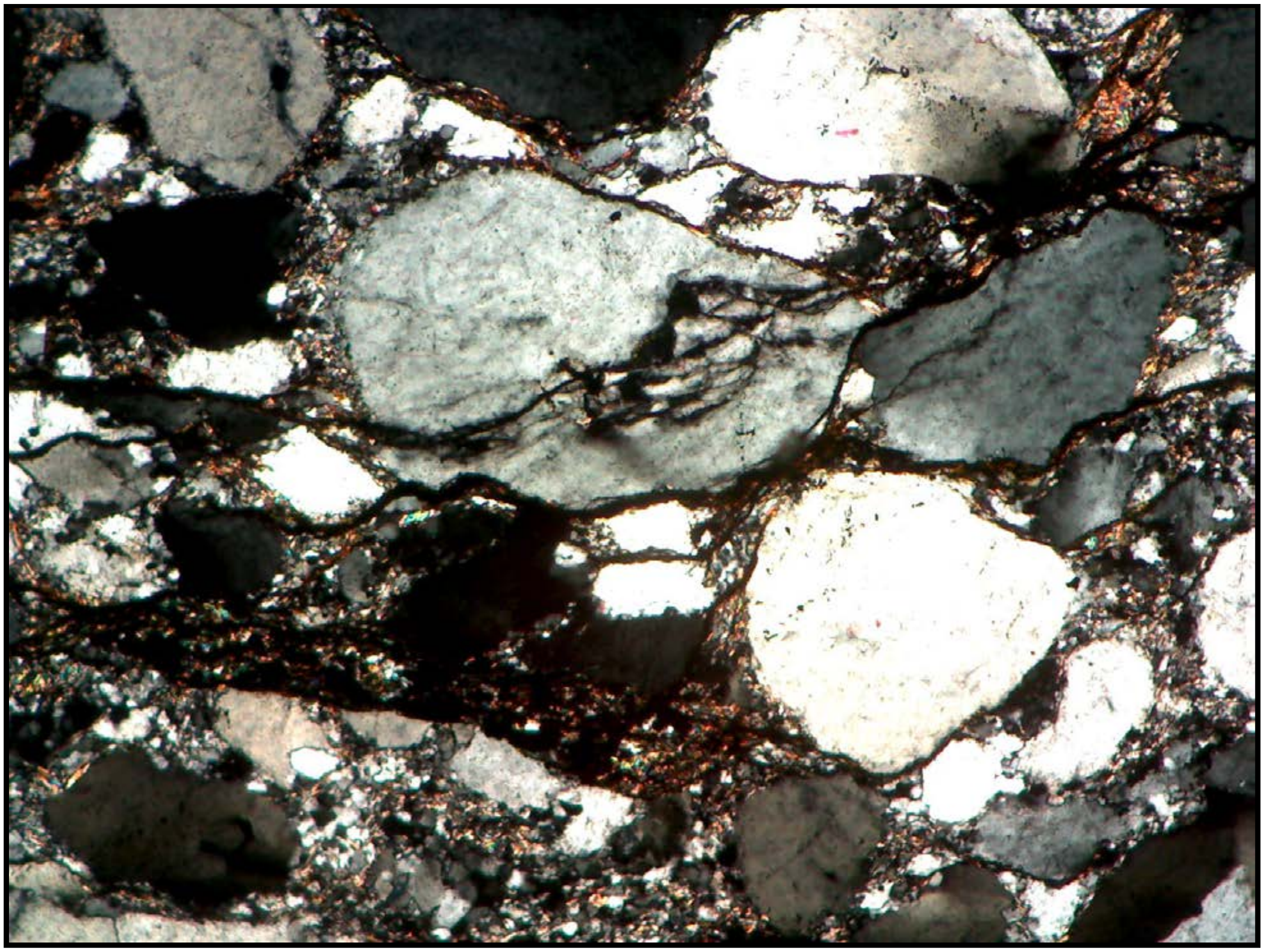
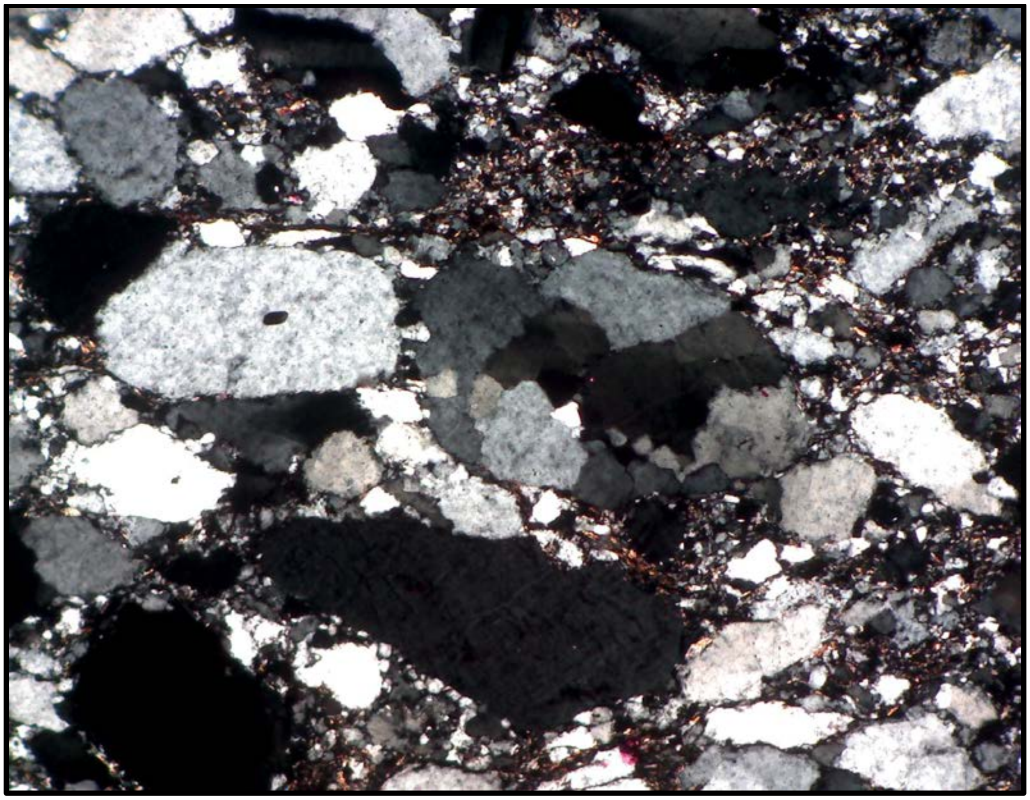


Figure 18. Photomicrograph of Shoo Fly sandstone (x-nicols) showing quartz grains deformed by shearing, with induced fracture oriented sub-parallel to foliation. The image shows the development of sub-grains within the larger grain's (top center of image) fracture zone or "deformation band" (DeVay, 1981). Also note that the adjacent smaller quartz grain to the right exhibits similar fracturing and incipient development of sub-grains near the contact with the larger grain. The larger deformed grain is approximately 1mm long.



Scale bar = 1 mm.

Figure 19. Photomicrograph (x-nicols) of typical Shoo Fly sandstone showing sub-angular to sub-rounded quartz framework grains oriented parallel and sub-parallel to foliation. The image also shows the apparent bi-modal size distribution that is common to the Shoo Fly sandstones and the mix of monocrystalline and polycrystalline grains.

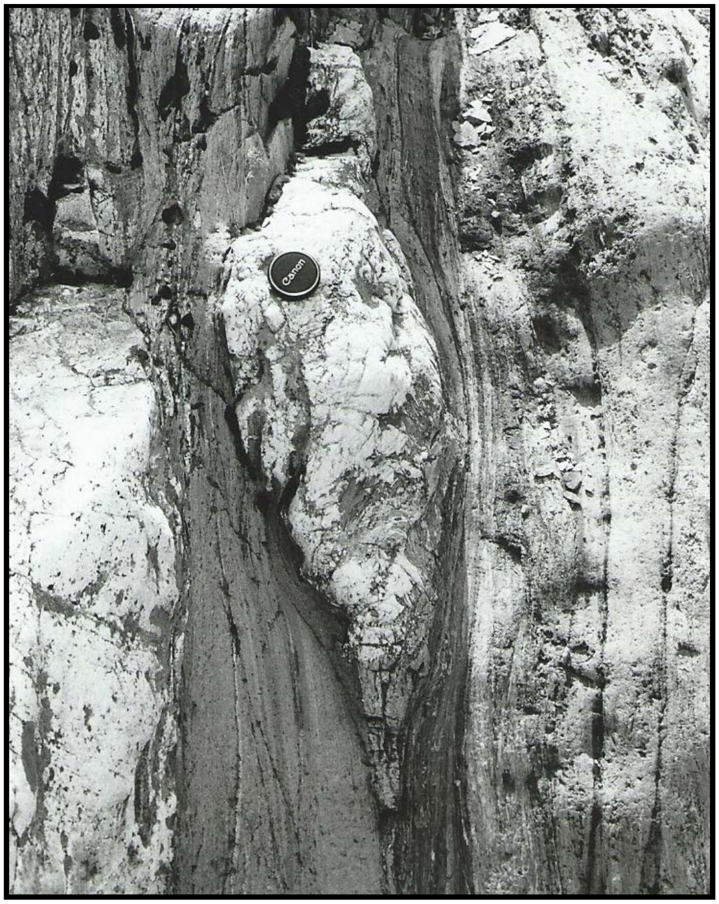
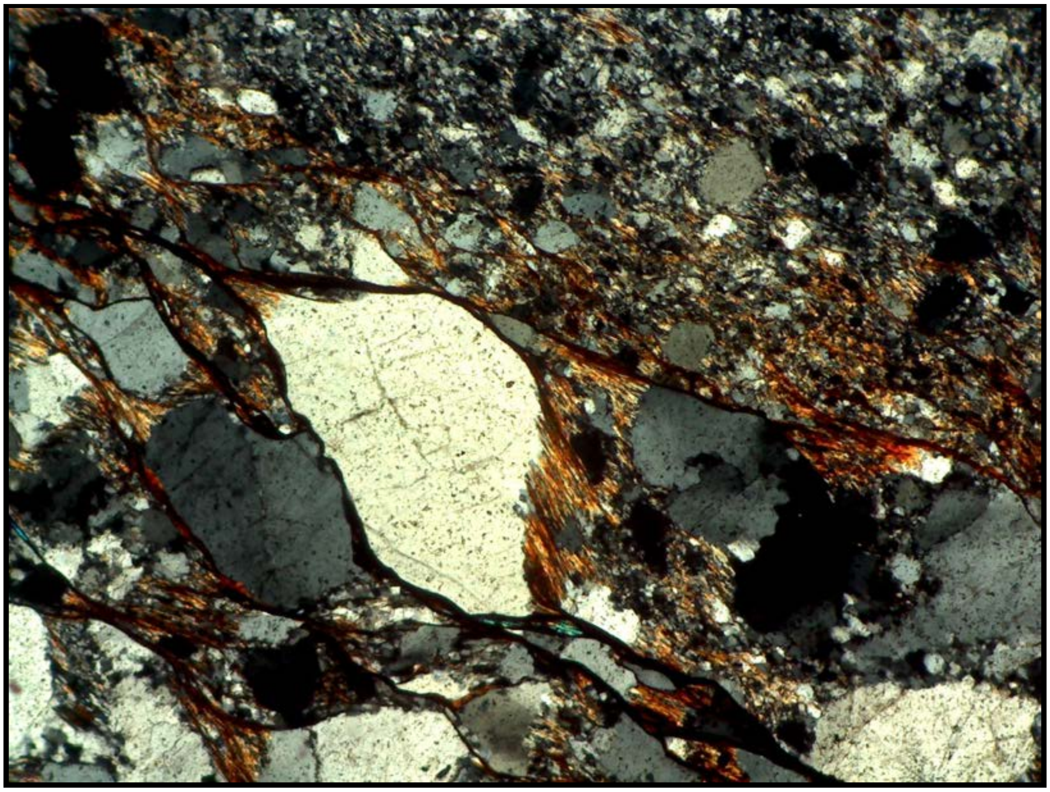
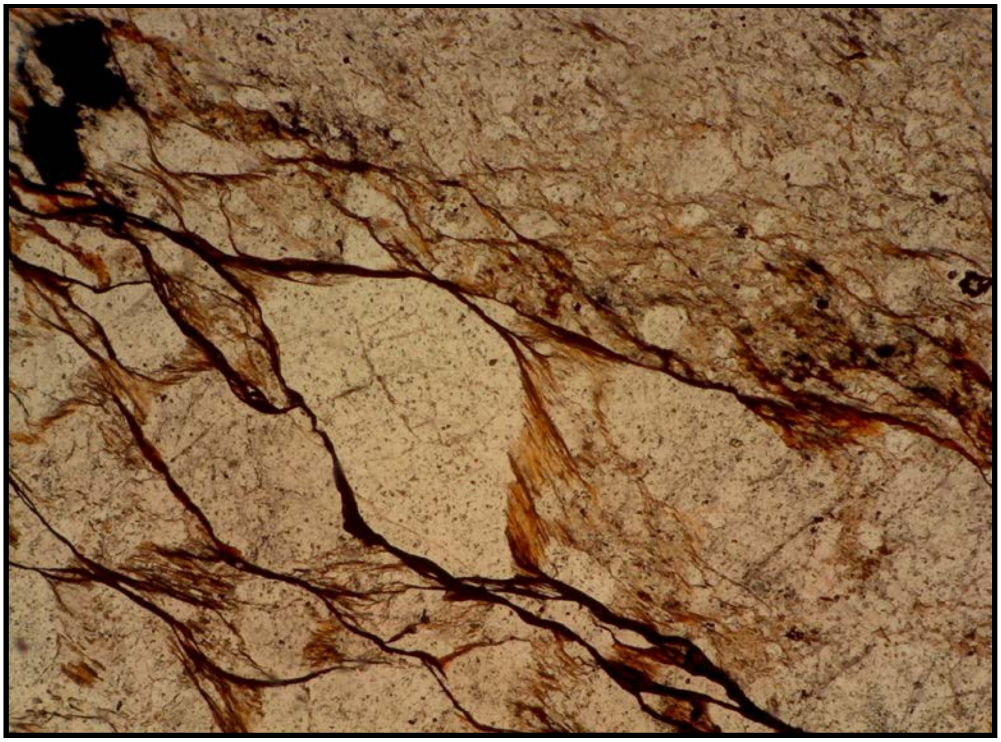


Figure 20. Photograph of white chert phacoid set in greenish-grey pyritiferous slate; located on the north side of the Middle Fork in the southeast quarter Section 17, T23N, R10E (Plate I). The image shows (a) the three predominant Shoo Fly rock types, sandstone (on the right), slate, and chert; (b) the ductility contrasts between the three rock types; and (c) transposition of bedding discussed by Standlee (1978) and Varga (1980). The view is toward the northwest. The orientation of cleavage in this outcrop is N45W/80E. Lens cap for scale.



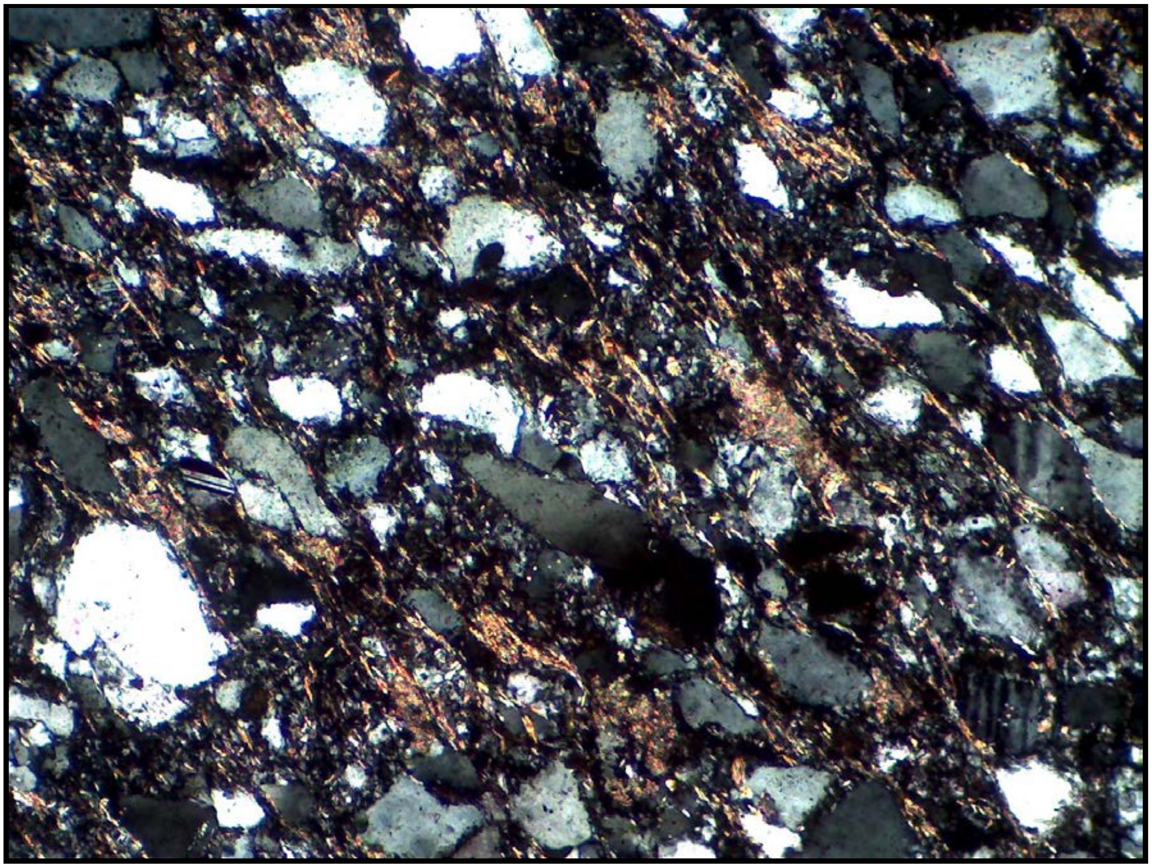
Scale bar = 1 mm.

Figure 21. Photomicrograph under x-nicols of Shoo Fly siltstone (upper left) juxtaposed against sandstone. The contact parallels foliation, partially defined by phyllosilicates, and may be tectonic (see Standlee, 1978, p. 19). A polycrystalline quartz grain in the sandstone, with extinct to partially-extinct sub-grains, is near the lower right-center.



Scale bar = 1 mm.

Figure 22. Same image as 21, but in plane-polarized light. The image also shows the development of “beards” or “trains” of matrix phyllosilicates and quartz in pressure shadows at the ends of and between quartz grains in response to deformation-induced pressure solution (DeVay, 1981).



Scale bar = 0.25 mm

Figure 23. Photomicrograph (x-nicols) of Shoo Fly feldspathic quartzose siltstone collected from the outcrop shown on Figures 12a and 12b. Foliation is shown mainly by the orientation of phyllosilicates in matrix; from upper left to lower right. The sample's fabric is consistent with the "well-developed phase 1 (S_1) rough cleavage" described by Gray (1978).

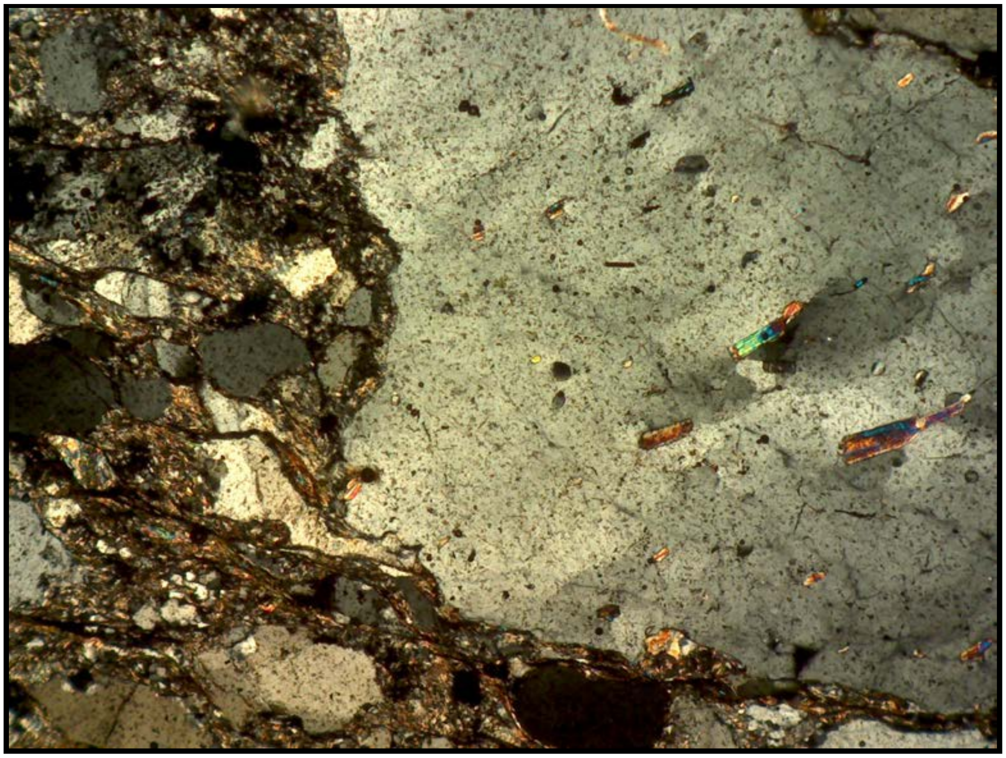


Figure 24. Photomicrograph (x-nicols) of Shoo Fly sandstone showing a comparatively large monocrystalline quartz grain with inclusions of white mica displaying a crude alignment within the grain. The sample was collected near the Quincy-La Porte Road bridge over the Middle Fork of the Feather River (Section 15, T23N, R10E). The maximum width of the large grain is 1.8 mm; measured parallel to the inclusion alignment.

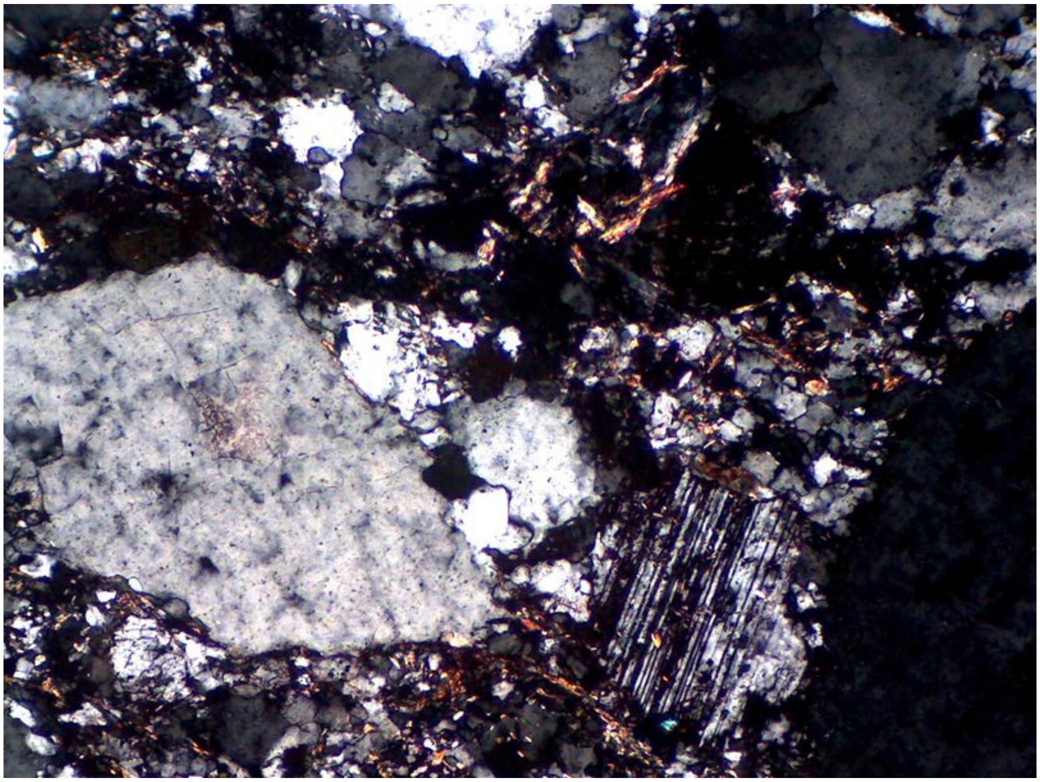
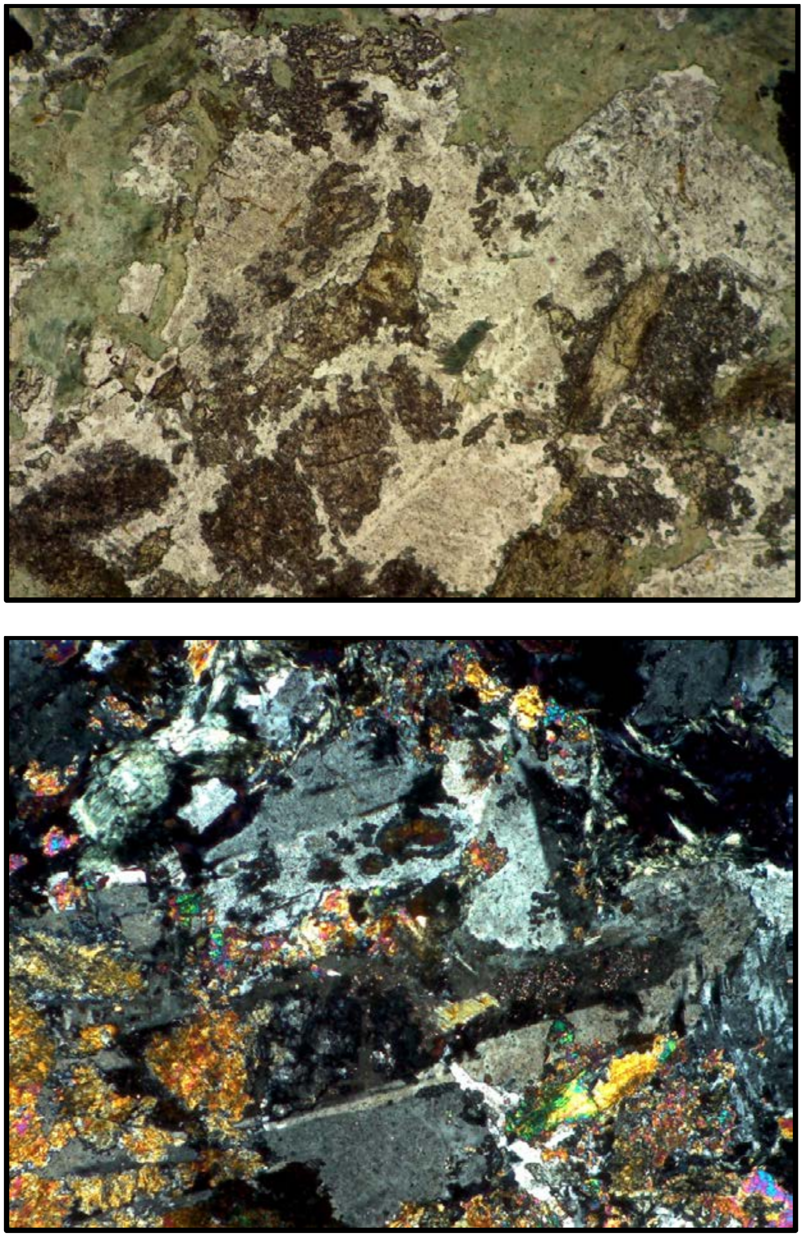


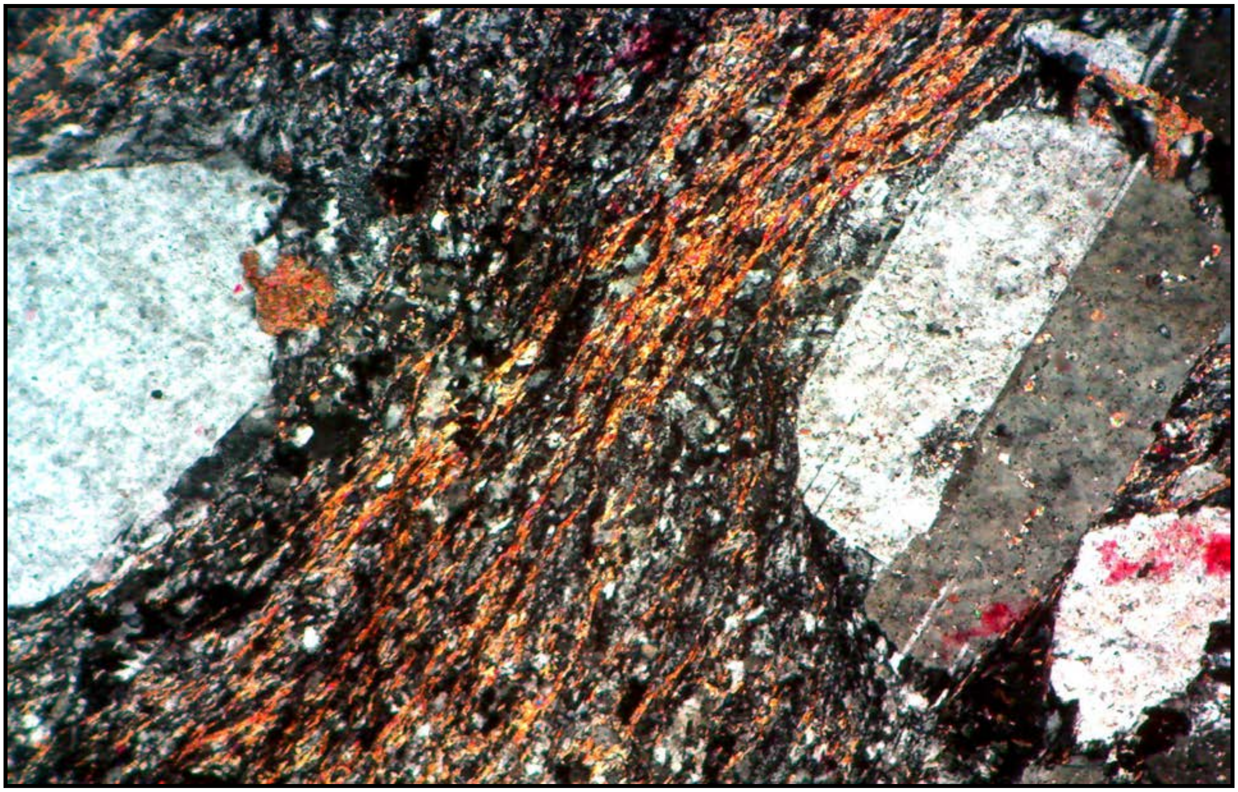
Figure 25. Photomicrograph (x-nicols) of Shoo Fly sandstone showing rare grain of twinned plagioclase feldspar, with quartz and quartz-phyllosilicate matrix. The larger subangular quartz grain to the left is approximately 0.5 mm long.

Figures 26a and 26b. Photographs of relatively massive outcrop of a quartz-feldspar porphyry dike within Shoo Fly slate (to right) exposed on the south side of the Middle Fork of the Feather River; near the southwest corner of Section 8, T23N, R11E. Despite the dike's massive appearance, thin section shows the rock is slightly foliated at the margin (see Figure 28). Images are toward the northwest. Geologist for scale.



Scale bar = 1 mm

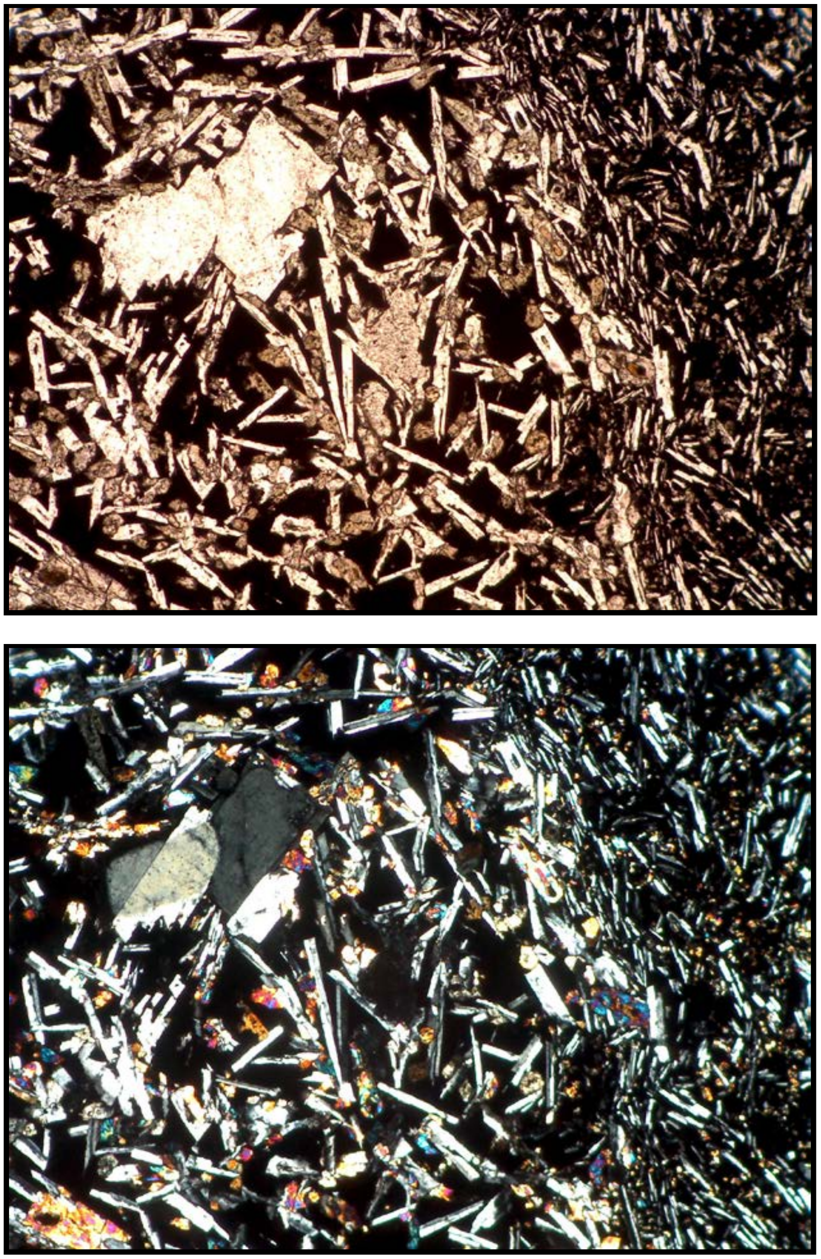
Figures 27a and 27b. Photomicrographs of metamorphosed diabase under, respectively, plane-polarized light (upper image) and x-nicols (lower image) showing relict hypidiomorphic-granular texture. The sample is from the block shown on Figure 10b. The minerals include altered plagioclase and pyroxene, epidote, and chlorite. The epidote appears to be the result of the saussuritization of the adjacent plagioclase. Iron oxide (possibly magnetite, ilmanite, or hematite) occurs elsewhere in the sample. The bottom image is rotated slightly clockwise compared to the upper image.



Scale bar = 0.7 mm

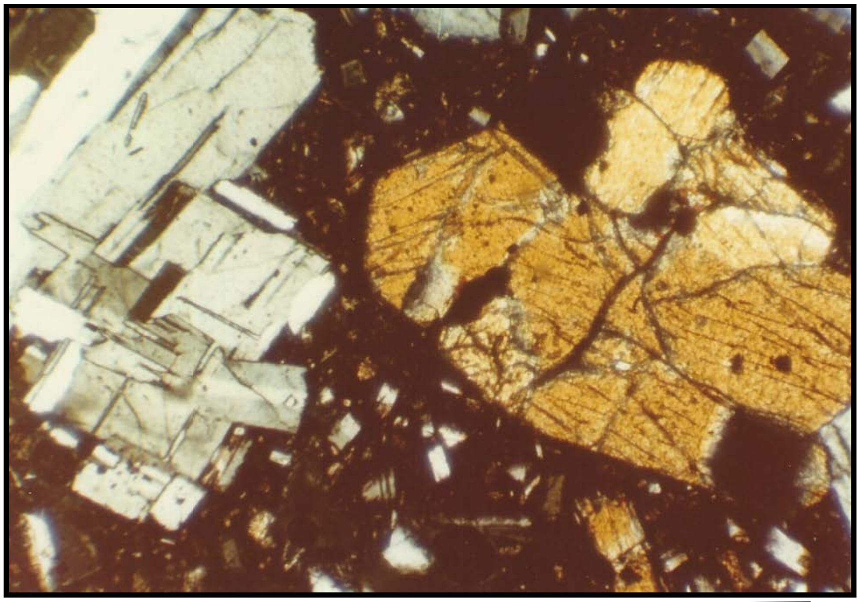
Figure 28. Photomicrograph under x-nicols of sample of foliated quartz-feldspar porphyry dike shown in Figures 26a and 26b. Foliation is shown mainly by the orientation of phyllosilicates in matrix; from upper right to lower left. Pinkish coloring in lower right is from staining for plagioclase. K-spar was not observed in the sample.

Figure 29. Close-up photograph of Middle Miocene Lovejoy basalt, showing distinctive jointing, fracturing, and weathering characteristics. This outcrop is located in the northeast quarter of Section 10, T23N, R10E (Plate I). Also see photomicrographs of Lovejoy basalt shown on Figures 30a and 30b. Lens cap for scale.



Scale bar = 0.74 mm

Figures 30a and 30b. Photomicrographs of Lovejoy basalt under plane-polarized light (upper) and crossed nicols (lower) showing a twinned plagioclase phenocryst, microlitic plagioclase, and intersertal pyroxene and olivine. The black areas are glass made opaque, possibly by finely-disseminated magnetite(?). The images show a textural contrast between relatively more chilled (trachytic right quarter of images) and less chilled portions. The sample is from the exposure adjacent to Highway 89 at Lee Summit (Section 6, T23N, R11E).



Scale bar = 0.45 mm

Figure 31. Photomicrograph (x-nicols) of Ingalls formation pyroxene andesite mudflow breccia (southwest quarter Section 9, T23N, R11E). Shown are phenocrysts of subhedral augite and euhedral, complexly-twined plagioclase set in a groundmass containing microlitic plagioclase, with subordinate augite, glass, and possibly magnetite(?).

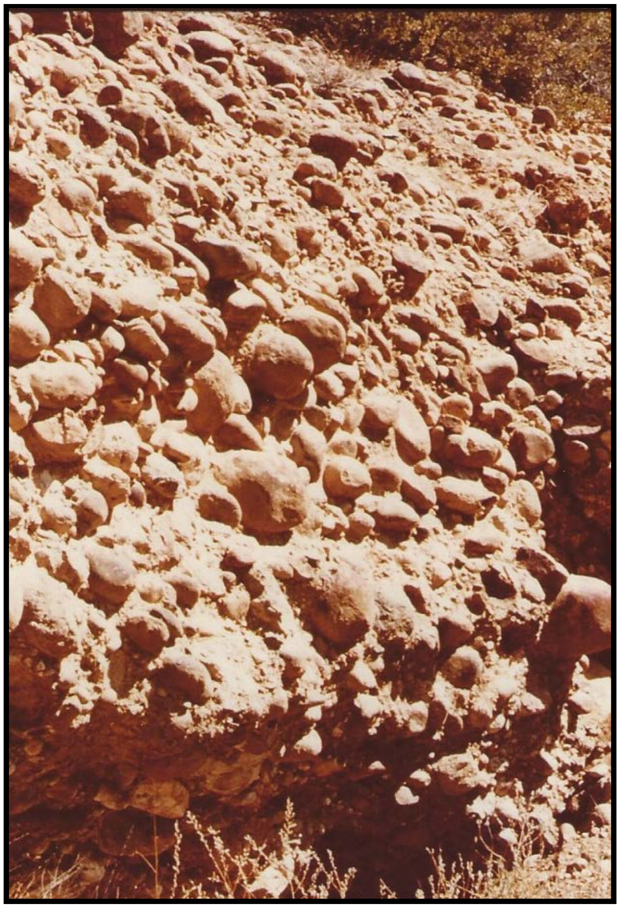


Figure 32. Close-up photograph of the Bonta gravels shown on Figure 33, located near the northwest corner of Section 15, T23N, R10E. The cavity at the base of the gravels, shown at the bottom of the image, is presumed to be a small adit. The gravels rest unconformably on the Shoo Fly Complex. A crude layering is somewhat apparent in this image. The rounded cobble partially exposed in the lower center of the image is approximately 0.3 meters (~1 foot) in diameter.

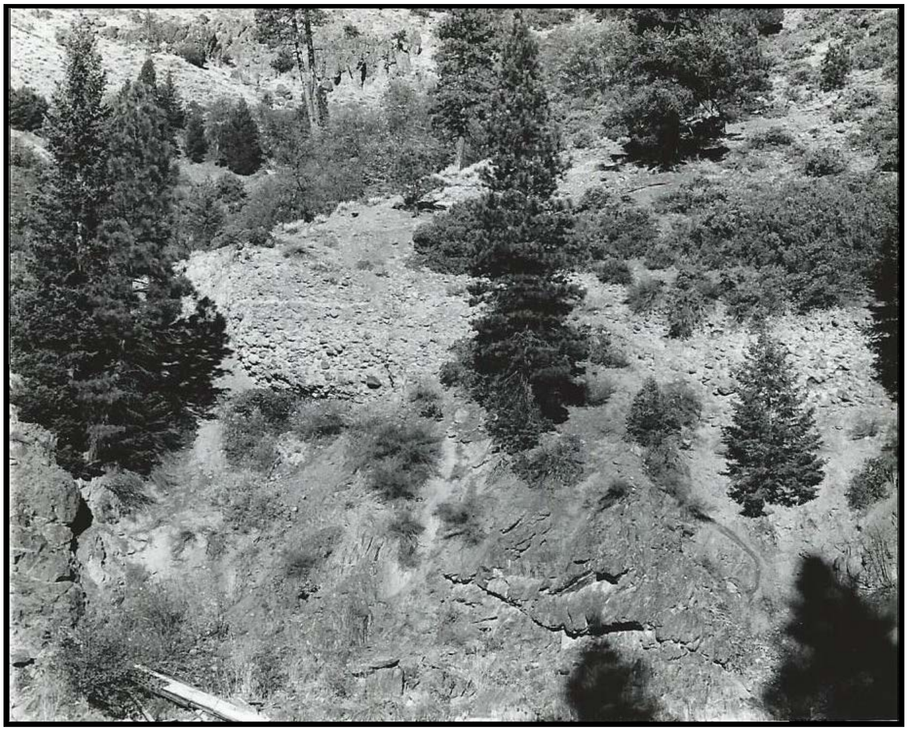


Figure 33. Photograph of Bonta gravels resting unconformably (center of image) on Shoo Fly Complex; north side of Middle Fork of the Feather River downstream from the Quincy-La Porte Road bridge, near northwest corner of Section 15, T23N, R10E.

Figures 34a and 34b. Photographs of Bonta volcanic conglomerate showing poor to moderately-well developed stratification. The upper photo is a road cut exposure located on the Quincy-La Porte Road in the northeast quarter of Section 4, T23N, R10E. The view is to the northwest. For scale is the poorly-visible hammer set against the boulder in lower center of photo. The bottom photo is of the hillside on the opposite side of the Middle Fork of the Feather River; in the southwest quarter of Section 10, T23N, R10E. The view is to the north.

Figure 35. The photograph is a close-up of Bonta volcanic mudflow breccia showing sub-angular clasts of hornblende andesite supported in a sandy matrix that contains scoria and ash fragments plus crystalline grains of hornblende (up to 3 mm long), feldspar, minor pyroxene, biotite, and black opaque grains (iron oxide?). The exposure is a road cut along the Quincy-La Porte Road in the southeast quarter of Section 33, T24N, R10E (Plate I). The view is to the west. Penny for scale.

Figures 36a and 36b. Photographs of “mega-clasts” of Taylor meta-andesite breccia in area underlain by Bonta debris flow. The broken tree trunk next to the clast in the upper image is about 1.8 meters (six feet) tall. The view is to the northeast in the southeast corner of Section 18, T23N, R11E. The lower image is of a nearby large, partially buried boulder of the Taylor displaying the breccia’s characteristic lithology (see D’Allura, 1977). Hammer for scale.

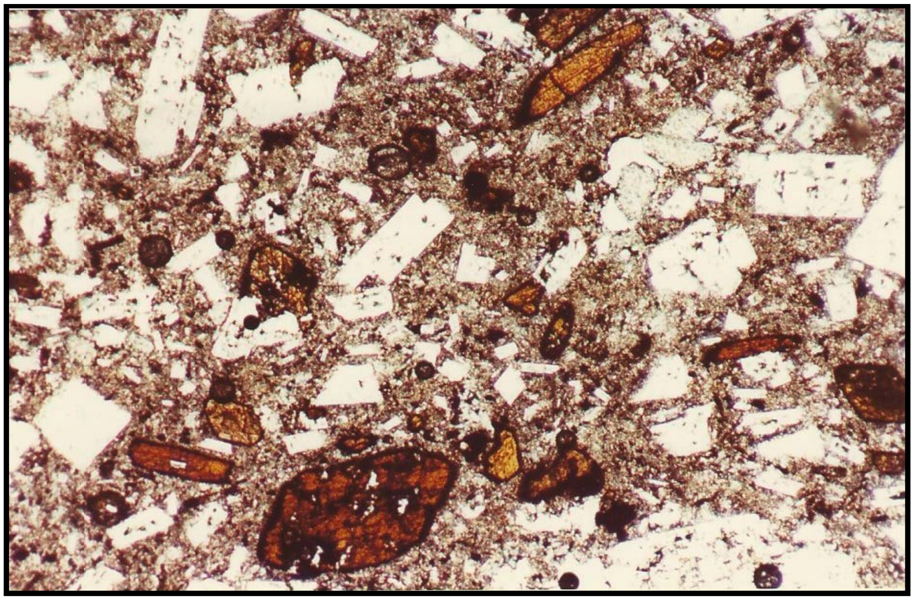
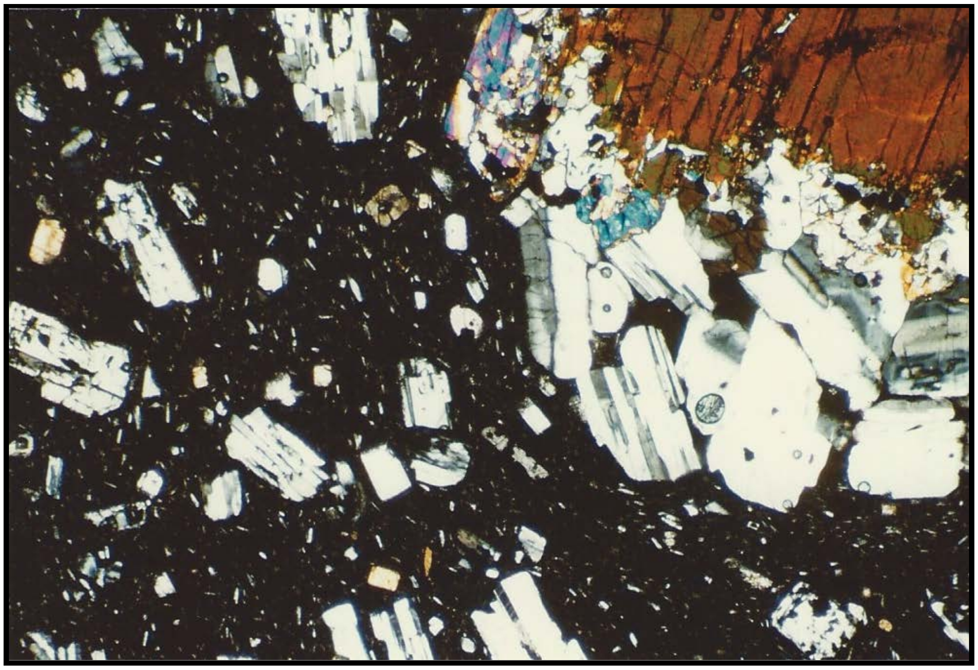


Figure 37. Photomicrograph (plane-polarized light) of a Bonta clast taken from the road cut shown on Figure 35 that exhibits a crude flow alignment (diagonally from lower left to upper right) of plagioclase (up to 2 to 3 mm) and hornblende phenocrysts. The elongate hornblende crystal in the upper right is 0.36 mm long. Nearly all the hornblende phenocrysts have rims of iron oxide. Feldspars include zoned albite, Carlsbad-pericline-twinned plagioclase; some with apatite(?) inclusions. The matrix is predominantly microlitic plagioclase, with sub-trachytic texture.

Figure 38. Photograph of road cut exposure of brecciated Tertiary intrusive andesite, located on the north side of Highway 70/89 in the northwest corner of Section 31, T24N, R11E. The dike shown here, part of a dike complex, is about 11 meters (35 feet wide) and is in fairly sharp contact with andesite mudflow breccia (left half of photo) that is mapped by D'Allura (1977) as Penman formation. About two-thirds of the width of the dike is shown. The fence at the base of the cut is about 1.2 meters (4 feet) high. The dike was sampled for description, including thin-section (Figure 39), on the slope above the cut-bench shown in the upper part of the image and near the dike's contact.



Scale bar = 0.65 mm

Figure 39. Photomicrograph (x-nicols) of sample of brecciated Tertiary intrusive andesite shown on Figure 38. The altered rim of the hornblende in the upper right corner is in contact with anhedral pyroxene (augite?), euhedral to anhedral plagioclase, and amorphous magnetite(?). The groundmass is composed of trachitic plagioclase plus microcrystalline pyroxene and magnetite(?) set in what is probably a combination of glass and clays. The specimen shows a crude flow alignment from upper left to bottom center.

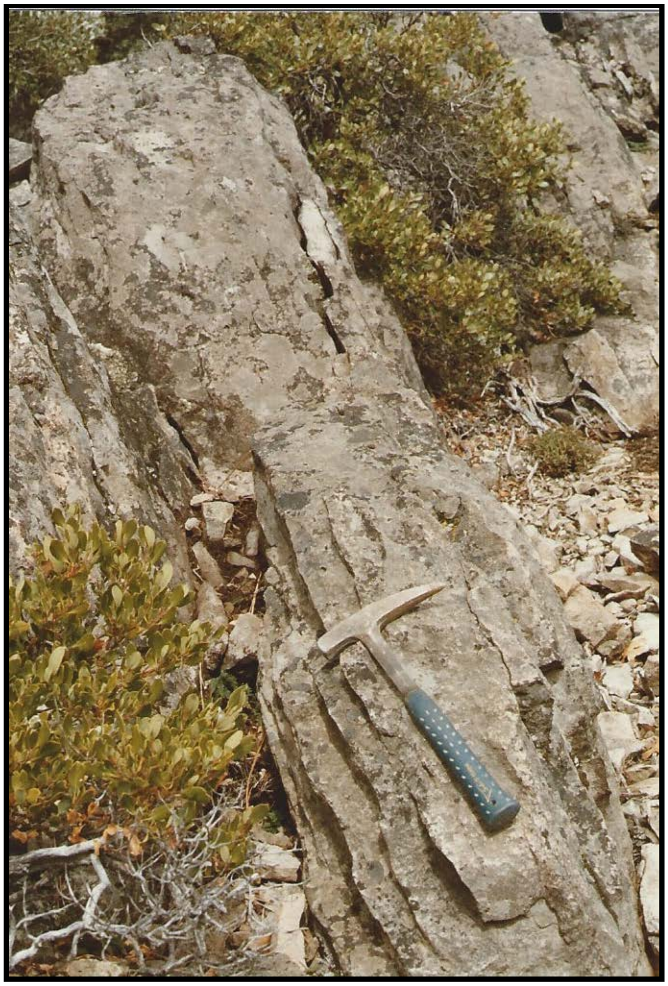
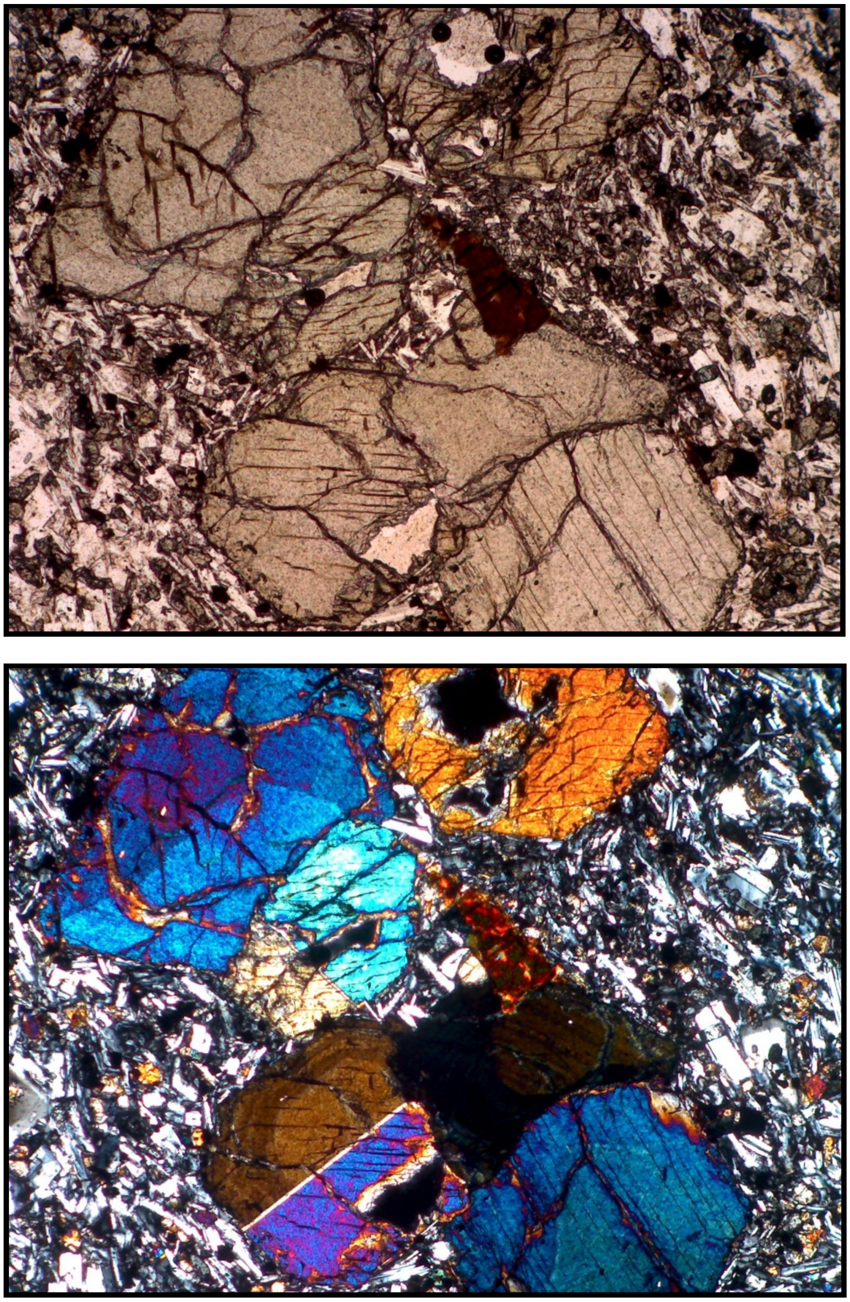


Figure 40. Photograph of Warner basalt, mapped by Durrell (1976), showing characteristic platy jointing. The outcrop is located in the southwest quarter of Section 9, T23N, R11E (Plate I). Hammer for scale.



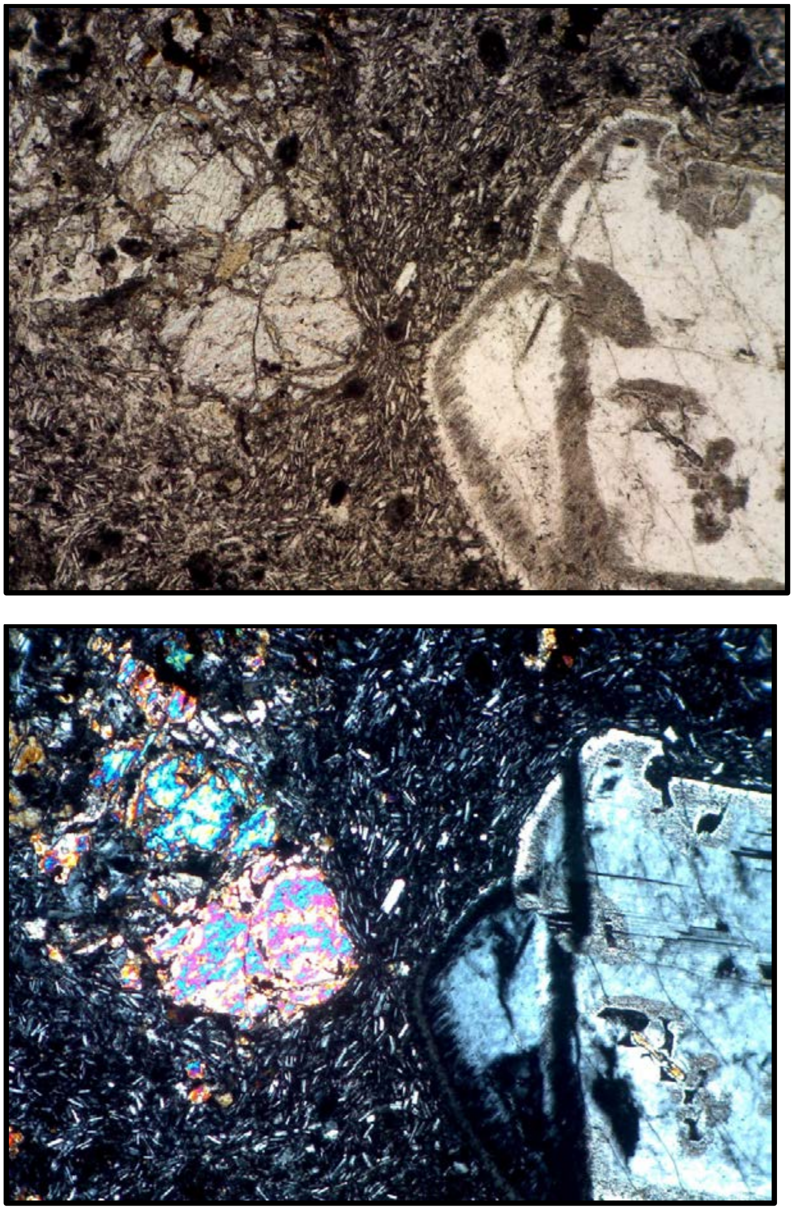
Scale bar = 0.6 mm

Figures 41a and 41b. Photomicrographs of Warner olivine-pyroxene basalt under, respectively, plane-polarized light (upper image) and x-nicols (lower image) showing pyroxene phenocrysts set in a groundmass of feltic to trachytic feldspar microlites with intergranular olivine and pyroxene. The sample is from exposures in the west half of Section 6, T23N, R10E (Plate I).

Figure 42. Photograph looking south toward the Nelson Creek drainage from a point on Bachs Creek Ridge. The knob in left center is underlain by a Warner intrusive plug in Sections 6 and 7, T23N, R10E (Plate I). The large knob in right-middle distance is Little Volcano-Limestone Point in Sections 17 and 18, T23N, R10E, that is underlain by oolitic to pisolitic limestone. The photograph was taken September 7, 2013, and shows the hazy conditions that were the result of smoke from the American Fire that was burning in the Tahoe National Forest near Foresthill (Placer County) and likely included smoke from the Rim Fire that was also burning in the Stanislaus National Forest and in and near Yosemite National Park. Shoo Fly Complex rocks form the foreground.

Figure 43. Photograph of talus from the Warner intrusive plug on Bachs Creek Ridge in Sections 6 and 7, T23N, R10E. The photo is toward the east and was taken at the plug's north end (Section 6). The planar surfaces on the blocks are the result of columnar jointing that is poorly developed on this flank of the plug, but better developed on its southeast flank (Figure 44). For scale, the block in the lower right quarter of the image, with its shaded end toward the camera, is about 46 centimeters (~18 inches) wide.

Figure 44. Photograph of the Warner intrusive plug on Bachs Creek Ridge showing columnar joining and associated talus slope. The image is toward the southeast. The canyon of the Middle Fork of the Feather River is beyond the forested ridge in the right middle distance. The topography in the far distance descends into the Plumas Trench (Durrell, 1959a).



Scale bar = 0.6 mm

Figures 45a and 45b. Photomicrographs of sample of Warner intrusive plug exposed on Bachs Creek Ridge (Section 6, T23N, R10E). Upper image (plane-polarized light) shows complexly-twinned phenocryst of plagioclase (right) in reaction with matrix composed of trachytic feldspar microlites, with minor olivine, and pyroxene, and opaque (iron oxide?) material set in a glassy groundmass. Lower image (x-nicols) shows fractured pyroxene phenocryst (left) that appears to also be undergoing some reaction with the matrix.

Figure 46. Photograph of eroded flank of the English Bar alluvium adjacent to the Middle Fork of the Feather River (eastern half of Section 11, T23N, R10E). The view is to the southeast. The photo was taken at the north side of the river near Fells Flat. Some indistinct bedding is visible in the center-right of the image. However, the reworking of virtually the entire bar (Plate I) in the search for gold renders unreliable such layering as evidence for original bedding and the amount of the river's rejuvenation into these deposits as suggested by this exposure. The height of the vertical face with the bedding is approximately 2.4 meters (8 feet).

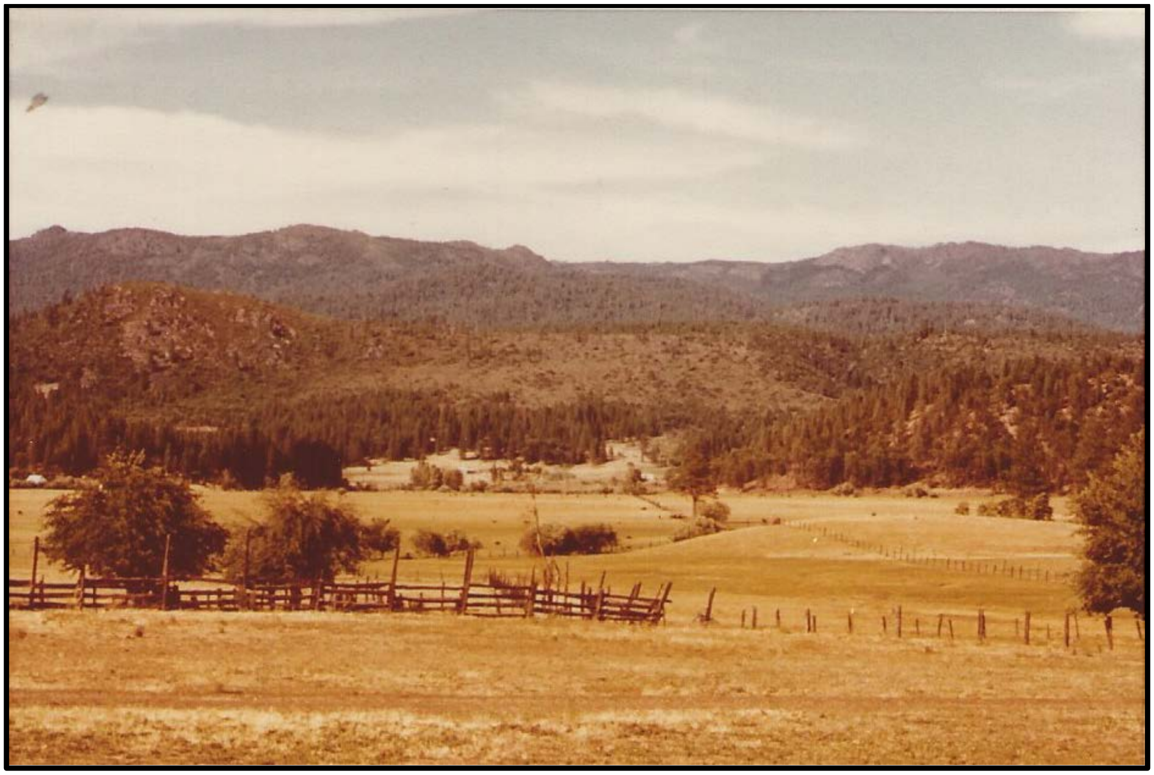


Figure 47. Photograph looking to the northeast across Thompson Valley from the Quincy-La Porte Road in the valley's southwest corner. The partially forested area at center is a portion of the southeast arm of American Valley; in Section 16, T24N, R10E, and northeast quarter of Section 21, T24N, R10E. The high knob with exposed outcrops in the left middle distance is Johnson Hill (Sections 15 and 16, T24N, R10E). Johnson Hill and its flanking ridge to the right are underlain by the Devonian age Taylor Formation (D'Allura, 1977, Plate I). Forming the left and right skylines are, respectively, Taylor Rock ridge and Argentine Rock ridge that are both underlain by the Taylor Formation. Grizzly Ridge is in the extreme distance.

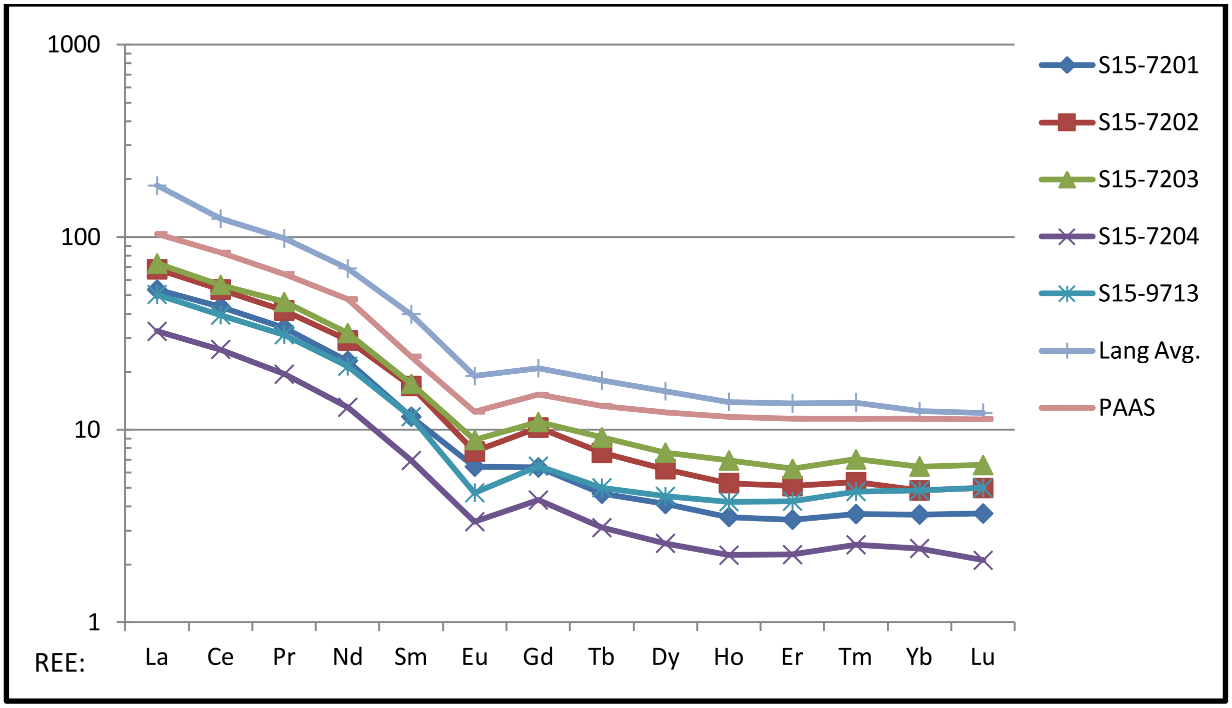


Figure 48. Chondrite-normalized rare earth element (REE) distribution diagram of the results by ICP-MS/ICP-OES analyses listed in Table 5 for Shoo Fly Complex sandstone samples collected in the study area. The chondrite-normalizing values are from Taylor and McLennan (1985).

The log-scale Y-axis displays REE/Chondrite results in parts per million. The average Europium (Eu) anomaly for the five samples is 0.62.

Included for comparison are (1) the averaged chondrite-normalized values for nine "Lang sequence" argillite samples collected within the aureole of the Emigrant Gap composite pluton (Garrison, et al, 1997, p. 127; also see Girty et al., 1996b, p. 12) and (2) the chondrite-normalized post-Archean Australian shale (PAAS) values using the averaged REE values reported by McLennan (1989, p. 172).

The Shoo Fly sample results show the pattern discussed by McLennan (1989, p. 189) that is similar to continental arc turbidites and includes light-REE enrichments, flat heavy-REE distributions, and negative Eu-anomalies. The pattern is also similar to that reported by Girty et al. (1996b, Figure 11) for the Lang sequence argillite samples, but shows that the Shoo Fly sandstone samples contain less of the REE than do the argillites.

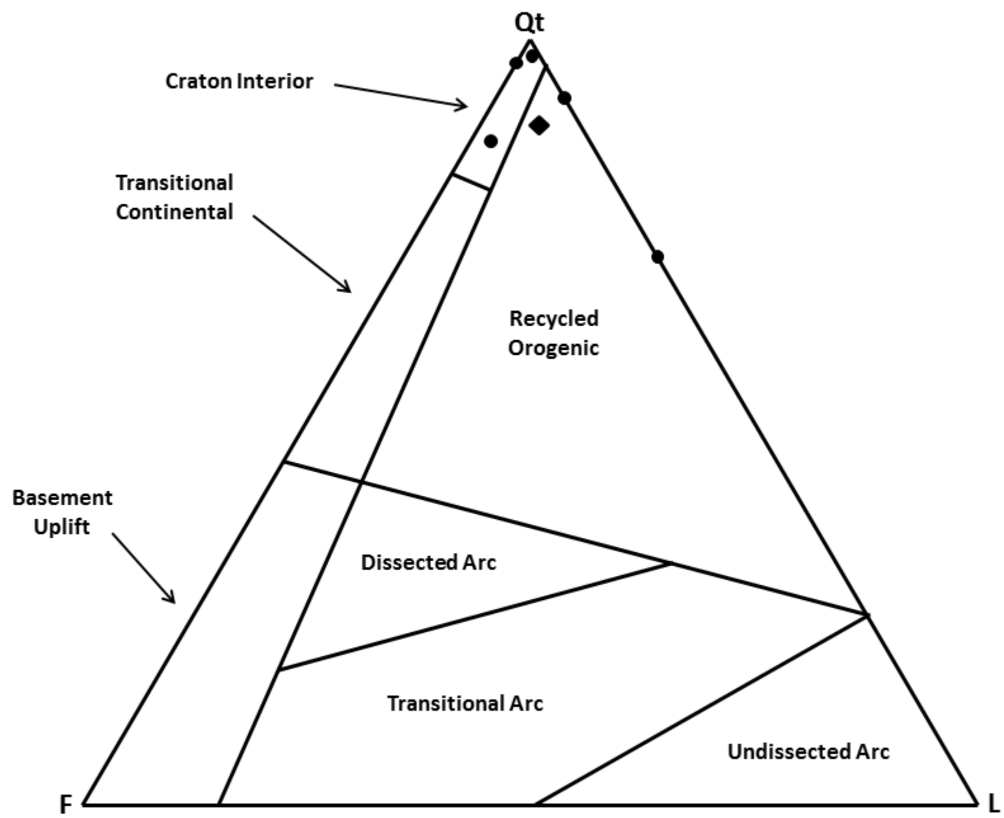


Figure 49. Provenance discrimination diagram of Dickinson (1985, p. 340) showing the plots of the data listed in Table 7 for this study's Shoo Fly Complex quartzose sandstone samples. The points are based on the results from the calculation of QFL component weight-percent data using the procedures of Cox and Lowe (1996). The weight-percent data are calculated from the point-counted results listed in Table 2a, with adjustments for the respective component densities. The diamond-shaped symbol represents the mean of the dataset.

Figure 50. Photograph of small-scale superposed folding involving Shoo Fly laminated grey chert and slate on the north side of the Middle Fork of the Feather River (southwest quarter of Section 16, T23N, R10E). The view is toward the east. Two generations of folds, informally F1 and F2, are represented in this outcrop. At center is a refolded, isoclinal F1 fold, with its crest pointing toward the pencil, that contains some white quartz in its hinge. The axial planes of these F1 folds are oriented generally N42W and are vertical. Two similar, refolded F1 folds are located below it, with the crests pointing to the left (one toward the seven o'clock direction, the other toward the six o'clock direction). These folds and appressed limbs also exhibit more open, superposed F2 folds with parallel axial plane traces oriented N32E (from lower right to upper left) and are also vertical. This same outcrop was examined by Varga (1980, p. 102, Figure 43B). Pencil for scale.

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XI. APPENDICES

XI.A. APPENDIX A: Whole-Rock Geochemical Analyses

Whole-rock chemical data (see Tables 3 and 4) were obtained for five metamorphosed Shoo Fly quartzose sandstone samples. Major-oxide data were obtained by x-ray fluorescence (XRF) analyses. Rare earth element (REE) data were obtained by either inductively-coupled plasma mass spectrometer (ICP-MS) or inductively-coupled plasma optical emission spectrometer (ICP-OES) analyses. The same sandstone samples were also examined in thin section and point counted for modal percentages of components. The geochemical analyses were conducted by SGS Mineral Services, Lakefield, Ontario, Canada. The XRF analyses were done using a Bruker S8WD-XRF instrument. The ICP-MS analyses used a Perkin Elmer Elan 6100 and ICP-OES analyses were by a Perkin Elmer Optica 5300.

Bulk-rock samples (approximately 250 grams for each field sample) were powdered in a tungsten-carbide shatterbox. The resulting powders for XRF were fused as individual glass disks using a mixture of rock powder and lithium tetraborate/lithium metaborate. Loss-on-ignition (LOI) values were determined separately and gravimetrically for each sample at 1,000°C. For the REE analyses, 0.1-gram subsamples were fused using sodium peroxide (Na2O2), with the resulting cakes dissolved in nitric acid (HNO3).

The required quality assurance/quality control acceptance criteria were met using certified reference materials, replicates, duplicates, and blanks to calculate accuracy, precision, linearity, range, detection and reporting limits, specificity, and measurement uncertainty (SGS, 2013, 2014a, 2014b).

SGS (2013, 2014b) established the following estimated Measurement Uncertainties (MU) for the major oxides and REE at the various concentration ranges in the following tables. The estimated MUs are assessed using reference materials and replicate or duplicate samples (involving different samples, analysts, laboratory conditions, equipment, etc.). Where live sample data were insufficient to calculate an estimated MU, either a theoretical estimate is shown (underlined) or is to be determined (TBD).

Major oxides (all tables duplicated with permission from SGS):

Element	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*												
	SiO2	Al2O3	MgO	Na2O	K2O	CaO	P2O5	TiO2	Cr2O3	V2O5	Fe2O3	MnO	LOI
Report limit,%	0.01												-10
0.01-<0.05%	111	85	86	85	85	85	85	85	85	85	98	85	TBD
0.05-<0.1%	39	37	64	70	35	50	38	35	54	59.4	35	35	TBD
0.1-<0.5%	14	12	18	31	10	12	11	10	10	10	13	10	TBD
0.5-< 1%	12	10	6.7	28	5.4	7.2	9.4	8.9	7.1	6.4	7.6	5.6	TBD
1-<5 %	3.7	4.2	4.6	4.3	4	5.3	3.5	3.5	3.8	TBD	4.3	4.3	10.6
5-<10 %	2.6	4.2	4.3	3.3	3.7	4.7	3	3.1	3.7	TBD	3.4	2.3	9.5
10-<50 %	2.1	4.0	2.4	2.1	2.4	2.1	3.1	3	3.5	TBD	2.1	2.1	2.5
50-<100%	2.1	4.0	2.4	2.0	2	2	2	2.7	2.7	TBD	2	2	0.7
Upper limit (%)	100												

Note:

"The reported uncertainty is expanded using a coverage factor k=2 for a level of confidence of approximately 95%, assuming a normal distribution" (SGS, 2014).

REE (and continued on following pages):

Element (majors)	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*							
	Report Limit	0.01- <0.05 %	0.05 - <0.1%	0.1 - <0.5%	0.5 - <1.0%	1.0 - <5.0%	5.0 - <10%	10 - <upper limit	Upper limit %
Al	0.01	93	43	18	13	11	10	10	25
Ca	0.1	N/A	N/A	93	43	18	13	11	25
Fe	0.01	93	43	18	13	11	10	10	25
K	0.1	N/A	N/A	93	43	18	13	11	25
Mg	0.01	93	43	18	13	11	10	10	25
P	0.01	93	43	20	16	11	10	10	25
Ti	0.01	93	43	18	13	11	10	10	25

Note:

"The reported uncertainty is expanded using a coverage factor k=2 for a level of confidence of approximately 95%, assuming a normal distribution" (SGS, 2014).

REE (continued):

Element	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*													
	Ag	As	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu
Reporting limit: ppm	1	5	10	5	0.1	0.2	0.1	0.5	10	0.1	10	0.05	0.05	0.05
0.01-<0.05 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.05-<0.1 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	177	177	177
0.1-<0.5 ppm	N/A	N/A	N/A	N/A	93	153	93	N/A	N/A	93	N/A	52	52	52
0.5-<1 ppm	N/A	N/A	N/A	NA	43	77	43	177	N/A	43	N/A	27	27	29
1-<5 ppm	93	N/A	N/A	N/A	18	27	18	52	N/A	18	N/A	14	14	14
5-<10 ppm	43	177	N/A	177	14	17	18	27	N/A	16	N/A	12	13	12
10-<50 ppm	21	52	93	52	14	14	18	14	93	11	93	11	12	10
50-<100 ppm	15	27	43	27	12	11	18	13	47	10	43	10	10	10
100-<500 ppm	11	15	18	14	12	10	13	10	23	10	18	10	10	10
500-<1000 ppm	10	15	13	12	10	10	10	10	21	10	13	10	10	10
1000-<5000 ppm	N/A	13	11	11	N/A	10	10	10	13	10	11	N/A	N/A	N/A
5000-<10000 ppm	N/A	10	10	N/A	N/A	10	10	10	10	10	10	N/A	N/A	N/A
10000-<50000 ppm	N/A	10	N/A	N/A	N/A	N/A	N/A	N/A	10	N/A	N/A	N/A	N/A	N/A
50000-100000 ppm	N/A	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Upper limit (%)	0.1	10	1	0.25	0.1	1	1	1	5	1	1	0.1	0.1	0.1

REE (continued):

Element	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*														
	Ga	Gd	Ge	Hf	Ho	In	La	Li	Lu	Mn	Mo	Nb	Nd	Ni	Pb
Report limit ppm	1	0.05	1	1	0.05	0.2	0.1	10	0.05	10	2	1	0.1	5	5
0.01-<0.05ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.05-<0. ppm	N/A	177	N/A	N/A	177	N/A	N/A	N/A	177	N/A	N/A	N/A	N/A	N/A	N/A
0.1-<0.5 ppm	N/A	52	N/A	N/A	52	153	93	N/A	52	N/A	N/A	N/A	93	N/A	N/A
0.5-<1 ppm	N/A	34	N/A	N/A	27	77	43	N/A	27	N/A	N/A	N/A	43	N/A	N/A
1-<5 ppm	93	17	93	93	14	27	18	N/A	14	N/A	153	93	19	N/A	N/A
5-<10 ppm	43	15	43	43	12	17	17	N/A	14	N/A	77	43	17	177	177
10-<50 ppm	18	11	18	18	10	17	13	93	10	93	27	28	17	52	52
50-<100 ppm	13	10	13	14	10	17	12	43	10	43	19	17	16	27	27
100<-50 ppm	11	10	11	11	10	12	10	18	10	18	12	11	11	14	14
500-<1000 ppm	10	10	10	10	10	12	10	13	10	13	11	10	11	12	12
1000-<5000p ppm	N/A	N/A	N/A	10	N/A	N/A	10	11	N/A	12	10	10	11	10	12
5000-<10000 ppm	N/A	N/A	N/A	10	N/A	N/A	10	10	N/A	10	10	10	10	10	10
10000-<50000 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10	N/A	10	N/A	N/A	N/A	N/A	N/A
50000-<100000 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10	N/A	N/A	N/A	N/A	N/A
100000-<500000 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Upper limit ppm (%)	0.1	0.1	0.1	1	0.1	0.1	1	5	0.1	10	1	1	1	1	1

REE (continued):

Element	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*														
	Pr	Rb	Sc	Sb	Sm	Sn	Sr	Ta	Tb	Th	Tl	Tm	U	V	W
Reporting limit: ppm	0.05	0.2	5	0.1	0.1	1	10	0.5	0.05	0.1	0.5	0.05	0.05	5	1
0.01-<0.05 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.05-<0.1 ppm	177	N/A	N/A	N/A	N/A	N/A	N/A	N/A	177	N/A	N/A	177	177	N/A	N/A
0.1-<0.5 ppm	52	153	N/A	93	93	N/A	N/A	N/A	66	93	N/A	52	52	N/A	N/A
0.5-<1 ppm	27	77	N/A	43	43	N/A	N/A	177	27	43	177	32	31	N/A	N/A
1-<5 ppm	18	27	N/A	25	18	93	N/A	52	14	32	51	14	19	N/A	93
5-<10 ppm	17	17	177	24	15	43	N/A	30	12	13	27	12	16	177	43
10-<50 ppm	13	13	52	20	13	19	93	14	10	13	14	10	13	52	18
50-<100 ppm	10	13	27	17	10	18	43	12	10	12	12	10	10	27	13
100-<500 ppm	10	10	14	10	10	14	18	10	10	10	10	10	10	14	11
500-<1000 ppm	10	10	12	10	10	10	13	10	10	10	10	10	10	12	10
1000-<5000 ppm	N/A	10	10	10	N/A	10	11	10	N/A	N/A	N/A	N/A	N/A	10	10
5000-<10000 ppm	N/A	10	10	10	N/A	10	N/A	10	N/A	N/A	N/A	N/A	N/A	10	10
10000-<50000 ppm	N/A	N/A	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
50000-<100000 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
100000-<500000 ppm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Upper limit (%)	0.1	1	5	1	0.1	1	0.5	1	0.1	0.1	0.1	0.1	0.1	1	1

REE (continued):

Element	Estimated Measurement Uncertainty in given concentration ranges (MU) +/- *(relative percent)*			
	Y	Yb	Zn	Zr
Reporting limit: ppm	0.5	0.1	5	0.5
0.01-<0.05 ppm	N/A	N/A	N/A	N/A
0.05-<0.1 ppm	N/A	N/A	N/A	N/A
0.1-<0.5 ppm	N/A	93	N/A	N/A
0.5-<1 ppm	177	43	N/A	177
1-<5 ppm	52	18	N/A	52
5-<10 ppm	27	15	177	27
10-<50 ppm	14	14	52	17
50-<100 ppm	12	10	27	16
100<-500 ppm	10	10	14	12
500-<1000 ppm	10	10	12	12
1000-<5000 ppm	N/A	N/A	10	10
5000-<10000 ppm	N/A	N/A	10	10
Upper limit (%)	0.1	0.1	1	1

Notes:

N/A = Not applicable to provide an estimated REE MU either above or below the reportable concentration range.

"The reported uncertainty is expanded using a coverage factor k=2 for a level of confidence of approximately 95%, assuming a normal distribution" (SGS, 2014).

XI.B. APPENDIX B: Rare Earth Element Analytical Results

REE / …………Sample:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	PAAS	Units	RL
Al	2.24	4.74	5.92	1.79	2.17	---	%	0.01
Ba	110	240	310	80	70	---	ppm	10
Be	<5	<5	<5	<5	<5	---	ppm	5
Ca	0.2	0.3	0.1	0.1	<0.1	---	%	0.1
Cr	50	70	60	30	40	---	ppm	10
Cu	<10	10	<10	<10	<10	---	ppm	10
Fe	1.23	2.91	3.57	1.12	2.02	---	%	0.01
K	0.7	1.4	1.8	0.6	0.5	---	%	0.1
Li	<10	20	20	<10	10	---	ppm	10
Mg	0.3	0.74	0.91	0.27	0.49	---	%	0.01
Mn	150	290	470	120	200	---	ppm	10
Ni	23	34	29	20	27	---	ppm	5
P	0.02	0.04	0.03	0.02	0.02	---	%	0.01
Sc	<5	7	9	<5	<5	---	ppm	5
Sr	10	30	40	10	<10	---	ppm	10
Ti	0.22	0.38	0.38	0.11	0.24	---	%	0.01
V	32	58	58	15	26	---	ppm	5
Zn	24	62	71	23	38	---	ppm	5
Ag	<1	<1	<1	2	2	---	ppm	1
As	<5	<5	8	<5	<5	---	ppm	5
Bi	<0.1	<0.1	0.2	<0.1	0.2	---	ppm	0.1
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	---	ppm	0.2
Ce	41.6	51.2	54.1	25	37.7	79.6	ppm	0.1
Co	570	400	240	735	698	---	ppm	0.5
Cs	0.8	1.7	1.9	0.6	0.5	---	ppm	0.1
Dy	1.57	2.38	2.9	0.98	1.72	4.68	ppm	0.05
Er	0.85	1.27	1.56	0.56	1.06	2.85	ppm	0.05
Eu	0.56	0.67	0.77	0.29	0.41	1.08	ppm	0.05
Ga	5	13	16	5	6	---	ppm	1
Gd	1.95	3.14	3.36	1.32	1.98	4.66	ppm	0.05
Ge	1	2	2	1	1	---	ppm	1
Hf	6	6	7	4	9	---	ppm	1
Ho	0.3	0.45	0.59	0.19	0.36	0.991	ppm	0.05
In	<0.2	<0.2	<0.2	<0.2	<0.2	---	ppm	0.2
La	19.6	25	26.8	11.9	18.5	38.2	ppm	0.1
Lu	0.14	0.19	0.25	0.08	0.19	0.433	ppm	0.05
Mo	<2	<2	<2	<2	<2	---	ppm	2
Nb	6	11	13	4	7	---	ppm	1
Nd	16.2	20.7	22.6	9.3	15.2	33.9	ppm	0.1
Pb	8	10	17	13	10	---	ppm	5
Pr	4.63	5.7	6.31	2.66	4.27	8.83	ppm	0.05
Rb	30.7	69.4	88.7	24.9	20.3	---	ppm	0.2
Sb	<0.1	0.2	0.1	0.1	<0.1	---	ppm	0.1
Sm	2.7	3.9	4	1.6	2.7	5.55	ppm	0.1
Sn	1	1	2	<1	<1	---	ppm	1
Ta	1	1.1	1	1	1.2	---	ppm	0.5
Tb	0.27	0.44	0.53	0.18	0.29	0.774	ppm	0.05

APPENDIX B: Rare Earth Element Analytical Results (continued)

REE / ....Sample:	**S15-7201**	**S15-7202**	**S15-7203**	**S15-7204**	**S15-9713**	PAAS	Units	RL
Th	7.5	9.7	11.7	6.3	11.8	---	ppm	0.1
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	---	ppm	0.5
Tm	0.13	0.19	0.25	0.09	0.17	0.405	ppm	0.05
U	1.05	1.49	2.08	0.94	1.46	---	ppm	0.05
W	1870	1260	767	2360	2250	---	ppm	1
Y	8.5	12.3	16.1	5.8	9.9	---	ppm	0.5
Yb	0.9	1.2	1.6	0.6	1.2	2.82	ppm	0.1
Zr	237	235	257	153	313	---	ppm	0.5
Eu/Eu*	0.75	0.59	0.64	0.61	0.54	0.65	---	---

Full suite of rare earth element (REE) analytical results by ICP-MS/ICP-OES (see Appendix A) for Shoo Fly Complex sandstone samples collected in the study area. Included are post-Archean Australian shale (PAAS) averaged values from McLennan (1989).
RL = laboratory reporting limit.
Eu/Eu* = europium-anomaly values calculated per McLennan (1989).
For calculation purposes, all values shown as less than the RL (e.g., <5) were converted to the RL.
The analyses were done by SGS Minerals Service, Lakefield, Ontario, Canada.

XII. PLATE I – GEOLOGIC MAP

XIII. PLATE II – GEOLOGIC CROSS-SECTIONS