# CENOZOIC PALEOCANYON EVOLUTION, ANCESTRAL CASCADES ARC VOLCANISM, AND STRUCTURE OF THE HOPE VALLEY - CARSON PASS REGION, SIERRA NEVADA, CALIFORNIA

**Hagan, Jeanette C.**

**Busby, Cathy J.**

Department of Earth Science, University of California Santa Barbara, Santa Barbara, California, 93106

**Putirka, Keith**

Department of Earth and Environmental Sciences, California State University, Fresno, California, 93710

**Renne, Paul R.**

Berkeley Geochronology Center, 2455 Ridge Rd, Berkeley, California, 94709

and

Department of Earth and Planetary Science, University of California, Berkeley, California, 94720

## ABSTRACT

We use new geologic mapping, geochronological and geochemical data on Tertiary volcanic, volcaniclastic and intrusive rocks to investigate the volcanic, stratigraphic and structural evolution of the Carson Pass region south of Lake Tahoe in the central Sierra Nevada. Volcanic and volcaniclastic rocks of the central Sierra Nevada were deposited in east-west-trending paleocanyons carved into Mesozoic granitic and metamorphic basement rocks; sediments were transported westward toward the present-day Central Valley. In the Carson Pass – Hope Valley area, two paleotributaries are preserved in faulted terrane east of the present-day Sierran crest (Hope Valley area);

these merge at the crest to form one large (6 km wide) paleocanyon that is undisrupted by faults west of the crest (Carson Pass – Kirkwood area). The single, large paleocanyon west of the crest roughly coincides with the present-day Mokelumne river drainage. New $^{40}Ar/^{39}Ar$ dates and stratigraphic data east of the crest, integrated with previously published data west of the crest, constrain the ages of strata and unconformities within Hope Valley – Carson Pass – Kirkwood paleocanyon system. We interpret three major erosional unconformities to record uplift events at ca. 23 – 16 Ma, 13.5 – 11 Ma, and 10 – 7 Ma. In other parts of the central Sierra, these uplift events are inferred to correspond to range-front faulting events.

We propose the term “Hope Valley graben” for the structural feature mapped immediately east of the Sierran crest at Carson Pass. It is a nearly symmetrical full graben that offsets volcanic rocks as young as 6 Ma at least 400 m (1300 ft) on each of its bounding faults (herein named the Red Lake fault on the west and the Hope Valley fault on the east). However, we infer that faulting began before eruption of the 6 Ma volcanic rocks for three reasons: (1) the graben localized emplacement of one of the largest volcanic centers in the Sierra, the 6.34 ± 0.14 Ma to 6.18 ± 0.14 Ma Markleeville Peak center; (2) andesite lava flows erupted at 6.22 ± 0.14 Ma from the Red Lake fault and abut it within the graben; and (3) brecciated granite along the Red Lake fault is intruded by altered andesite, indicating that the fault started slipping before magmatism ceased. Our stratigraphic and geochronologic data do not permit an estimate of the amount of pre-6 Ma displacement in the Hope Valley graben. The geometry of the paleocanyon system indicates that the dextral component of slip demonstrated for transtensional faults in other parts of the region did not operate in the Hope Valley graben.

## INTRODUCTION

In the central Sierra Nevada (Figure 1), Tertiary deposits of dominantly fragmental volcanic-volcaniclastic andesitic rocks of the Ancestral Cascades arc were deposited into, and are preserved in paleochannels (Lindgren, 1911; Wagner et al., 2000; Curtis, 1954). Volcanic and volcaniclastic rocks from Carson Pass in the central Sierra Nevada record part of this paleocanyon fill. These rocks record the Late Cenozoic volcanotectonic history of the Sierra Nevada, including the deposition of Oligocene ignimbrites erupted in central Nevada, *in situ* Ancestral Cascades arc magmatism, initiation of Walker Lane transtensional faulting, and onset of Basin and Range extensional faulting.

In the Late Cretaceous, the Sierra Nevada formed the western edge of a Tibetan-type plateau, termed the 'Nevadaplano' (Coney and Harms, 1984; Chase et al., 1998; Wolfe et al., 1998; DeCelles, 2004), with a drainage divide in central Nevada (Henry, 2008). Paleorivers drained westward across western Nevada and eastern California into the present-day Central Valley, carving wide canyons into the Sierra Nevada basement rock (Lindgren, 1911; Bateman and Wahrhaftig, 1966; Huber, 1990; Wakabayashi and Sawyer, 2001; Garside et al., 2005). During Oligocene time large-volume caldera-forming eruptions in central Nevada produced ash-flows that were funneled down the channels across western Nevada and the Sierra Nevada (Davis et al., 2000; Henry et al., 2003). From the late Oligocene to early Miocene, the arc front swept westward across Nevada, accompanying slab fallback (Wernicke, 1992; Dilles and Gans, 1995; Schweickert et al., 2004; Dickinson, 2006; Cousens et al., 2008). Debris from calc-alkaline andesitic eruptions was transported westward, down the paleocanyons, as debris flows and streamflows. The calc-alkaline Ancestral Cascades arc swept westward into the present-day northern and central Sierra Nevada by 16 Ma (Putirka and Busby, 2007; Busby et al. 2008a, 2008b; Cousens et al, 2008; Busby and Putirka, 2009). New $^{40}Ar/^{39}Ar$ age data suggest that arc magmatism in the central Sierra occurred from ~16 - 6 Ma (Busby et al., 2008a, 2008b; this paper).

A westward encroachment of normal faulting may have accompanied the westward magmatic sweep, although the timing and nature of onset of Sierran range-front faulting remains controversial (Dilles and Gans, 1995; Trexler et al., 2000; Henry and Perkins, 2001; Stockli et al., 2002; Surpless et al., 2002). Our recent research at Sonora Pass (Figure 1A) shows that dextral transtension began at that latitude by ~10 Ma, triggering high-K magmatism from the Little Walker center (Putirka and Busby, 2007; Busby et al., 2008b). We proposed that this center formed at a releasing stepover of dextral transtensional faults at the inception of the Walker Lane belt, and may record the birth of the future Pacific-North American plate boundary (Busby and Putirka, 2009).

The Sierra Nevada lie within a microplate bounded to the west by the San Andreas fault and to the east by the Walker Lane belt (Figure 1), an ~150 km wide zone of complex, dominantly northwest-striking right-lateral strike-slip faults. GPS measurements reveal that the Walker Lane Belt currently accommodates ~20-25% of Pacific-North America plate motion (Dixon et al., 1995; Thatcher et al., 1999; Dixon et al., 2000; Wernicke et al., 2000; Faulds et al., 2005). Field data from Sierra Nevada range front faults are notably lacking, however, and thus very little is known of the long-term history of slip on them (Hearn and Humphreys, 1998; Faulds et al., 2005).

Most existing maps of the central Sierra Nevada were made before modern volcanological facies analysis techniques were developed, and many Tertiary rocks of the region remain undivided. The Sierran Tertiary volcanic rocks are largely undated, making lithologic correlations tenuous at best, and relationships to structures unknown. Therefore, little is known about the volumes and compositions of magmas emplaced through time. There are very few publications with detailed geologic maps that use modern volcanologic and stratigraphic approaches and report new geochemical and geochronological data (Busby et al., 2008a, 2008b; Garrison et al.,2008; this paper).

The central Sierra Nevada is an ideal place to determine long-term slip history on Sierra range-front faults, because there are abundant Neogene volcanic-volcaniclastic and intrusive rocks that can be used to determine the nature and timing of range-front faulting relative to magmatic events (Busby et al., 2008b). The paleocanyon fill also provides ideal piercing points with a trend roughly perpendicular to the faults.

In this paper, we describe the volcanic, volcaniclastic and intrusive lithofacies that we use to divide the Cenozoic rocks into mappable units and use the map data to recognize unconformities within the section. We then interpret the paleocanyon in a sequence stratigraphic framework, and propose a model to interpret the unconformities to record uplift events. Last, we present a model for the development of Sierra Nevada range front faults at Carson Pass.

## PREVIOUS MAPPING

Unfaulted Tertiary rocks in the Carson Pass – Kirkwood area (Figure 1), from the Sierran crest westward, were undivided prior to the work of Busby et al. (2008a). That research showed that the 650 m deep Carson Pass – Kirkwood paleocanyon preserves six unconformity-bounded sequences deposited between ~15 and 6 Ma (Busby et al., 2008a). We tentatively correlated the three deepest unconformities in the Carson Pass – Kirkwood paleocanyon with unconformities of the same age in paleocanyon fill of the Sonora Pass area about 50 km to the south (Figure 1). In both regions, these unconformities formed at ~16 Ma, ~11 Ma, and ~7 Ma (Busby et al., 2008b).

Tertiary rocks east of the crest, in the Hope Valley area (Figure 1), are faulted and less completely exposed than rocks of the Carson Pass – Kirkwood area. Previous mapping of two 15 minute quadrangle maps covering the Hope Valley region (Armin et al., 1983, 1984) divided Tertiary rocks into undifferentiated volcanic-volcaniclastic rocks, which they referred to as Relief Peak Formation, as well as intrusions, which were further divided by mineralogy. The Relief Peak Formation was originally defined to apply only to calc-alkaline volcanic rocks that underlie 10-9 Ma high-K volcanic rocks of the Stanislaus Group found near Sonora Pass (Slemmons, 1966; Busby et al., 2008b). Because no high-K rocks occur in the Carson pass region, we follow previous workers by referring to andesitic volcanic and volcaniclastic rocks in the Carson Pass area as the Mehrten Formation (Piper et al., 1939; Curtis, 1951, 1954; Wilshire, 1956; Wagner and Saucedo, 1990; Saucedo and Wagner, 1992).

Mosier (1991) divided volcanic-volcaniclastic rocks in the Markleeville Peak – Jeff Davis Peak area (Figure 2A), where he recognized welded ignimbrites that he assigned to the Valley Springs Formation, as well as lahar deposits, andesitic lava flows, and dikes that he assigned to the Relief Peak Formation. While we agree with some of Mosier’s interpretations of rock types and contacts, we differ in one important way. On Markleeville Peak, Mosier mapped a very thick sequence of lava flows, with the oldest interfingering with the Oligocene Valley Springs Formation and the youngest dated at 7 Ma. We reinterpret Markleeville Peak as a dacite to andesite intrusive complex that formed between about 6.3 to 6.14 Ma (Figure 2A).

Busby et al. (2008b) presented a preliminary, simplified geologic map of the Hope Valley graben. Here, we present new geochemical and geochronologic data, modal analyses, and a more detailed geologic map. The new map includes correlations of fluvial and debris flow deposits across the graben and a chronostratigraphic column correlating units on the basis of age, petrography, and geochemistry (Figure 2B). We integrate these data with data published by Busby et al. (2008a) to construct a new sequence stratigraphic model for the evolution of the Kirkwood – Carson Pass – Hope Valley paleocanyon system, and to interpret the history of the range-front faults at Carson Pass.

## FIELD STUDIES

We divide Tertiary rocks into ignimbrites, block-and-ash-flow tuffs, debris flow deposits, fluvial deposits, lava flows, and intrusions, and further divide primary volcanic and intrusive rocks by mineralogy and chemistry (Figure 2). Many contacts between basement rocks and the Tertiary rocks mapped by Armin et al. (1983, 1984) are retained with slight modifications described below. All Cretaceous plutonic rocks mapped by Armin et al. (1983, 1984) are grouped into one unit. All of the Quaternary deposits also are grouped into one unit, because there are no exposed fault scarps within these units. We re-interpreted some of the lithofacies in Mosier's (1991) M.S. thesis area, including some of his debris flow units that we recognize as block-and-ash-flow tuffs, and as noted above, his lava flows, which we map as intrusions. We added more detail to the eastern edge of the Carson Pass – Kirkwood map published by Busby et al. (2008a), along the present-day Sierran crest at Elephant's Back and Red Lake Peak (Figure 2A). New correlations of map lithofacies and unconformities between the Carson Pass – Kirkwood area of Busby et al. (2008a) and the Hope Valley area (this study) are summarized in Figure 2B. North-south and east-west cross-sections are shown in Figure 3. The stratigraphic section is divided into four sequences by geologic mapping and correlation of four unconformities within the paleochannel fill (Figure 2B).

## $^{40}Ar/^{39}Ar$ DATING

$^{40}Ar/^{39}Ar$ dating of key igneous units was performed at the Berkeley Geochronology Center. Methods used were similar to those reported by Verdel et al. (2007). Samples were generally ca. 10-20 mg multigrain aliquots of handpicked crystals from the 20-60 mesh size fractions. Samples were irradiated for 10 hours in the CLICIT facility at the Oregon State University TRIGA reactor, along with Fish Canyon sanidine

(FCs) as a neutron fluence monitor. Stepwise degassing with a $CO_2$ laser beam steered through an integrator lens yielded the apparent age spectra (Figure 8).

All but two samples yielded well-defined age plateaux. Of the remaining eight samples, two with plateau ages indicated by an asterisk (*) failed to meet an arbitrary but commonly used criterion that plateaux should comprise three or more consecutive steps with ages mutually indistinguishable at 95% confidence, containing >70% of the $^{39}$Ar released. These samples' departure from "ideal" plateaux is minor and the plateau ages given are judged to be reliable. Age uncertainties shown (Figure 8) at one standard deviation but discussed in the text at two standard deviations, and do not include contributions from uncertainties in decay constants or the age of the standard.

Ages are summarized in Table 3 both as "nominal" and "preferred" values. Nominal ages are based on an age of 28.02 Ma for FCs, as recommended by EARTHTIME community consensus. However, direct intercalibration of FCs with the astronomical time scale was recently accomplished (Kuiper et al., 2008), yielding an age of 28.201 Ma for FCs. We adopt this age herein to calculate the "Preferred" ages shown in Table 3, which are believed to be more accurate and more appropriate for comparison with the astronomically-calibrated geomagnetic polarity time scale of Gradstein et al. (2004). Consequently, preferred ages (based on FCs = 28.201 Ma) are used herein throughout, except in the Nominal age column of Table 3.

## TERTIARY VOLCANIC, VOLCANICLASTIC AND INTRUSIVE SUITES

We define twenty-three Tertiary map units in the Hope Valley area (Figure 2), based on outcrop and thin section characteristics, described and interpreted in Table 1. Mappable units include intrusions, primary volcanic and volcaniclastic rocks (ignimbrites, lava flows and block-and-ash-flow tuffs), and secondary volcaniclastic rocks (debris flow deposits and fluvial deposits). The volcanic-volcaniclastic terminology used in this paper largely follows that of Fisher and Schmincke (1984) and Heiken and Wohletz (1985). We assign lithofacies names based on compositions and mineralogy, sedimentary structures and textures, and inferred eruptive and depositional processes. Representative photos of each of the lithofacies are shown in Figure 4. For convenience, the reader is referred to the sequence number in discussion of specific map units. Modal analyses for the all of the intrusive and the primary volcanic-volcaniclastic map units are given in Figure 5, and geochemical data are given in Table 2 and Figure 6. Representative photomicrographs are shown in Figure 7. $^{40}Ar/^{39}Ar$ ages for intrusions and primary volcanic-volcaniclastic rocks are summarized in Table 3, and the spectra are shown in Figure 8. All errors given for ages in the text are two-sigma. The age data are presented together with the field, thin section, and geochemical description of each unit dated. Geochemical work was completed at Putirka's lab at California State University at Fresno, and the methods are described in Busby et al. (2008b).

## Ignimbrites

The oldest Tertiary rocks in the area are ignimbrites, referred to as the Valley Springs Formation, that are preserved within the Hope Valley – Carson Pass – Kirkwood paleocanyon system (Figure 2; also see Figure 2 of Busby et al., 2008a). These rocks are found in paleochannels throughout the Sierra Nevada and consist of silicic ignimbrites that erupted from Oligocene sources in central Nevada (Figure 9A; Garside et al., 2005; Hinz et al., 2003; Henry et al., 2003; Davis et al., 2000). In our field area, these ignimbrites are preserved as thin deposits on paleochannel floors and walls (Figure 9B; Busby et al., 2008a, 2008b; Busby and Putirka, in review) forming outcrops in the southeastern part of the field area, between Markleeville Peak and Jeff Davis Peak (Figure 2A). The outcrops contain sanidine, quartz, biotite, hornblende, lithic clasts, and pumice shards up to 1 cm in size in a grey-white ash matrix containing bubble-wall shards. The ignimbrites are weakly welded to nonwelded. Mosier (1991) reported a sanidine K/Ar age of 28.2 ± 1.1 Ma for this unit and Armin et al. (1983) reported a biotite K/Ar age of 25.9 ± 0.4 Ma on an ignimbrite which we re-map as ignimbrite clasts inside volcanic fluvial sandstone (Tvs) at the northwestern end of the field area.

## Shallow-level intrusions

We distinguished six intrusions or intrusive suites in the Hope Valley area (Figure

2) and report modal analyses (Figure 5), geochemical data (Figure 6; Table 2), and geochronological data (Figure 8; Table 3). They are described below from oldest to youngest.

The hornblende basaltic andesite Round Top intrusions (Tbai; Table 1) contain large hornblende glomerocrysts, locally in clots as large as 10 cm long. These distinctive glomerocrysts, coupled with resorbed plagioclase, indicate a complex magmatic history. Morton et al. (1977) reported a 13.4 ± 1.5 Ma K/Ar age for this intrusion. We found clasts containing these large hornblende glomerocrysts in many of the surrounding fluvial and debris flow deposits.

The 10.77 ± 0.10 Ma (Figure 8D; Table 3) two pyroxene andesite plugs of Pickett Peak and Hawkins Peak (Tpai; Table 1) are identical in composition and mineralogy (Figure 5 and Table 3). The plugs are up to 300 m in diameter (Figure 4A). In thin section (Figure 7A), clinopyroxene and orthopyroxene are present in subequal amounts, subordinate to plagioclase (Figure 5), and plagioclase commonly grows in clusters around clinopyroxene (Figure 7A).

The 6.34 ± 0.14 Ma to 6.18 ± 0.14 Ma (Figure 8I, 8J; Table 3) hornblende-biotite dacitic and andesitic intrusions of Markleeville Peak (Thbdi; Table 1) crosscut the southeastern paleocanyon tributary (Figure 2), and consist of complex multiple plugs of irregular shape and composition that we did not attempt to map individually. They range from dacite to basaltic andesite in composition and contain varying amounts of hornblende, biotite, and plagioclase phenocrysts (Figures 5 and 6; Table 2). As noted above, these were mapped previously as Oligocene to late Miocene lava flows by Mosier (1991), but they clearly intrude Oligocene to late Miocene strata, and lack features typical of lava flows (described below). Small hornblende andesite dike and plugs intrude the hornblende-biotite andesites and dacites on top of Markleeville Peak (Thadp). A sample of one of these hornblende andesite dikes from the top of Markleeville Peak yielded an age of 6.37 ± 0.24 (Figure 8G, Table 3), which is indistinguishable from the age of the main Markleeville Peak plugs (Thbdi) that they intrude.

A small undated olivine basaltic andesite intrusion (Tbi; Table 1) intrudes sequence 3 debris flow deposits on Pickett Peak (Figure 2). The olivine has been partially altered to iddingsite. We also mapped a small olivine basalt intruding fluvial deposits

(Tvf1) on the NE Sierran crest (Figures 2, 5, and 6).

A hornblende basaltic andesite intrudes strata (map units Tvf1 and Tvdf2) at Steven's Peak (Thai; Table 1). It has a reported K/Ar age of 5.2 ± 0.8 Ma (Armin et al., 1984), but due to alteration we were unable to find phenocrysts suitable for $^{40}Ar/^{39}Ar$ dating.

The larger shallow-level intrusions in the map area could be easily mistaken for thick sequences of lava flows, but they differ from lava flows in several ways. Erosional benches are well developed in both the Round Top and Markleeville Peak intrusions, but they are less continuous and less prominent than those formed in lava flow sections, and lack the laterally continuous vesiculated tops of lava flows. Although the intrusions may be locally brecciated, the breccias lack the lateral continuity of flow-top breccias. Columnar jointing is common in both lava flows and intrusions, but the intrusions commonly have thin (<5 cm thick) horizontal joints which resemble flow banding.

To summarize, most of the shallow-level intrusions, except for the 8 km diameter Markleeville Center, are small (<2 km across). They range from basalt to two pyroxene andesite through hornblende andesites to hornblende-biotite dacites. They were emplaced at about 14 Ma (hornblende andesite), about 11 Ma (two pyroxene andesites), and about 6 Ma (hornblende-biotite andesites and dacites and hornblende andesites). The small basalt plugs are undated. Although the number of intrusions is small, there does not appear to be any temporal trend in compositions.

## Lava flows

Lava flows are much less common than fragmental rocks in the Carson Pass – Markleeville region, as first noted by Curtis (1951, 1954). We mapped two lava flow section in the Carson Pass – Hope Valley area: (1) sequence 4 basalt lava flows (Tbl) on the Sierran crest, dated at 6.80 ± 0.20 Ma by Busby et al. (2008a), recalculated to our preferred age of 6.95 ± 0.20 Ma (Table 3) and (2) sequence 4 hornblende andesite lava flows (Thall and Thalu) deposited on the footwall of the Red Lake Peak fault (Figures 2 and 3) here dated at 6.22 ± 0.14 Ma (Figure 8H; Table 3).

The basalt lava flow (Tbl; Table 1) section is variable in thickness, because it onlaps unconformity surface 4 (unconformity 6 of Busby et al., 2008; Figure 2). It consists of two to five flows, 2 – 6 m thick, that are mainly aphyric, with one containing olivine and plagioclase phenocrysts. The top of each flow is marked by breccia or by a vesicular horizon, and the flow interiors are columnar jointed.

The andesite lava section lies inside the Hope Valley graben, and consists of two very thick lava flows separated by a block-and-ash-flow tuff (Thaba3, Figure 2, Table 1), referred to as the lower and upper hornblende andesite lava flows (Thall and Thalu; Figure 2; Table 1). A topographic bench marking the contact between the underlying fluvial deposits (Tvf1) and the lower hornblende andesite flow, is visible in aerial photos and in the field. The lower hornblende andesite lava flow has a basal breccia of varying thickness, averaging 4 m, with sparse accidental clasts, passing upward into a coherent interior ~60 m (200 ft) thick and containing hornblende crystals up to 0.4 cm long, with columnar jointing. A prominent bench marks the top of the hornblende andesite flow at its northern extent. A hornblende andesite block-and-ash-flow tuff forms lenses that are too thin to map between the lower and upper flows on the north margin of their exposure, but thickens southward, at the expense of the lower flow, where it is mapped as a separate unit (Thaba3; Figure 2). This block-and-ash-flow tuff is described below.

The upper lava flow (Thalu) is a crystal-rich porphyritic hornblende andesite, with hornblende phenocrysts up to 1 cm long (Figure 7B). The basal breccia is ~10 m (~30 ft) thick with an irregular base (Figure 4B). There is no evidence for a preserved flow-top breccia and it is locally overlain by a debris flow deposit (Figure 2A), although the flow top does form a slight bench in the topography. The upper flow is less extensive and thicker (>100 m thick) than the lower flow (Thall). The upper flow yielded a hornblende $^{40}Ar/^{39}Ar$ date of 6.22 ± 0.14 Ma (Figure 8H; Table 2). We tentatively infer that two lava flows were erupted from the Red Lake fault, because they lie along it and are restricted to the hanging wall of the fault (see Hope Valley Graben, below).

To summarize, lava flows in the Carson Pass – Markleeville region are small volume and include one section of olivine basalt flows and one section consisting of two hornblende andesite flows with intervening block-and-ash-flow tuff. They are restricted to the youngest sequence (4), at about 6 Ma.

Block-and-ash-flow tuffs

Block-and-ash-flow tuffs are the most common primary volcanic rock type in the area. The block-and-ash-flow tuffs are small-volume pyroclastic flow deposits characterized by a large fraction of monolithic juvenile blocks set in a massive, unsorted, medium- to coarse-grained ash matrix of the same composition (Figure 4C). They commonly show evidence for hot emplacement, such as bread-crust texture on blocks (Figure 4D), jigsaw-fit texture indicating in situ fragmentation, and carbonized wood. These textures cannot survive significant transport, and indicate vent-proximal locations (Fisher and Schminke, 1984; Freundt et al., 2000; Miyabuchi, 1999). The block-and-ash-flow tuffs also show evidence for hot emplacement with oxidized bases and tops of flows (Figure 4E, unit Tpaba). Explosive volcanic deposits, such as ash fall or pumiceous fall or flow deposits, are absent from Miocene rocks in the map area and the central Sierra in general; thus, the block-and-ash-flow tuffs probably formed by lava dome collapse (Fisher and Heiken, 1982; Camus et al., 2000; Voight et al., 2000).

The oldest block-and-ash-flow tuff (Tphaba of sequence 2; Table 1) is also the most extensively-preserved block-and-ash-flow tuff in the field area. It lies on the east side of the Hope Valley graben, in the southeast tributary south of Markleeville Peak, and forms a unit up to 195 m (640 ft) thick. Its blocks are relatively small (dominantly lapilli-sized), and it has minor debris flow deposits interstratified with it, suggesting it represents medial rather than proximal facies of lava dome collapse. This block-and-ash-flow tuff contains a phenocryst assemblage of two pyroxenes, hornblende, and plagioclase (Figure 5). Plagioclase from two samples of this unit reveals saddle-shaped age spectra indicative of excess Ar (Figure 8A and 8B); the saddle minimum age of 15.5 ± 0.6 Ma (Figure 8A) is interpreted to be a maximum age for this unit.

The second oldest block-and-ash-flow tuff (Thaba1 of sequence 2, Figure 2; Table 1) is only slightly younger than the oldest; it was dated by Busby et al. (2008a) at 14.69 ± 0.06 Ma and recalculated to our preferred age of 15.5 ± 0.06 Ma. This gray-colored unit lies west of the Hope Valley graben along the present-day Sierra Nevada crest (Figure 2), and is preserved as a 210 m (700 ft) thick erosional remnant at the base of the main paleocanyon (see Figure 4B of Busby et al., 2008a) where the two paleotributaries apparently joined (Figure 1B). This hornblende trachyandesite block-and-ash-flow tuff, contains abundant large blocks, as well as complexly intercalated debris flow deposits, suggesting mixing of primary and reworked deposits by slumping (Busby et al., 2008a).

The third oldest block-and-ash-flow tuff (Thaba2 of sequence 2, Figure 2; Table 1) is a white orthopyroxene biotite-hornblende block-and-ash-flow tuff that was at least 90 m (300 ft) thick. It has a hornblende $^{40}Ar/^{39}Ar$ date of 13.61 ± 0.16 Ma (Figure 8C). This unit is only preserved at the base of the paleocanyon at the Sierran crest, where it directly overlies basement metamorphic rocks (Figure 2).

Both of these block-and-ash-flow tuffs (Thaba1 and Thaba2) underlie the fluvial deposits of unit Tvf1, and were deeply incised by the paleoriver. Erosional remnants remained on the walls of the paleocanyon, even though the younger fluvial deposits (Tvf1) fill lower elevations to their northwest (Figure 2A).

In the southwestern part of the map area, we mapped a block-and-ash-flow tuff (Thaba3 of sequence 4, Figure 2; Table 1) between the two lava flows (Thall and Thalu). This unit is a hornblende andesite of similar mineralogy and geochemistry to the lava flows (Figures 5 and 6). It is thickest at the south end of the flows, where it is up to 95 m (320 ft), and lenses out to the north. Because it is interstratified with the lava flows, it must be 6.22 ± 0.14 Ma or slightly older (Table 3).

A two-pyroxene andesite block-and-ash-flow tuff (Tpaba of sequence 4, Figure 2; Table 1) overlies sequence 4 debris flow deposits (Tvdf2), as well as sequence 2 block-and-ash-flow tuffs (Thaba2), forming Red Lake Peak (Figures 2A and 4E). It is about 65 m (220 ft) thick, although much of it likely has been eroded. Two samples from this unit have $^{40}Ar/^{39}Ar$ ages of 6.29 ± 0.10 Ma and 6.13 ± 0.34 Ma (Figures 8E and 8F). These ages are the same as that on the Sentinels two-pyroxene andesite block-and-ash-flow tuff in Kirkwood Valley (6.18 ± 0.12 Ma, Table 4; recalculated from Busby et al., 2008a; unit Taba3 of Figure 2A).

Debris flow deposits

Volcanic debris flow deposits (map units Tvdf1 and Tvdf2; Table 1) are massive to thick-bedded matrix-supported deposits with sub-rounded to angular clasts that range in size from pebble to boulder (up to 15 m wide); they are unsorted, and show no internal stratification.  The abundance of the matrix varies and is commonly coarse-grained volcanic lithic sandstone.  Debris flow deposits are polylithic, but nearly all of the clasts are some variety of andesitic rock, with minor mafic volcanic rock fragments, granitic rock fragments, and sparse silicified or petrified wood fragments (Figure 4F).  Unlike block-and-ash-flow tuffs, debris flow deposits do not contain blocks with bread-crust texture or prismatically jointed blocks.  They can also be distinguished by their tan, rather than gray, color.  Although the debris flow deposits in the map area are indistinguishable from one another in outcrop, they are divided by their stratigraphic position relative to other map units.  They frequently contain minor lenses of fluvial conglomerates, sandstones, and flood flow deposits, but these are too small to map, and have been grouped into the debris flow deposit units (Figure 4G).  First the older debris flow map unit (Tvdf1 of sequence 4/5) is described and then the younger debris flow map unit (Tvdf2 of sequence 6; Figure 2B) is described.

In the southeastern paleotributary (Figure 1B), at Jeff Davis Peak, we mapped a debris flow deposit (Tvdf1 of sequence 3) that rests upon the oldest block-and-ash-flow tuff in the map area (Tphaba of sequence 2; Figure 2A).  It measures 175 m (580 ft) thick. This map unit is dominated by debris flow deposits but also contains minor flood flow and fluvial deposits of well-stratified coarse-grained sandstone and clast-supported conglomerate.  Block size in the debris flow deposits increases up-section to 2 m. The top of the section on Jeff Davis Peak has crude stratification dipping 20° north, and contains a lens of block-and-ash-flow tuff.  The steepness of this dip indicates that it is probably a slide block within the debris flow deposit.  We correlate this debris flow deposit (Tvdf1) across the Markleeville Peak intrusive complex to debris flow deposits on both sides of Charity Valley (Figure 2).  These deposits are up to 210 m (700 ft) thick and were deposited directly on granitic basement, suggesting that they onlap the north wall of the southeastern paleotributary.

In the northeastern paleocanyon tributary, on the east side of Hope Valley (Figure 2A), the older volcanic debris flow map unit (Tvdf1 of sequence 3; Table 1) forms nearly all of the Pickett Peak and Hawkins Peak areas. These debris flow deposits have a cliff-forming clast-supported base of flood flow deposits that grades upward into a more matrix-rich deposit. Crude bedding strikes N-S and dips 4° west. The preserved thickness of the deposit is at least 450 m (1500 ft), and an additional 60 m (200 ft) must have eroded away to expose the intrusions that make up Pickett Peak and Hawkins Peak. We correlate these debris flow deposits (Tvdf1) with those that lie to the northeast, across the modern west fork of the Carson River, where debris flow deposits of Horsethief Mountain (Tvdf1, Figure 2A) are more than 490 m (1600 ft) thick, and rise 135 m (445 ft) above the surrounding granite. The basal contact is gradational with underlying fluvial deposits (Tvf1). Similar to the deposits to the south at Pickett Peak, this unit grades upward from clast-supported flood flow deposits to matrix-supported debris flow deposits.

The younger debris flow deposit map unit (Tvdf2 of sequence 4; Table 1) is preserved in the western part of the Hope Valley graben and along the present-day Sierran crest (Figure 2), in the region where the two paleotributaries merge to form a single paleocanyon (Figure 1B). East of Elephant's Back, within the graben, a debris flow deposit (Tvdf2) rests upon both the upper and lower andesitic lava flows (Thall and Thalu, Figure 2A). In some localities, the base of the debris flow deposit interfingers with the block-and-ash-flow tuff (Thaba3) that lies between the two lava flows (Figure 4D). The upper part of the deposit contains a 30 m long clast of flow-banded andesite that is geochemically similar to the 10.77 ± 0.1 Ma Pickett Peak and Hawkins Peak intrusions (Tpai; sample 65, Figure 6). The deposit measures 115 m (380 ft) thick in both localities. Where the debris flow deposits rests directly on the lower andesite lava flow, the lava flow's flow top breccia is preserved beneath it. Since there is no evidence for a debris flow between the two flows, we infer that deposition of the debris flow postdated emplacement of both the lava flows, and filled paleotopography created by emplacement of the second flow. Therefore, the younger debris flow deposit (Tvdf2) is younger than the upper andesite lava flow (Thalu), which is 6.22 ± 0.14 Ma (Table 3).

The younger debris flow deposit (Tvdf2) also crops out on the Sierran crest west of the Hope Valley graben, in the footwall of the Red Lake fault (Figure 2), where it is at least 160 m (520 ft) thick. It overlies fluvial deposits, and has a readily-identifiable contact defined by the change in slope: the fluvial deposits are cliff-formers while the debris flow deposits are slope-formers. There, the 200 m (660 ft) thick deposit overlies 6.95 ± 0.20 Ma basalt lava flows (Tbl, Figure 2; Table 3) and is overlain by the Red Lake Peak pyroxene andesite block-and-ash-flow tuff (Tpaba) at 6.13 ± 0.34 Ma - 6.29 ± 0.10 Ma (Figures 8E and 8F; Table 3).

Fluvial deposits

Fluvial deposits in the Carson Pass area are highly varied, but commonly are poor- to well-stratified, well-sorted, clast-supported conglomerates composed primarily of sub-rounded to rounded andesitic volcanic clasts (Figure 4H). Clasts range in size from pebble to boulders (up to 1 m diameter). Sandstone beds are planar-laminated and cross-laminated, with cut-and-fill structures. A fluvial sandstone unit is present at the base of sequence 2, which contains only minor pebble conglomerate (Tvs), and two fluvial conglomerate units contain lesser sandstone interbeds (Tvf1 and Tvf2 of sequence 3, Figure 2).

We correlate the volcanic fluvial sandstone unit (Tvs of sequence 2, Figure 2B) from the footwall of the Red Lake fault, east into the Hope Valley graben, and farther east into the footwall of the Hope Valley fault, in the northeastern paleotributary at Horsethief Canyon and in the southeastern paleotributary at Jeff Davis Peak. This unit thus forms the basal unit of the Miocene section. In the footwall of the Red Lake fault at Elephant's Back, the volcanic fluvial sandstone (Tvs) consists of a well-sorted, subrounded, coarse-grained volcaniclastic sandstone with thin interbeds of siltstone (Tvs), which grades upward into a stratified cobble conglomerate-breccia (Tsb, Figure 2; Table 1). The conglomerate-breccia is clast-supported, medium-bedded with a sandstone matrix, and is altered to a distinctive purplish-gray color. The same conglomerate-breccia (Tsb) is dropped down to the east into the Hope Valley graben along the Red Lake fault, as discussed below. The volcanic fluvial sandstone (Tvs) at Horsethief Canyon and the northwest end of the Sierran crest has pebble-sized clasts of pumice and sanidine-bearing silicic ignimbrite fragments derived from the Oligocene ignimbrites (Ti). The volcanic fluvial sandstone (Tvs) at Jeff Davis Peak is a well-sorted, coarse-grained sandstone, with andesite fragments and crystals of plagioclase, hornblende, and pyroxene. It was presumably deposited on top of the Valley Springs Formation in the southeastern paleotributary, but the contact relations have been obliterated by the Markleeville Peak intrusions (Thbdi). It is overlain in erosional unconformity by the 15.5 ± 0.6 Ma Jeff Davis Peak pyroxene-hornblende andesite block-and-ash-flow tuff (Tphaba, Figure 2).

The lower of the two fluvial conglomerate and sandstone units (Tvf1 of sequence 3, Figure 2; Table 1) is the most extensive map unit in the Hope Valley – Carson Pass – Kirkwood palecanyon. It occurs east of the Hope Valley graben at Horsethief Canyon (in the northeastern paleotributary), it lies within the graben south of Red Lake, and it forms much of the Sierra crest north of Carson Pass (Figure 2). From there we have mapped it another 12 km westward in the Carson Pass – Kirkwood paleocanyon, where it forms a section up to 300 m thick (Busby et al, 2008a). At the Sierran crest the fluvial conglomerate and sandstone unit (Tvf1) is 300 m (1000 ft) thick, and up to 275 m (900 ft) of it lies in buttress unconformity against sequence 2 block-and-ash-flow tuffs and basement rocks. Bedding dips 6°-9° to the west, with cut-and-fill structures and trough cross-laminations that give a paleocurrent direction of flow to the south/southwest. It is sandier near the base and becomes more conglomeratic towards the top, where much of the section is cliff-forming. At Horsethief Canyon, the fluvial conglomerate and sandstone unit (Tvf1) is greater than 275 m (900 ft) thick and dips ~10° west. The age of the fluvial conglomerate and sandstone unit was stratigraphically constrained between 15.01 ± 0.06 Ma and 10.72 ± 0.12 Ma by Busby et al. (2008a; recalculated dates shown in Table 4). Our new dates further constrain the age of this unit to be between 13.61 ± 0.16 Ma and 10.72 ± 0.12 Ma, that is, after deposition of the Red Lake Peak hornblende andesite block-and-ash-flow tuff (Thaba2; Table 3) and before the intrusion of a peperitic andesite dike in debris flow deposits that overlie it (Tvdf1) in Kirkwood Valley (Table 4; Busby et al., 2008a).

The upper of the two fluvial conglomerate and sandstone units (Tvf2 of sequence 3, Figure 2; Table 1) is restricted to the southeastern paleotributary north of Charity Valley (Figure 2) and is at most 50 m (160 ft) thick; it is distinguished from the lower fluvial conglomerate and sandstone unit (Tvf1) by its stratigraphic position above, rather than below, the lower debris flow unit (Tvdf1).

Altered Andesite

Altered andesitic volcanic rocks (Taa) lie within the southern end of the Hope Valley graben (Taa, Figure 2; Table 1). These are block-and-ash-flow tuffs, lava flows, intrusions, and debris flow deposits that are too strongly altered to map individually. The altered rocks are hornblende and plagioclase phyric andesites (Figures 5 and 6, samples 27 and 34), with plagioclase largely altered to clay, hornblende either completely oxidized or with oxidized rims, and epidote common. The rocks are purple to red to copper-tinged green due to propylitic alteration. This unit is intruded by small, irregularly shaped hornblende-biotite dacites (Thbdi and Thadp), similar to the much larger intrusive complex and hornblende andesite dikes and plugs that make up Markleeville Peak on the footwall of the Hope Valley fault to the east (Figure 2A). As discussed below, we interpret the altered andesite unit (Taa) to represent the altered roof rocks of the Markleeville Peak intrusive complex, which have been downdroppped into the Hope Valley graben. Furthermore, we interpret the small, irregular hornblende-biotite dacite to represent apophyses coming off the top of the Markleeville Peak intrusions. The altered andesite unit is also intruded by a small altered rhyolite plug of unknown age (Tri, Figure 2; Table 1). It has liesegang banding and is too altered to be suitable for modal analysis.

## SEQUENCE STATIGRAPHY

In this section, we reconstruct the stratigraphic evolution of the Hope Valley – Carson Pass – Kirkwood paleocanyon system in a series of time slices, by describing each unconformity and the strata that lie above it. The basal unconformity (unconformity 1), where Cenozoic strata fill a paleocanyon cut into Cretaceous mesozonal granitic rock, is by far the most obvious unconformity. As noted above, the shape of the contact between basement rocks and Cenozoic cover defines two paleotributaries that merge at the present-day Sierran crest (Figure 1B).

Unconformity surfaces within the paleocanyon fill are more easily mapped from the Sierran crest westward to the Kirkwood Valley area (Busby et al., 2008a) than they are east of the crest in the Hope Valley area (Figure 2). This is because the rocks are unfaulted from the crest westward, exposures are better there, and intrusions and associated altered rocks are less abundant there. Nonetheless, we have been able to map and correlate most of the unconformity surfaces, described by Busby et al. (2008a) for the Carson Pass – Kirkwood segment, into the Hope Valley segment of the paleocanyon. Only unconformity surfaces 4 and 5 could not be traced into Hope Valley, but these have limited lateral extent in Kirkwood Valley and are not interpreted to record significant tectonic events (Busby et al., 2008a, 2008b). Unconformities 1, 2, 3 and 6 are not only traceable along the length of the Hope Valley – Carson Pass – Kirkwood paleocanyon, but are also age-correlative with the deepest, most extensive unconformities in other parts of the central Sierra (Busby et al., 2008b; Busby and Putirka, 2009). Therefore, we have dropped unconformities 4 and 5 of Kirkwood Valley from our numbering system, a renumber unconformity 6 of Busby et al. (2008A) as unconformity 4 (Figure 2). As is customary, the sequence that overlies an unconformity is assigned the same number as the unconformity (Busby and Putirka, 2009)..

Sequence 1:

Unconformity 1 is mapped as the contact between the undifferentiated Mesozoic granitic rocks (Kgu) or Jurassic – Triassic metamorphic rocks (JTrm), and Tertiary volcanic rocks (Figure 2). Many lines of evidence support the interpretation that this unconformity formed by uplift and unroofing of the Cretaceous batholith during Late Cetaceous to Paleocene low-angle subduction (see discussion in Busby and Putirka, in review). Paleorelief on unconformity 1 is measured from the lowest Tertiary unit to highest preserved granitic basement, and does not account for fill that is higher than granite. Therefore, these numbers represent a minimum amount of relief, as both the granite and the Tertiary fill have eroded away. In the Kirkwood Valley – Carson Pass map area, the vertical relief on unconformity 1 is up to ~650 m (2100 ft; Busby et al., 2008a). In the northern paleotributary at Horsethief Canyon (Figure 2), the preserved vertical relief on unconformity 1 is 580 m (1900 ft), while in the southern paleotributary it is 340 m (1100 ft). The base of the paleocanyon is V-shaped at Horsethief Canyon: the base of the paleocanyon is less than 60 m (195 ft) wide, but it widens to 250 m (820 ft) at the top of the fluvial sandstone unit (Tvs) and to 1.5 km (~5000 ft) at the top of the fluvial conglomerate and sandstone unit (Tvf1). Elsewhere, the base of the paleocanyon is highly irregular in shape. For example, on the Sierra crest north of Carson Pass, the paleocanyon has a very steep wall defined by a Jurassic metamorphic fin (Figure 2A), and a less steep wall cut into Cretaceous granitic rock (Figure 3A).

Like all paleocanyons of the central Sierra Nevada (Busby and Putirka, 2009), the oldest fill in the Hope Valley - Carson Pass - Kirkwood paleocanyon consists of Oligocene rhyolitic ignimbrites that were erupted from central Nevada (Faulds et al., 2005; Garside et al., 2005). The southern paleotributary was clearly active during the Oligocene, because it contains outcrops of Oligocene ignimbrites south of Markleeville Peak (Figure 9A). The northern paleotributary lacks primary ignimbrite deopsits, indicating that it was either inactive during the Oligocene, or all Oligocene rocks were eroded away during the development of unconformity 2; the latter interpretation is supported by the presence of ignimbrite clasts in the basal fluvial sandstone deposits (Tvs).

Sequence 2:

Unconformity surface 2 is mapped as an erosional surface between Oligocene ignimbrites below and Miocene andesitic volcaniclastic rocks above (Figure 2). It merges with unconformity 1 where the Valley Springs Formation is not present, such as in the northeastern paleotributary. In the Kirkwood Valley – Carson Pass area, this unconformity has a maximum vertical relief of 291 m and a lateral extent of 1.5 km. We are unable to accurately measure the depth of unconformity 1 in the Hope Valley area because it is cross-cut by Markleeville Peak intrusions. Throughout the central Sierra Nevada, Oligocene ignimbrites are commonly preserved below unconformity 2 at the base of paleocanyons or higher on paleocanyon walls on paleoledges that were created by joints in the granitic basement rock (Busby et al., 2008b). This indicates that the ignimbrite canyon fill was very thick before it was largely eroded away during the development of unconformity 2 (Figure 9B). This unconformity may have formed in response to thermal uplift and regional extension at the onset of Ancestral Cascades arc volcanism in what is now the central Sierra Nevada (Busby and Putirka, 2009).

In the Hope Valley to Sierran crest area, the basal deposits of sequence 2 consist of volcanic fluvial sandstones (Tvs), which locally pass upward into stratified cobble breccia-conglomerate deposits of Elephant's Back (Figure 2). The volcanic fluvial sandstone unit (Tvs) is finer grained and better sorted than any other volcaniclastic map unit in the paleocanyon, and may represent relatively distal deposits from a volcanic source well east of Carson Pass. However, this relatively thin unit is overlain by about 16 – 14 Ma block-and-ash-flow tuffs, and intrusive activity began in the area while sequence 2 was deposited (intrusions of Little Round Top, Figure 2). Furthermore, the contact between the volcanic fluvial sandstone (Tvs) and the overlying block-and-ash-flow tuff at Jeff Davis Peak (Tphaba) is an erosional unconformity (Figure 2), with 60 m (200 ft) of relief. All of these observations are consistent with the interpretation that unconformity 2 records uplift associated with a thermal pulse as arc volcanism swept westward into the area.

Unconformity 2 merges with unconformity 1 on the Sierran crest north of Carson Pass. Here, the sequence 1 ignimbrites and the sequence 2 fluvial sandstone unit are absent, and the basal paleocanyon fill consists of a sequence 2 trachyandesite block-and-ash-flow tuff (Thaba1) dated at 15.01 ± 0.06 Ma (recalculated from Busby et al., 2008a; Table 3). This unit passes down-paleocanyon (westward) into interstratified debris flow and fluvial deposits (Figures 2B and 9B). Several hundred thousand years later, the trachyandesite block-and-ash-flow tuff (Thaba1) was overlain by the 13.61 ± 0.16 Ma andesite block-and-ash-flow tuff (Thaba2).

In summary, sequence 2 volcaniclastic strata and age-correlative intrusions preserve a record of ~16 to 14 Ma arc magmatism within the area of the paleocanyon, as well as sedimentation of volcanic debris derived from more distal areas to the east.

Sequence 3:

Unconformity 3 is mapped as an erosional surface between block-and-ash-flow tuffs and reworked equivalents below, and a thick, widespread fluvial conglomerate and sandstone unit (Tvf1) above. Between the Sierran crest at Carson Pass and Kirkwood Valley, this unconformity has a maximum vertical relief of 315 m (1030 ft), extends across the entire 7-8 km width of the paleocanyon and has been traced for 18 km along the length of the paleocanyon. In the southeastern paleotributary, this unconformity surface is obscured by the Markleeville Peak intrusion. In the northeastern paleotributary, unconformity 3 lies at the bottom of a narrow part of the paleocanyon, so it is very limited in lateral extent. Geochronological and stratigraphic constraints place the cutting of unconformity 3 at between 13.5 and 11 Ma (Figure 9C). However, age constraints from other paleocanyons in the Central Sierra show this unconformity formed at 11 Ma, during faulting associated with the inception of the Sierra Nevada microplate (Busby and Putirka, 2009).

The fluvial conglomerate sandstone unit (Tvf1) forms a coarsening-upward sequence 370 m (1220 ft) thick along the Sierran crest north of Carson Pass. There, the base of the unit is similar to the fluvial sandstone unit (Tvs; see Figure 4H), but upsection the fluvial conglomerate sandstone unit (Tvf1) becomes more conglomeratic, and debris flow deposits are interbedded with fluvial conglomerates at the top (Tvdf1, Figure 2). Additionally, the sequence 3 fluvial conglomerate and sandstone (Tvf1) passes gradationally upward into the lower debris flow deposit (Tvdf1) at Horsethief Canyon. This apparent progradation (Figure 9C) may record an up-paleocanyon (eastward) increase in volcanic activity.

Our new mapping shows that unconformities 4 and 5 in Kirkwood Valley (Busby et al., 2008a) do not extend beyond that small area (Figure 2B). Although we correlate the lower volcanic debris flow deposit (Tvdf1) on the east side of the Hope Valley graben with the lower volcanic debris flow deposit (Tvdf1) of Kirkwood Valley, it could also be in part age-correlative with the block-and-ash-flow tuff there (Taba2, Figure 2, Busby et al., 2008a).

Volcanic necks forming Pickett and Hawkins Peaks are included in the same sequence as the lower debris flow deposits (Tvdf1), because these intrusions are the same age (10.77 ± 0.10 Ma) as peperitic intrusions within the lower debris flow deposit at Kirkwood Valley (10.72 ± 0.12 Ma; Table 4), which there lie beneath unconformity 4 (unconformity 6 of Busby et al. 2008a). The peperitic margins on the intrusion in Kirkwood Valley indicate that the lower debris flow deposits there were water-saturated and unlithified when they were intruded, and are thus penecontemporaneous with the intrusion (Busby et al. 2008a). These intra-canyon intrusions passed upward into lava domes that shed block-and-ash-flows into the canyon (Figure 9D).

Sequence 4:

As noted above, this is sequence 6 of Busby et al. 2008a (Figure 2). Unconformity 4 is mapped as an erosional surface beneath volcanic rocks that are about 6 Ma old. In the westernmost part of the paleocanyon, west of Kirkwood Valley and east of Silver Lake, unconformity 4 cuts through all Tertiary strata to granitic basement below the paleocanyon, a depth of ~300 m (994 ft; Busby et al., 2008a). In Kirkwood Valley, unconformity 4 cuts down 120 m into the lower volcanic debris flow unit (Tvdf1) of sequence 3, which is there dated at ≥10 Ma by peperitic intrusions interpreted to be penecontemporaneous with the debris flow deposits (Busby et al., 2008a; Figure 2). Farther east in the paleocanyon at the Sierran crest, unconformity 4 cuts into the volcanic fluvial conglomerate and sandstone (Tvf1), also of sequence 3 (Figure 2). The unconformity surface on top of the volcanic fluvial conglomerate and sandstone (Tvf1) has relatively low relief, of about 30 m (100 ft.), perhaps because the top of the volcanic fluvial conglomerate and sandstone unit formed a laterally extensive planar surface that was resistant to erosion. Unconformity 4 locally merges with unconformity 3 along the Sierran crest, where intra-canyon paleo-ridges composed of sequence 2 block-and-ash-flow tuff units (Thaba1 and Thaba2) are directly overlain by sequence 4 basalt lava flows (Tbl) and debris flow deposits (Tvdf2). East of the Hope Valley graben, the ≅ 6 Ma volcanic rocks that overlie unconformity 4 are replaced by ≅ 6 Ma subvolcanic intrusions, whose eruptive equivalents have been eroded away; thus, unconformity surface 4 has also been eroded at the eastern mapped limit of the Hope Valley – Carson Pass – Kirkwood paleocanyon system (Figure 2).

The oldest dated unit in sequence 4 is the Carson Pass basalt lava flow unit (Tbl) along the Sierran crest north of Carson Pass (Figure 2), dated at 6.95 ± 0.20 Ma (recalculated from Busby et al., 2008a; Table 3). The second oldest dated unit in sequence 4 is the hornblende andesite lava flow sequence (Thall and Thalu, Figure 2), dated at 6.22 ± 0.14 Ma (Table 3). Both the basalt lava flow unit and the andesite lava flow units are overlain by the upper volcanic debris flow deposit (Tvdf2), which occurs as erosional remnants along the Sierran crest as far north as Stevens Peak (Figure 2). This debris flow unit does not occur in the westernmost mapped part of the paleocanyon at Kirkwood Valley (Busby et al., 2008a; Figure 2); it is not known whether this area was beyond the depositional limit of the unit, or if its absence there indicates the presence of a local erosional unconformity within sequence 4. At Kirkwood Valley, unconformity 4 is overlain by the up to 300-m-thick Sentinels pyroxene block-and-ash-flow tuff (Taba3, Figure 2 of Busby et al., 2008a), which was deposited across the width of this segment of the paleocanyon. The Sentinels pyroxene andesite block-and-ash-flow tuff was dated at 6.18 ± 0.12 Ma (recalculated from Busby et al., 2008a; Table 4) and tentatively correlated with the Red Lake Peak pyroxene andesite block-and-ash-flow tuff, on the basis of stratigraphic position, lithology, and mineralogy by Busby et al. (2008a). New $^{40}Ar/^{39}Ar$ dates of 6.29 ± 0.10 Ma – 6.13 ± 0.34 Ma on the Red Lake Peak pyroxene andesite block-and-ash-flow tuff (Tpaba; Figures 8E and 8F; Table 3) show that these two units are the same age, supporting this correlation. These ages also constrain the maximum duration of deposition for the upper volcanic debris flow deposit (Tvdf2) to about 0.8 Ma

Sequence 4 intrusions

On the map key and correlation diagram of Figure 2B, intrusions east of the Hope Valley graben in sequence 4 are included even though they are not stratified rocks, because they are the same age as extrusive rocks of sequence 4 (Table 3). The Markleeville Peak intrusive complex (Thbdi) consists of multiple small plugs, including hornblende-biotite dacite, dated at 6.34 ± 0.14 Ma, hornblende-biotite andesite, dated at 6.18 ± 0.14 Ma, and hornblende basaltic andesite (Figures 5 and 6; Table 2). These $^{40}Ar/^{39}Ar$ ages are younger than but overlap the K/Ar age of 6.9 ± 0.7 Ma reported by Mosier (1991). The intrusive complex and the altered andesite (Taa) are intruded by hornblende andesite dikes and plugs (Thadp) that are dated at 6.37 ± 0.24 Ma, which, within error, are the same age as the rocks they are intruding.

Sequence 3 or 4 intrusions

The Horsethief Canyon hornblende-biotite andesite intrusion (Thbai; Table 1) is included in sequence 4 due to the presence of biotite, which is also found in the Markleeville Peak intrusions (Thbdi). It intrudes sequence 3 volcanic debris flow deposits (Tvdf1), so it could be age-equivalent to sequence 3 rather than sequence 4.

The olivine basaltic intrusion (Tbi) at Pickett Peak also is undated. We tentatively include it in sequence 4, because the only other basalt in the area (Tbl at the Sierran crest) erupted during sequence 4.

**Summary of Sequence Stratigraphy**

We recognize four major unconformity-bounded units in the Hope Valley – Carson Pass – Kirkwood paleocanyon system (Figure 9). Unconformity 1 records the unroofing of the Mesozoic Sierra Nevada batholith to mesozonal levels in Late Cretaceous to Paleocene time. The paleocanyon was later filled with sequence 1 Oligocene ignimbrites erupted from sources in central Nevada, over a timespan of millions of years (Figure 9A). These ignimbrites were largely eroded from the canyon during development of unconformity 2, and overlain by block-and-ash-flow tuffs that record the onset of arc magmatism in the central Sierra Nevada (Figure 9B). These were reworked down the paleocanyon into debris flow and fluvial deposits (Figure 9B). These deposits were in turn eroded during the development of unconformity 3, and overlain by volcanic fluvial deposits of sequence 3 (Figure 9C). In most localities, the fluvial deposits pass gradationally upward into volcanic debris flow deposits (Figure 9D) also included in sequence 3, because the erosional surfaces between these units in Kirkwood Valley (unconformities 4 and 5 of Busby et al., 2008a) are areally restricted. Peperitic intrusions in the west part of the paleocanyon at Kirkwood Valley are included in sequence 3, as are volcanic necks of the same age in the northeastern paleotributary; these presumably formed feeders for andesite lava domes. Unconformity 4 (Figure 9E) is the youngest unconformity preserved in the paleocanyon, and locally cuts down to granitic basement. Sequence 4 has the bulk of the primary volcanic rocks in the paleocanyon fill, including basaltic and andesitic lava flows, and basaltic andesite to andesite block-and-ash-flow tuffs, as well as their reworked equivalents in the form of volcanic debris flow deposits, and it lacks fluvial deposits. During deposition of sequence 4 volcanic rocks in the main paleocanyon, the southeastern paleotributary was intruded by the Markleeville Peak dacite and andesite plugs, which hydrothermally altered their roof rocks (Figure 9E). We infer that this relatively large intrusive complex was emplaced within an incipient Hope Valley graben (Figure 9E). We also infer that the andesite lava flows erupted after the Red Lake Peak fault initiated, as they are restricted to the hangingwall of that fault and banked against it. Furthermore, debris flow deposits that overlie the lava flows on the hangingwall of the fault have mega-blocks that could represent material that avalanched off the developing fault. Ultimately, the paleocanyon was disrupted by the development of the Hope Valley graben.

## HOPE VALLEY GRABEN

In this section, we provide new age controls on the development of the range-front fault system at Carson Pass, and provide estimates of the amount of offsets on these faults. We propose a new term, “Hope Valley graben” for the structure of the range front at Carson Pass.

The Hope Valley area marks a change in geomorphological style of the Sierra Nevada range front. From Hope Valley south, the Sierra Nevada frontal fault system forms a narrow, steep east-facing escarpment (Figure 1A). In that segment, steep river canyons run east from the crest to the Owens Valley. In contrast, to the north of Hope Valley, the Sierra Nevada frontal fault system forms the western boundary of the Tahoe graben, and the northern Sierra Nevada is broken by a series of north-northwest striking faults (Figure 1A). The rivers in the Hope Valley and Tahoe area (West Fork Carson and Upper Truckee Rivers, respectively) run north-south on relatively gentle gradients, in contrast with rivers to the south. The Hope Valley graben is a much smaller, shallower structure than the Tahoe graben, but because it is not filled by a lake, it offers a relatively complete view of its structure.

The Hope Valley graben has historical significance as well. Our new mapping shows that the fault that forms the western boundary of the graben, herein named the Red Lake fault, takes a major right step or bend under Red Lake (Figure 2A). The range front relief is much gentler at this bend or stepover, indicating that it is a lateral ramp. Indeed, the highway over Carson Pass exploited this ramp until 1977, when the modern highway was blasted out of the mountainside north of Red Lake (Figure 2A). Even more interestingly, a Forest Service display at the top of what we interpret to be a lateral ramp tells visitors of the fact that the pioneers made use of the relatively gentle relief here to pull their wagons over the pass.

**Western Graben Margin: Red Lake Fault**

The Red Lake fault runs from Upper Blue Lake to Red Lake, and continues north buried under Quaternary deposits in Hope Valley, creating the 600+ m (2000+ ft) escarpment east of the Sierran crest ridge (Figure 2A). Armin et al. (1984) previously ended this fault below the volcaniclastic rocks on top of Red Lake Peak, where we mapped a metamorphic fin that forms a paleocanyon wall. Instead, we infer that this fault bends or jogs west to the south of Red Lake Peak (Figure 2A).

Just south of Red Lake, the Red Lake fault places Cretaceous granite against Miocene volcanic rocks (Figure 3B). The fault surface is hidden by 10-m-wide zone of trees and talus along old Highway 88 where the upper andesite lava flow (Thalu) strikes into granitic rock. Beneath the lower lava flow (Thall), the fluvial conglomerate and sandstone unit (Tvf1) crops out along Red Lake's southeastern shore. This fluvial deposit also crops out at Red Lake Peak, so we have used this unit to determine a minimum offset of 365 m (1200 ft) across the Red Lake fault (Figure 3A). This is a minimum, because the base of the fluvial unit on the down-dropped side of the fault is not exposed. However, a check on this estimate is provided by the offset of the stratified cobble breccia-conglomerate (Tsb) along the Red Lake fault. This unit lies at the base of Elephant's Back on the footwall side of the fault in the southern end of the hills east of the hangingwall. A minimum offset estimate of ~400 m (1300 ft) is consistent with the estimate for offset of the fluvial conglomerate and sandstone unit (Tvf1 offset 365 m; Figure 3B). The andesite lava flows (Thall and Thalu) are restricted to the hangingwall of the Red Lake fault and abut it directly (Figure 2). This may indicate that the fault served as a conduit for the eruption of the lava flows, or it forms a buttress unconformity with the lava flows.

Farther south along the Red Lake fault, the altered andesite unit (Taa) is downdropped against granitic basement (Figure 2). In this area, a 40-m-wide zone of shattered granite is intruded by a porphyritic andesite, labeled as a body of altered andesite (Taa) within the granitic rock (Figure 4F). This non-brecciated andesite likely formed due to magma rising along the fault and intruding brecciated granite along the fault zone. This intrusion is propylitically altered and therefore not suitable for Ar/Ar dating. However, the presence of an altered andesite intrusion in shattered granitic rocks along the fault zone indicates that volcanism and faulting overlapped in time, that the fault started slipping before magmatism ceased. Because most of the volcanic and intrusive activity in the map area occurred at ~6 Ma, and the intrusions within the altered andesite are dated at ~6 Ma (Figure 2), we tentatively interpret that to be the age of the intrusion in the brecciated granite. An up to 750 m (~2500 ft) wide zone of brecciated and sheared granite extends south from the altered andesite intrusion for at least 1,500 m (~4,900 ft). This zone of deformed granite has numerous calcite veins up to 2 m wide by 30 m long, which trend 340°, the same orientation as the fault (Figure 2A).

**Eastern Graben Margin: Hope Valley Fault**

The Hope Valley Fault runs through the center of the map area, along the east side of Hope Valley (Figure 2A). It forms a 365 m (1200 ft) tall, west-dipping topographic escarpment in granitic rock on the east side of Hope Valley, suggesting that it is a west-dipping normal fault. Otherwise, it is hidden by Quaternary deposits or cuts altered rocks in which it is difficult to identify.

We propose that the altered andesites at the south end of Hope Valley (unit Taa) are altered roof rocks of the Markleeville Peak intrusions, downfaulted into the Hope Valley graben. This interpretation is supported by the presence of small, irregularly-shaped hornblende-biotite dacite intrusions, unique to the Markleeville Peak intrusive complex in the map area, that cut the altered rocks west of the fault. These are interpreted to be roof rocks of the intrusive complex, which we infer forms a continuous body beneath the altered rocks in the graben. A crude minimum estimate of 370 m (1200 ft) offset along the Hope Valley fault can be made using the offset between the base of the altered unit on the hangingwall (west of the fault) and the highest point on the eroded top of the intrusion on the footwall (east of the fault; Figure 3C) assuming that the top of the intrusion was relatively flat.

**Possible Horsethief Canyon Fault**

Armin et al. (1983) mapped a fault along Horsethief Canyon, between granitic rocks to the west (Kgu) and undivided Tertiary volcaniclastic deposits to the east that we map as units Tvs, Tvf1, and Tvdf1 (Figure 2). We see no evidence for a fault there. There is no topographic escarpment along this proposed fault, nor does it appear to continue south through Tertiary strata of Hawkins Peak and Pickett Peak (Figure 2). The lower volcanic debris flow deposit unit (Tvdf1) occurs on both sides of Horsethief Canyon, and although the base of this unit rests on granitic basement at a higher elevation west of Horsethief Canyon than it does on the east side, this is likely a paleotopographic effect. Thus, the modern Horsethief Canyon follows a steep, 550 m (1800 ft) high paleocanyon wall. Instead of a fault, we use our more detailed lithofacies mapping to define a paleocanyon with a v-shaped base that widens upwards (Figure 2).

**Hope Valley Graben: Symmetrical in South and Asymmetrical in North**

At the south end of our map area (Figure 2), we estimate subequal normal offset across the Hope Valley graben between the Red Lake fault on the east and the Hope Valley fault on the west (Figure 3). However, the Hope Valley fault appears to die out to the north (Figure 2), whereas normal offset on the Red Lake fault appears to increase northward. The granitic escarpment increases from < 425 m (1400 ft) near Elephant's Back to 800 m (2600 ft) at Steven's Peak (Figure 2). Along the northern segment of the Red Lake fault, the base of the paleocanyon west of the graben lies at an elevation of ~2530 m (8400 ft), while the base of the paleocanyon east of the graben at Horsethief Canyon is 430 m (1400 ft) lower. This is consistent with the interpretation that normal offset on the Red Lake fault grows northward, while the Hope Valley fault dies out northward.

**Possible Role of Faults in Emplacement of Igneous Rocks**

We propose that faults of the Hope Valley graben guided the emplacement of magmas of the Ancestral Cascades arc. Most significant is emplacement of the Markleeville Peak center (Thbdi) in the south end of the Hope Valley graben. This ~6 km diameter center is one of the largest volcanic centers we have recognized in the central Sierran segment of the Ancestral Cascades arc (Busby and Putirka, 2009). Furthermore, it forms part of an extensive alteration zone (altered andesite, Taa) that extends southward along range-front faults toward Ebbetts Pass (Wilshire, 1956, and our unpublished data). This alteration is the effect of hydrothermal activity associated with major ~6 Ma magmatism and faulting in the area. Also significant is the emplacement of andesite lava flows (Thall and Thalu) and interstratified block-and-ash-flow tuffs (Thaba3) on the graben floor adjacent to the Red Lake fault. Last, although the source of the 6.95 ± 0.20 Ma basalt lava flows is not known, their location just down-paleocanyon from the Red Lake fault may indicate that incipient faulting controlled their eruption and emplacement.

### Lack of Evidence for Transtension in the Hope Valley Graben

The GPS velocity field for the central Sierra Nevada has displacements consistent with westward extension and northwest-directed shear (Oldow et al., 2001). Earthquake focal plane mechanisms for the area also suggest a present-day right-lateral transtensional stress or strain setting (Oldow, 2003; Unruh et al., 2003). However, the Hope Valley – Carson Pass paleocanyon system does not appear to be offset in a strike-slip sense and perhaps indicate lateral motion is partitioned on faults farther east.

## CONCLUSIONS

In the Carson Pass area, Oligocene ignimbrites and Miocene calc-alkaline volcanic and volcaniclastic rocks fill a paleocanyon that was carved into mesozonal granitic basement between Cretaceous and Eocene time. Miocene volcanic-volcaniclastic and intrusive rocks form part of the Ancestral Cascades arc, and range from mafic to silicic compositions, including olivine basalts, pyroxene basaltic andesites, hornblende-pyroxene andesites, and hornblende-biotite dacites with a minor rhyolitic intrusion. We found no consistent trend in composition versus age for these volcanic rocks, nor did we find a consistent trend in dominant compositions of clasts in fluvial or debris flow deposits.

Our new $^{40}Ar/^{39}Ar$ age data show that three phases of volcanism occurred in the Hope Valley – Carson Pass region during the Miocene (Figure 2B): at about 16–13.5 Ma (middle Miocene), 11–10 Ma (early late Miocene) and 7–6 Ma (late Miocene). The three pulses in volcanism are recognized across the central and northern Sierra (Busby and Putirka, 2009). Volcanic activity in the Hope Valley – Carson Pass area resulted in emplacement of small volume block-and-ash-flow tuffs and lesser lava flows, which were reworked down-paleocanyon into volcaniclastic debris flow and fluvial deposits. Intrusive plugs of less than ~250 m (820 ft) in diameter are scattered throughout the area, and may represent feeders to some of the primary volcanic deposits. The Markleeville Peak intrusion (Thbdi) is the largest in the area; its intrusions are exposed across a width of ~3 km and are inferred to lie beneath the altered andesite (Taa) for an additional ~3 km to the west. We infer that late Miocene (7–6 Ma) magmas exploited the Red Lake and Hope Valley faults as they began to grow, and have found no evidence for faulting in the map area before that time. Thus, while minor middle Miocene and early late Miocene volcanism occurred in the area prior to any fault activity we recognize, we propose that the major volcanism occurred at the onset of range-front faulting here.

The volcanic and volcaniclastic rocks of Hope Valley are preserved in a paleocanyon carved into Mesozoic basement rock. In this paper, we integrated the sequence stratigraphic analysis of the Carson Pass – Kirkwood Valley segment of the paleocanyon fill, described by Busby et al. (2008a), with analysis of a more headward part of the paleocanyon in the Hope Valley – Carson Pass segment (Figures 2 and 9). In the Hope Valley segment, we identified two paleotributaries that merge at the present-day Sierran crest to form an over 7 km wide paleocanyon that was at least 550 m (1800 ft) deep. The southern paleotributary is 6 km wide and 240 m (800 ft) deep, while the northern paleotributary is up to 10 km wide and over 750 m (2500 ft) deep. Detailed lithofacies mapping of Oligocene through Miocene fill of these paleocanyons is used to identify four major incision events. The first incision occurred between about 83 – 30 Ma (unconformity 1), and is the contact between Mesozoic basement rocks and Oligocene ignimbrites of sequence 1. The ignimbrites were largely eroded away sometime between 23 – 16 Ma (unconformity 2), and the paleocanyons were filled with volcanic fluvial sandstones and andesitic block-and-ash-flow tuff deposits that pass downstream to volcanic fluvial and debris flow deposits (sequence 2). Between 13.5 and 11 Ma, the paleocanyon was again re-incised (unconformity 3) and then filled with andesitic volcaniclastic debris (sequence 3). Also included in sequence 3 are ~10.7 Ma shallow-level intrusions at Pickett Peak and Hawkins Peak (Figure 2A) that were emplaced coevally with a peperitic andesite dike at Kirkwood Valley (Figure 2B). Sometime between the emplacement of the 10.7 Ma volcanic intrusions and renewed volcanic activity at ~7 Ma, the canyon was re-incised (unconformity 4, Figure 2B). Regional stratigraphic relations indicate that this happened at about 8 Ma (Busby and Putirka, 2009). From 7 – 6 Ma (sequence 4), the region was rife with volcanic and intrusive activity (sequence 4). We propose that the Red Lake fault and Hope Valley faults began moving at this time, but they could have started movement any time after 10 Ma.

Hope Valley is a full graben bounded on the west by the Red Lake fault and on the east by the Hope Valley fault. The Red Lake fault has at least 400 m (1300 ft) of normal offset since its initiation. The Hope Valley fault has at least 370 m (1200 ft) of normal offset since 6.34 Ma. Both of these faults have subequal offset at the south end of the Hope Valley graben, but the Hope Valley fault dies out to the north, while offset on the Red Lake fault grows by the same amount. The timing of the end of movement along the faults is poorly constrained, because we have found no volcanic rocks younger than 6 Ma and found no scarps in Quaternary deposits.

Recent studies use geodetic and fault focal mechanism data to infer that at least some Sierra Nevada range-front faults have a strike-slip component, i.e., they are transtensional. However, we see no evidence for strike-slip offset of the Hope Valley – Carson Pass – Kirkwood paleocanyon across the Hope Valley or Red Lake faults, nor do we see evidence for a fault taking up pure strike-slip motion in the map area.

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## FIGURE CAPTIONS

Figure 1:

(A) Map of the Central Sierra Nevada, showing modern drainages and the Sierra Nevada range crest, range-front faults (after Wakabayashi and Sawyer, 2001), major roads, and distribution of Cenozoic volcanic-volcaniclastic rocks. Map area (Figure 2) and other localities of the central Sierra referred to in text are shown.

(B) Inferred position of two paleocanyon tributaries in the Hope Valley area that merge at the Sierran crest to form one paleocanyon in the Carson Pass – Kirkwood area, based on mapping presented here (Figure 2A) and by Busby et al. (2008a). As discussed in text, dextral transtensional motion is inferred from focal mechanisms and from geologic mapping of other range-front faults, but there is no evidence here for dextral offset of the paleocanyon along range-front faults. Pink lines = faults; red lines = roads; arrows = paleoflow direction.

Figure 2:

(A) Geologic map of the Hope Valley area; key to map units is given in Figure 2B. Mapping by Jeanette Hagan (2005, 2008). Previous mapping by Armin et al. (1983, 1984) and Mosier (1991) described in text.

(B) Chronostratigraphic correlation chart for the map units of the Kirkwood Valley – Carson Pass – Hope Valley area. These map units form the fill of, or intrude, the Hope Valley – Carson Pass – Kirkwood paleocanyon system, shown in Figure 9. The column on the left edge displays the stratigraphy at Kirkwood Valley, taken from Figure 2 of Busby et al. (2008a). The NW Sierran crest column is updated from that map, based on more detailed geologic mapping and geochronology completed for this study. Map unit Thaba1 in this paper was labeled Taba1 in Busby et al. (2008a). The other four columns represent stratigraphic relationships recognized in the present study (Figure 2A). Unconformity surfaces are noted by zig-zag bold black lines and labeled at left in red. Unconformity 1 records late Cretaceous unroofing of the Sierra Nevada batholith during low-angle subduction (Busby and Putirka, in review). Unconformities 2, 3 and 4 can be traced along the mapped length of the paleocanyon system, from Kirkwood to the east side of the Hope Valley graben; these are interpreted to occur across the central Sierra and record Miocene uplift events (Busby and Putirka, in review). We do not find the previously mapped unconformities 4 and 5 of Busby et al. (2008a) at Hope Valley, and do not consider them to be significant unconformities. Correlations of units across regions are noted by dashed lines; abbreviations include conglomerate (cg), sandstone (ss), biotite (bt), hornblende (hb), and pyroxene (pyx).

Figure 3: Geologic cross sections through the Hope Valley graben.

(A) Cross-section A-A’ from north to south through Red Lake Peak, Red Lake, the Red Lake fault, and the hills east of Elephant’s Back. We correlate a fluvial unit (Tvf1) near the base of the paleocanyon across the fault, and use it to estimate an offset of at least 365 m (1200 ft) across the fault.

(B) Cross-section B-B’ from Elephant’s Back on the Sierran crest eastward, through the Red Lake fault south of cross section A – A’. The stratified cobble breccia-conglomerate of Elephant’s Back (Tsb, Figure 2A) is offset at least 400 m (1300 ft).

(C) Cross-section C-C’, through the Hope Valley fault and Markleeville Peak. To the east of the fault, Markleeville Peak is an intrusive complex (Thbdi) that intrudes the paleocanyon fill. We interpret the heavily altered rocks west of the fault (Taa) to represent the roof rocks to this intrusive complex, downdropped along the Hope Valley fault by about 370 m (1200 ft).

Figure 4: Representative photos of lithofacies described in Table 1.

(A) Distinctive columnar joints in the 10.77 ± 0.10 Ma intrusions of Pickett Peak (Tpai); the western of the two plugs is shown here. Height of outcrop in the center of the image is approximately 200 feet.

(B) Hornblende andesite lava flow with basal flow breccia and coherent, faintly columnar jointed interior. Photo taken just south of Red Lake (Thalu; Figure 2A).

(C) Pyroxene andesite block-and-ash-flow tuff, with monolithic, angular nonvesicular (dense) clasts set in a matrix of ash-sized material of the same composition. Photo taken on Red Lake Peak (Tpaba; Figure 2A).

(D) Andesite block with well-developed, delicate bread crust texture indicating deposition while still hot. Photo taken of block-and-ash-flow tuff at the base of map unit Tvdf2 (east of Elephant’s Back; Figure 2A).

(E) 6.29 ± 0.10 Ma – 6.13 ± 0.34 Ma Red Lake Peak pyroxene andesite block-and-ash-flow tuff (Tpaba) with oxidized basal interval, resting directly upon 13.61 ± 0.16

Ma Red Lake Peak hornblende andesite block-and-ash-flow tuff (Thaba2), on the north face of Red Lake Peak.

(F) Massive, unsorted, coarse-grained volcanic debris flow deposit with a variety of angular to subrounded andesite clast types, supported by a buff pebbly sandstone matrix (Tvdf2 east of Elephant's Back).

(G) Crudely-stratified, clast-supported deposit, with sedimentary structures and textures transitional between those of debris flow deposits and fluvial deposits; mapped as a debris flow deposit throughout the field area. Photo taken at the base of map unit Tvdf1 west of Pickett Peak.

(H) Well-stratified and well-sorted fluvial deposit, with planar-laminated and cross-laminated beds and rounded clasts of a variety of types of andesite. Photo taken from map unit Tvf1 above Crater Lake on the Sierran crest.

(I) The contact between the white, ignimbrite-clast rich well-stratified pebbly sandstone (Tvs) and the light brown, pebble to cobble crudely stratified fluvial conglomerate and sandstone (Tvf1). Photo taken from Horsethief Canyon, looking east.

(J) Brecciated Cretaceous granitic rock, intruded by a plagioclase andesite porphyry. This granite breccia forms an approximately 200 m long and 40 m wide elongate pod that lies along the Red Lake fault zone between Elephant's Back and Blue Lake, where the fault zone forms a southward-widening zone of brecciated granite with calcite veins (Figure 2A, indicated by wavy lines).

Figure 5: Modal analyses of primary volcanic deposits and intrusions in the Hope Valley area. Map unit names, symbols and sequence numbers correspond to Figure 2 and Table 1. Sequence 2 has three block-and-ash-flow tuffs, sequence 3 has one intrusive suite, and sequence 4 has the rest of the primary volcanic and intrusive rocks, arranged here in order of increasing silica content from bottom to top (Table 3, Figure 6). All samples geochemically analyzed except ERLPk and sample 85. One thin section per analysis with 1000 counts per thin section; GPS localities given in Table 2.

Figure 6: Alkali-silica (Le Bas, 1986) classification diagram for the Kirkwood Valley – Carson Pass - Hope Valley volcanic rocks and intrusions. Open circle represents present-

day calc-alkaline Cascades arc volcanism from Lassen data (Clynne, 1990). Data and GPS coordinates given in Table 2. Locations for samples labeled SBD# are plotted on Figure 2 of Busby et al., 2008a. Organized by mineralogy; color and shape of symbol indicates the presence of identifying minerals.

Figure 7: Photomicrographs of selected rocks dated in this study, showing that these Miocene rocks have unaltered plagioclase, clinopyroxene, orthopyroxene, hornblende and biotite.

(A) Photomicrograph of the western sequence 5 10.70 ± 0.1 Ma Pickett Peak two pyroxene andesite intrusion (Tpai, Figure 2) in crossed polarized light. Cluster of large clinopyroxene (cpx) surrounded by plagioclase (plag) and othropyroxene (opx).

(B) Photomicrograph of the upper hornblende andesite lava flow (Thalu, Figure 2) dated at 6.18 ± 0.14 Ma in crossed polarized light. Note the zoning of the hornblende (hb), with its distinctive cleavage angles, and the euhedral plagioclase crystals (plag).

(C) Photomicrograph of the Markleeville Peak hornblende-biotite andesite and dacite intrusion (Thbdi, Figure 2) in crossed polarized light, containing both biotite (bt) and hornblende (hb).

(D) Photomicrograph of an olivine basaltic intrusion (Tbi) where the olivine (Ol) has begun to alter to iddingsite in a fine-grained plagioclase plus olivine groundmass. Intrusion cut fluvial deposits on the Sierran crest (sample 20).

Figure 8: $^{40}Ar/^{39}Ar$ age spectra for samples from Hope Valley. See Figure 2 for sample localities, Table 2 for a summary of the data, and Table 3 for GPS localities. Plateau ages are shown with errors at one standard deviation. (A) Plagioclase age spectrum for the Jeff Davis Peak pyroxene-hornblende andesite and dacite block-and-ash-flow tuff (Tphaba), sequence 2. (B) Plagioclase age spectrum for the Jeff Davis Peak pyroxene-hornblende andesite and dacite block-and-ash-flow tuff (Tphaba), sequence 2. (C) Hornblende age spectrum for the Red Lake Peak hornblende andesite block-and-ash-flow tuff (Thaba2), sequence 2. (D) Hornblende age spectrum for the Pickett Peak pyroxene andesite intrusion (Tpai), sequence 3. (E) Hornblende age spectrum for the Red Lake Peak pyroxene basaltic andesite block-and-ash-flow tuff (Tpaba), sequence 4. (F)

Hornblende age spectrum for the Red Lake Peak pyroxene basaltic andesite block-and-ash-flow tuff (Tpaba), sequence 4. (G) Hornblende age spectrum for the Markleeville Peak hornblende andesite dike (Thadp), sequence 4. (H) Hornblende age spectrum for the upper hornblende andesite lava flow (Thalu), sequence 4. (I) Hornblende age spectrum for the Markleeville Peak hornblende-biotite dacite and andesite intrusions (Thbdi), sequence 4. (J) Hornblende age spectrum for the Markleeville Peak hornblende-biotite dacite and andesite intrusions (Thbdi), sequence 4.

Figure 9: A block diagram of the Hope Valley – Carson Pass – Kirkwood Valley area, modeling the topographic and volcaniclastic evolution from Oligocene until Late Miocene. Volcanic debris is transported down the paleotributaries in the east (upper right), and merges to form one paleocanyon in the west (lower left). (A) Unconformity 1, the contact between granitic basement rock and Tertiary volcanic rock, was cut into the bedrock in the Cretaceous. From 30-23 Ma the Oligocene ignimbrites filled the paleocanyon. (B) Unconformity surface 2 formed between ~23 and ~16 Ma, and eroded away much of the ignimbrite deposits. Then from 16 to ~13.5 Ma the paleocanyons filled with block-and-ash-flow tuffs (Tphaba, Thaba1, and Thaba2), which were reworked down-canyon into debris flow and fluvial deposits (Figure 2, Busby et al., 2008a). (C) Unconformity 3 was cut between 13.5 and 11 Ma, after the block-and-ash-flow tuff deposition (Thaba2) and before the deposition of thick fluvial deposits fed by debris flow lobes (Tvf1). (D) Unconformities 4 and 5 are mapped in the Kirkwood region (Busby et al., 2008a), but are not found within the massive debris flow deposits of Hope Valley (Tvdf1). They may not exist, or may be cryptic and not visible due to the lack of bedding. At 10.7 Ma, lava domes, volcanic necks (Tpai) and peperites intruded into the debris flow deposits (Busby et al., 2008a). (E) Unconformity 4 was cut post 10.5 Ma, but prior to 6.9 Ma. Volcanic activity resumed at 6.9 Ma (Tbl) and continued through ~6 Ma (Thbdi, Tpaba) or possibly 5.2 Ma (Thai; Armin et al., 1984). The Red Lake and Hope Valley faults were active by 6 Ma, as the hornblende andesite lava flows (Thall, Thalu) erupted at the Red Lake fault, and the Markleeville intrusive complex is

exposed along the footwall of the Hope Valley fault while the altered roof of the complex (Taa) lies in the Hope Valley graben.

Table 1 – Description of lithofacies and intrusions for map units shown on Figure 2B. Each Tertiary map unit is named and described through field observations and through petrographic observations.

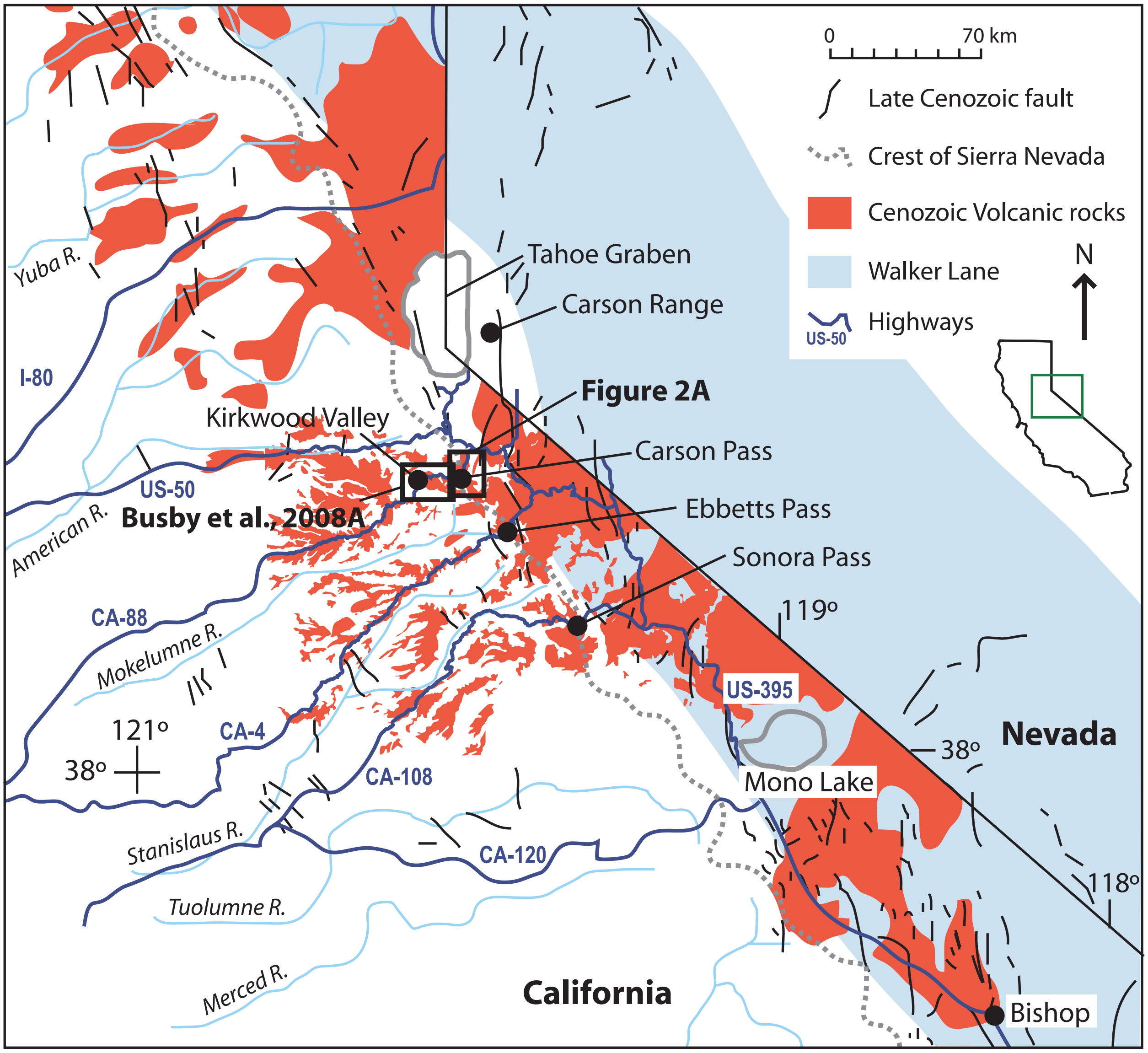
Table 2 – Geochemical analyses from primary volcanic rocks (lava flows and block-and-ash-flow tuffs), intrusions, and lesser clasts within debris flow deposits, Hope Valley – Carson Pass – Kirkwood area. Data organized by phenocrystic content. All map units analyzed are shown chronostratigraphically on Figure 2B. Samples labeled "JHCP" are plotted on the geologic map in Figure 2A. Chemistry of samples labeled ** and 'SBD' were reported in the data repository of Busby et al. (2008a); modal analyses and plots of the samples on a geologic map were presented in that paper. Rock names are from Figure 6. [1]Geochemistry on clast within labeled debris flow deposit; [2]Geochemistry on small-volume block-and-ash-flow tuff within labeled debris flow deposit; [3]Geochemistry on small dike within labeled debris flow deposit.

Table 3 – Summary of the $^{40}Ar/^{39}Ar$ dates we have acquired for the Hope Valley – Carson Pass – Kirkwood region. Locations for samples are plotted on Figure 2A. This table includes the two dates for map units Tbl and Thaba1 that were previously presented in Busby et al. (2008a); Map unit Thaba1 was previously labeled Taba1 on Figure 2 of Busby et al. (2008a).

Table 4 – Summary of the recalculated $^{40}Ar/^{39}Ar$ dates from Busby et al. (2008a).

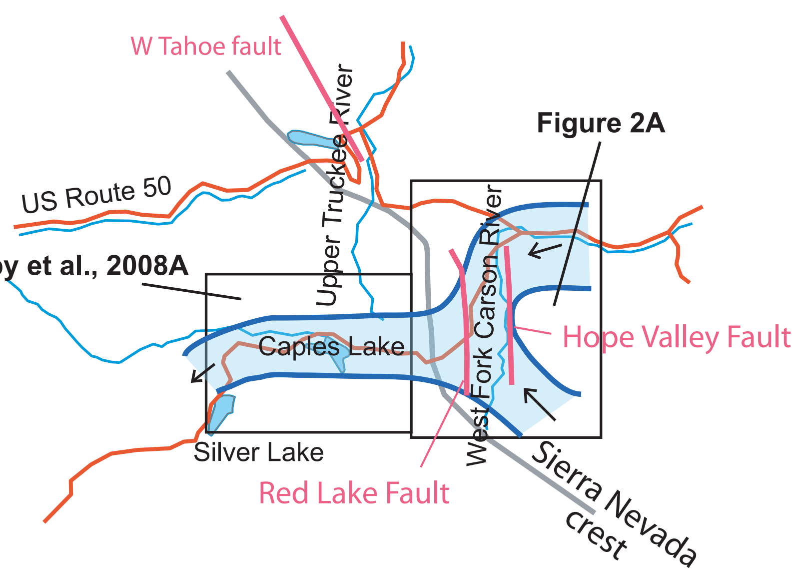
Figure 1

(A)

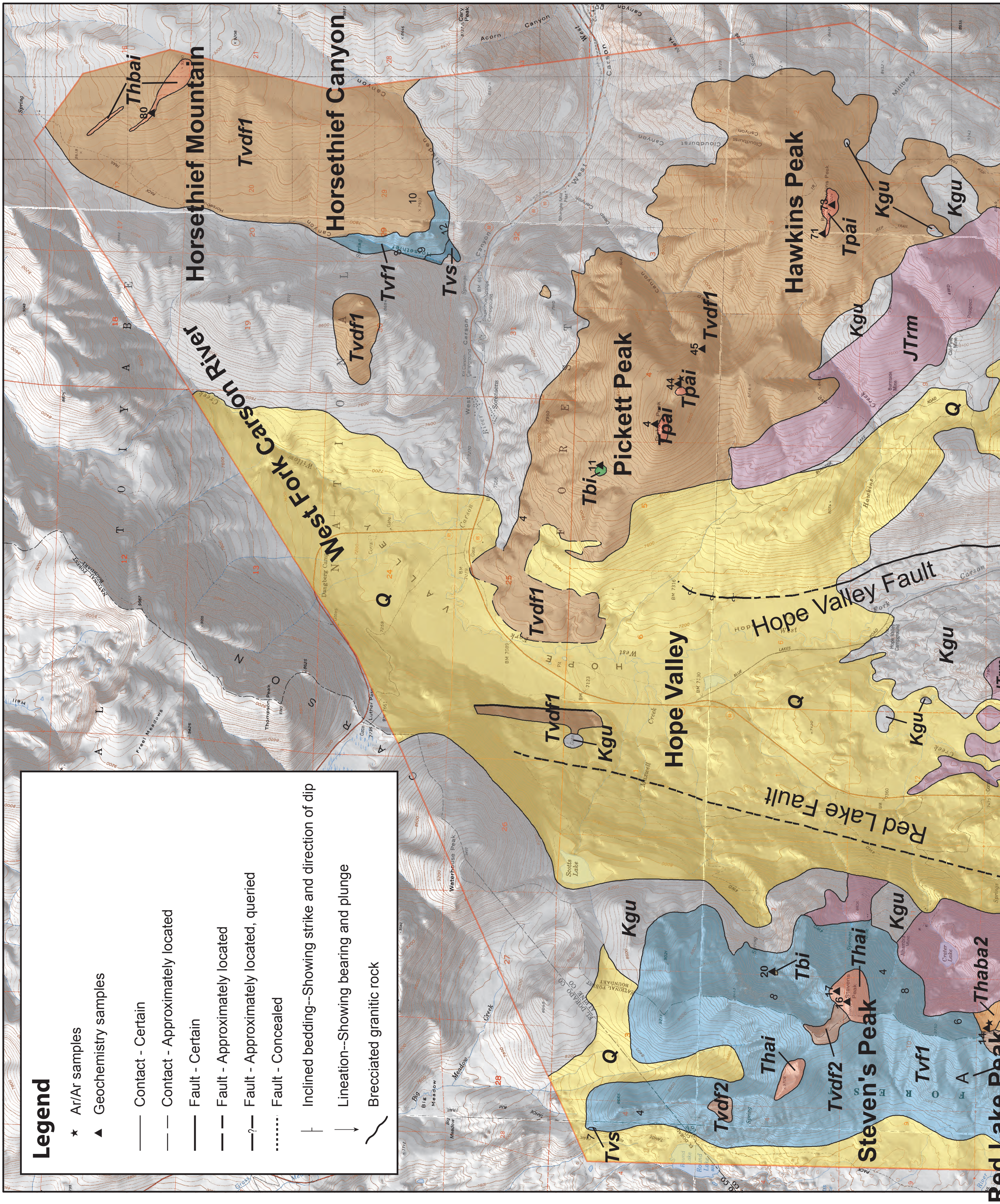


0
70 km
Late Cenozoic fault
Crest of Sierra Nevada
Cenozoic Volcanic rocks
Walker Lane
Highways
US-50
N
Tahoe Graben
Carson Range
Figure 2A
Kirkwood Valley
Carson Pass
Ebbetts Pass
Sonora Pass
Busby et al., 2008A
Yuba R.
I-80
US-50
American R.
CA-88
Mokelumne R.
121º
38º
CA-4
CA-108
Stanislaus R.
CA-120
Tuolumne R.
Merced R.
California
119º
US-395
Mono Lake
38º
Nevada
118º
Bishop

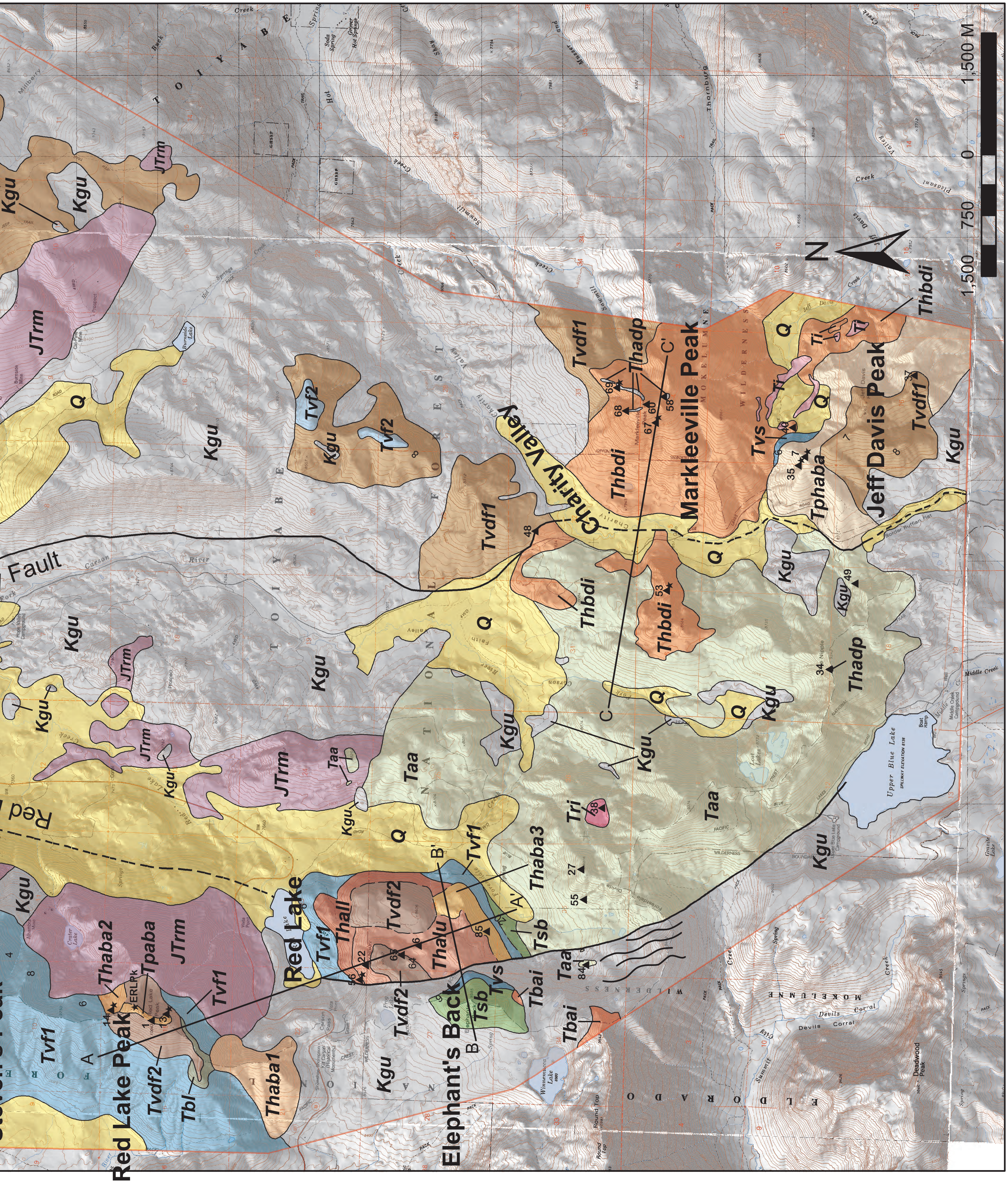

(B)



W Tahoe fault
Upper Truckee River
Figure 2A
US Route 50
Busby et al., 2008A
West Fork Carson River
Caples Lake
Hope Valley Fault
Silver Lake
Red Lake Fault
Sierra Nevada crest

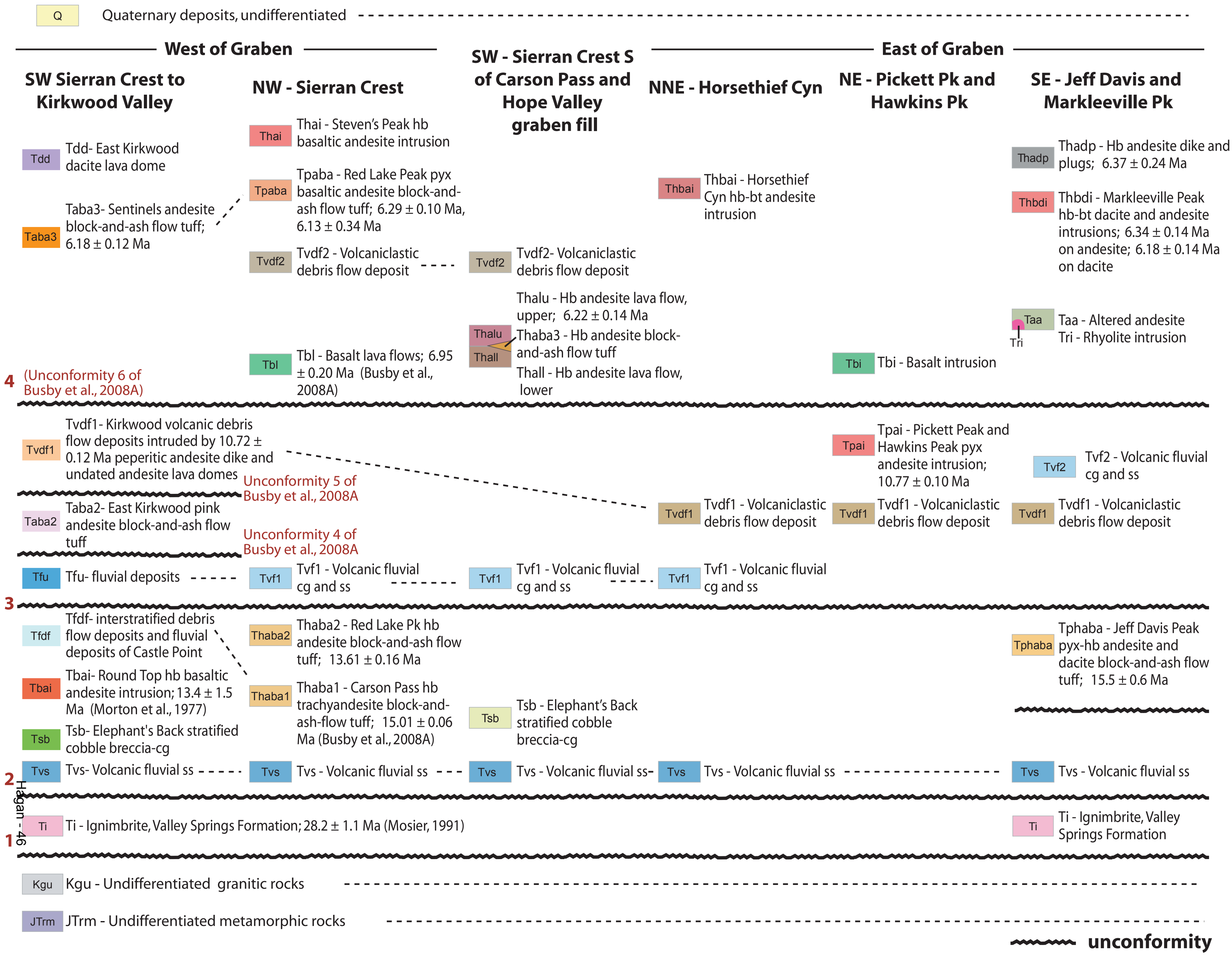


Legend
Ar/Ar samples
Geochemistry samples
Contact - Certain
Contact - Approximately located
Fault - Certain
Fault - Approximately located
Fault - Approximately located, queried
Fault - Concealed
Inclined bedding--Showing strike and direction of dip
Lineation--Showing bearing and plunge
Brecciated granitic rock
Horsethief Mountain
Horsethief Canyon
Thbai
Tvdf1
Tvf1
Tvs
West Fork Carson River
Pickett Peak
Tbi
Tpai
Hawkins Peak
Kgu
JTrm
Q
Hope Valley
Hope Valley Fault
Red Lake Fault
Steven's Peak
Thai
Tvdf2
Thaba2



Red Lake Peak
Elephant's Back
Red Lake
Markleeville Peak
Jeff Davis Peak
Charity Valley
Fault
Upper Blue Lake
N
1,500
750
0
1,500 M
Kgu
JTrm
Q
Tvf1
Tvf2
Tvdf1
Tvdf2
Thbdi
Thadp
Taa
Tri
Tsb
Tvs
Tbai
Thall
Thalu
Thaba1
Thaba2
Thaba3
Tpaba
Tphaba
Tbl
Ti
A
A'
B
B'
C
C'

Figure 2B



Q
Quaternary deposits, undifferentiated
West of Graben
East of Graben
SW Sierran Crest to Kirkwood Valley
NW - Sierran Crest
SW - Sierran Crest S of Carson Pass and Hope Valley graben fill
NNE - Horsethief Cyn
NE - Pickett Pk and Hawkins Pk
SE - Jeff Davis and Markleeville Pk
Tdd
Tdd- East Kirkwood dacite lava dome
Taba3
Taba3- Sentinels andesite block-and-ash flow tuff; 6.18 ± 0.12 Ma
Thai
Thai - Steven's Peak hb basaltic andesite intrusion
Tpaba
Tpaba - Red Lake Peak pyx basaltic andesite block-and-ash flow tuff; 6.29 ± 0.10 Ma, 6.13 ± 0.34 Ma
Tvdf2
Tvdf2 - Volcaniclastic debris flow deposit
Tbl
Tbl - Basalt lava flows; 6.95 ± 0.20 Ma (Busby et al., 2008A)
Tvdf2
Tvdf2- Volcaniclastic debris flow deposit
Thalu
Thall
Thalu - Hb andesite lava flow, upper; 6.22 ± 0.14 Ma
Thaba3 - Hb andesite block-and-ash flow tuff
Thall - Hb andesite lava flow, lower
Thbai
Thbai - Horsethief Cyn hb-bt andesite intrusion
Tbi
Tbi - Basalt intrusion
Thadp
Thadp - Hb andesite dike and plugs; 6.37 ± 0.24 Ma
Thbdi
Thbdi - Markleeville Peak hb-bt dacite and andesite intrusions; 6.34 ± 0.14 Ma on andesite; 6.18 ± 0.14 Ma on dacite
Taa
Tri
Taa - Altered andesite
Tri - Rhyolite intrusion
4
(Unconformity 6 of Busby et al., 2008A)
Tvdf1
Tvdf1- Kirkwood volcanic debris flow deposits intruded by 10.72 ± 0.12 Ma peperitic andesite dike and undated andesite lava domes
Unconformity 5 of Busby et al., 2008A
Taba2
Taba2- East Kirkwood pink andesite block-and-ash flow tuff
Unconformity 4 of Busby et al., 2008A
Tpai
Tpai - Pickett Peak and Hawkins Peak pyx andesite intrusion; 10.77 ± 0.10 Ma
Tvf2
Tvf2 - Volcanic fluvial cg and ss
Tvdf1
Tvdf1 - Volcaniclastic debris flow deposit
Tvdf1
Tvdf1 - Volcaniclastic debris flow deposit
Tvdf1
Tvdf1 - Volcaniclastic debris flow deposit
Tfu
Tfu- fluvial deposits
Tvf1
Tvf1 - Volcanic fluvial cg and ss
Tvf1
Tvf1 - Volcanic fluvial cg and ss
Tvf1
Tvf1 - Volcanic fluvial cg and ss
3
Tfdf
Tfdf- interstratified debris flow deposits and fluvial deposits of Castle Point
Tbai
Tbai- Round Top hb basaltic andesite intrusion; 13.4 ± 1.5 Ma (Morton et al., 1977)
Tsb
Tsb- Elephant's Back stratified cobble breccia-cg
Thaba2
Thaba2 - Red Lake Pk hb andesite block-and-ash flow tuff; 13.61 ± 0.16 Ma
Thaba1
Thaba1 - Carson Pass hb trachyandesite block-and-ash-flow tuff; 15.01 ± 0.06 Ma (Busby et al., 2008A)
Tsb
Tsb - Elephant's Back stratified cobble breccia-cg
Tphaba
Tphaba - Jeff Davis Peak pyx-hb andesite and dacite block-and-ash flow tuff; 15.5 ± 0.6 Ma
2
Tvs
Tvs- Volcanic fluvial ss
Tvs
Tvs - Volcanic fluvial ss
Tvs
Tvs - Volcanic fluvial ss-
Tvs
Tvs - Volcanic fluvial ss
Tvs
Tvs - Volcanic fluvial ss
1
Ti
Ti - Ignimbrite, Valley Springs Formation; 28.2 ± 1.1 Ma (Mosier, 1991)
Ti
Ti - Ignimbrite, Valley Springs Formation
Kgu
Kgu - Undifferentiated granitic rocks
JTrm
JTrm - Undifferentiated metamorphic rocks
unconformity

Figure 3

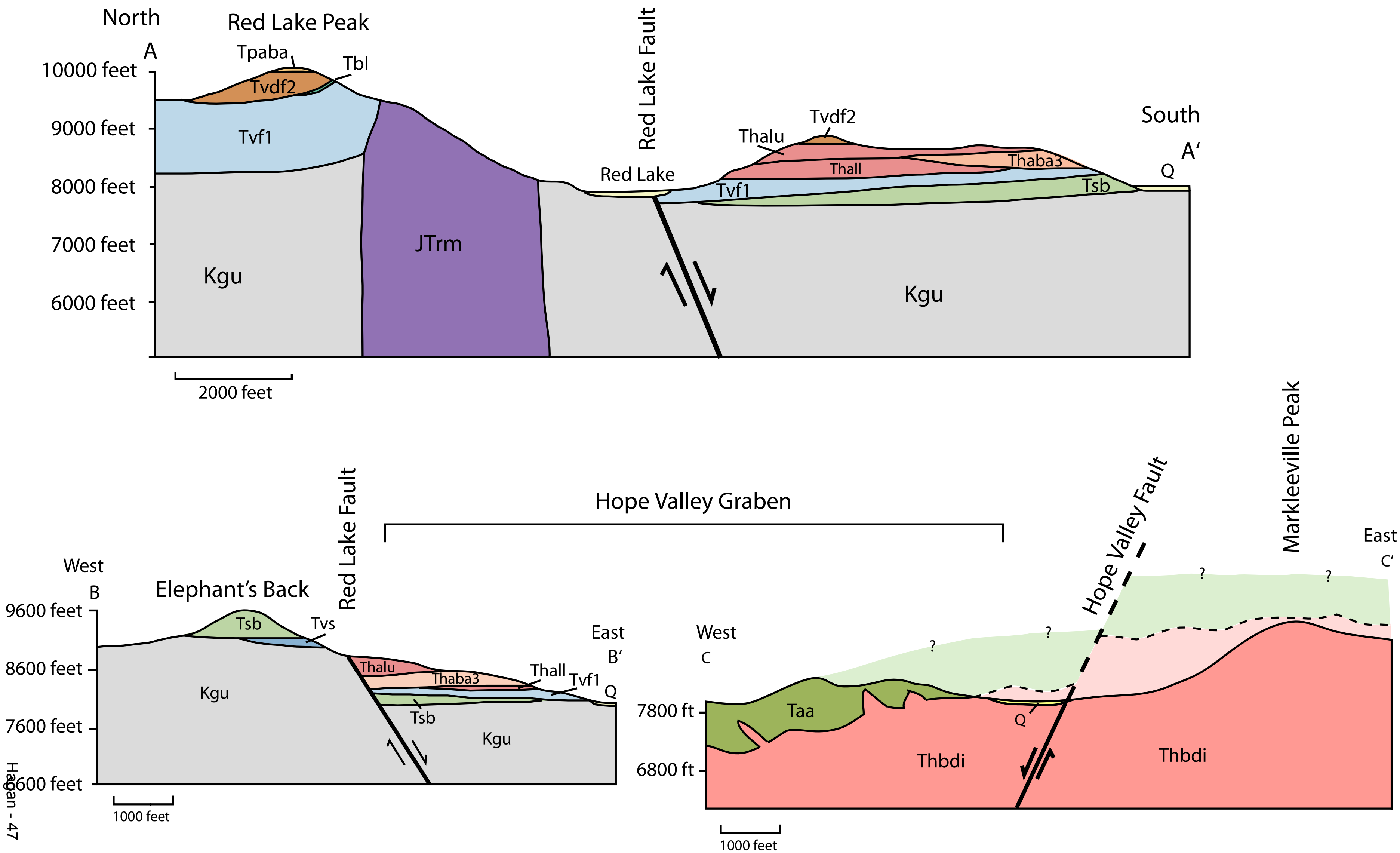

North
Red Lake Peak
A
Tpaba
Tbl
Tvdf2
10000 feet
9000 feet
8000 feet
7000 feet
6000 feet
Tvf1
Kgu
JTrm
Red Lake Fault
Red Lake
Thalu
Tvdf2
Thall
Thaba3
Tsb
Tvf1
Q
South
A′
Kgu
2000 feet
Hope Valley Graben
West
B
Elephant's Back
Tsb
Tvs
Red Lake Fault
9600 feet
8600 feet
7600 feet
6600 feet
Kgu
Thalu
Thaba3
Thall
Tvf1
Tsb
Kgu
East
B′
Q
1000 feet
Hope Valley Fault
Markleeville Peak
East
C′
West
C
7800 ft
6800 ft
Taa
Thbdi
Q
Thbdi
?
1000 feet

Figure 4

(A) (B) (C) (D) (E) (F)

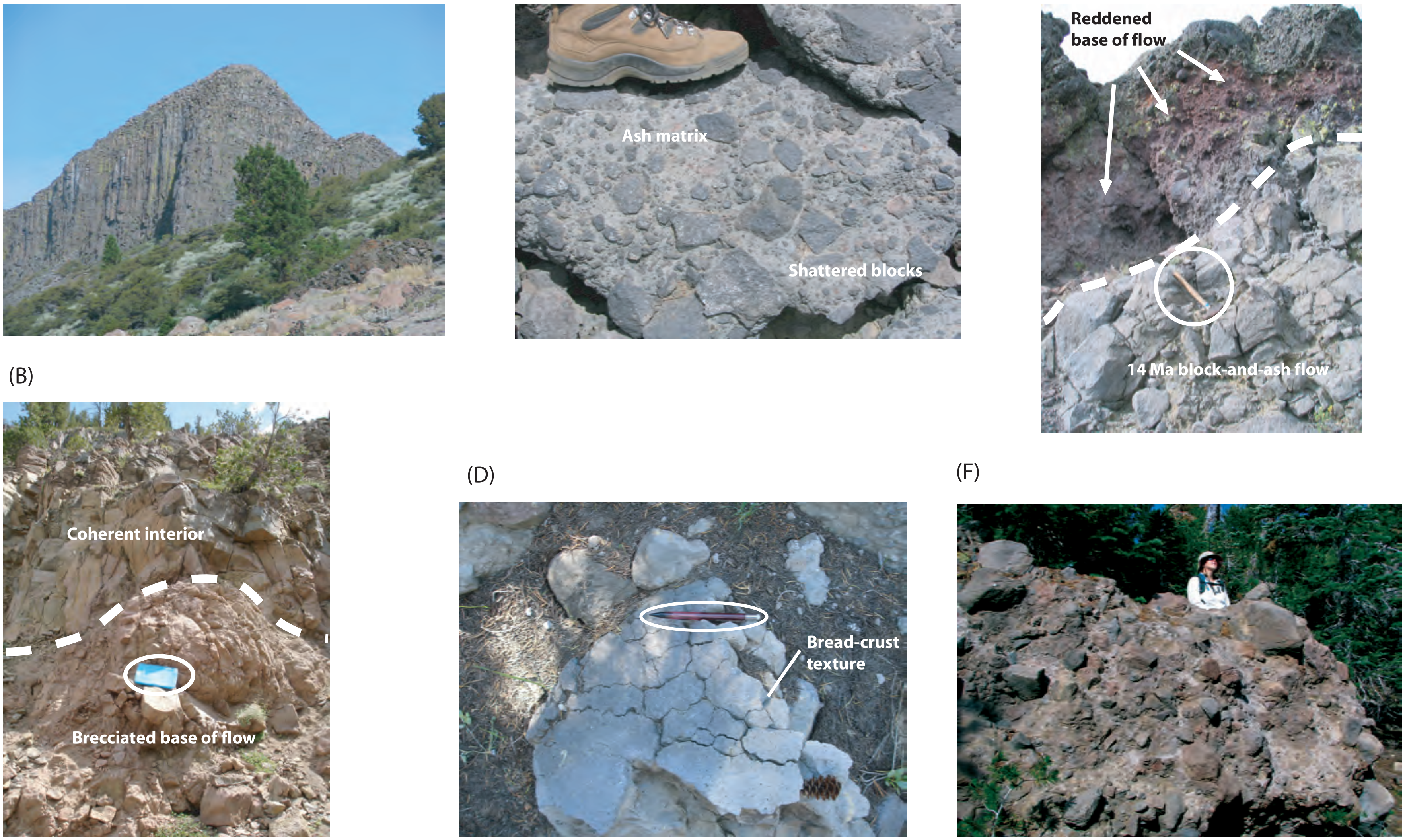
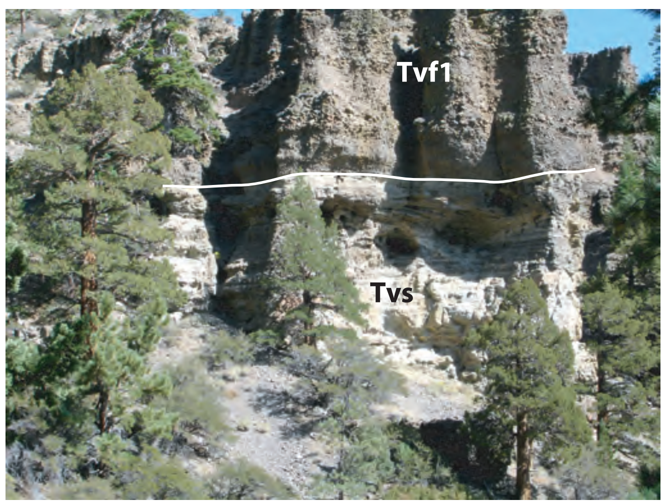


Figure 4

(G)

(H)

(I)




(J)

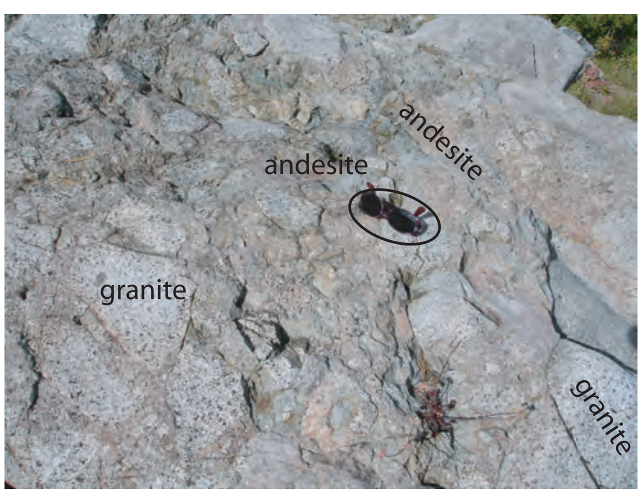


Figure 5

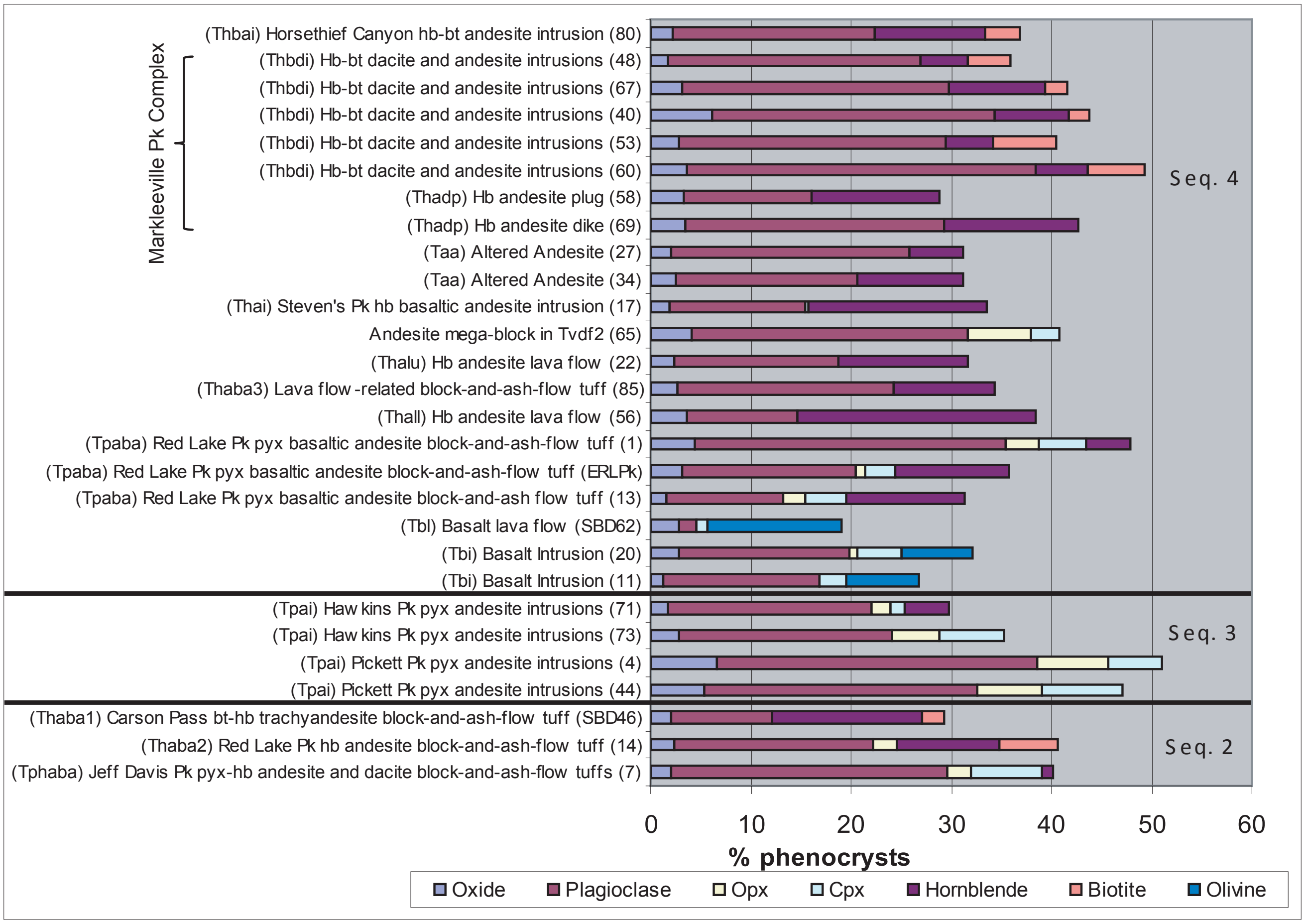



Figure 6

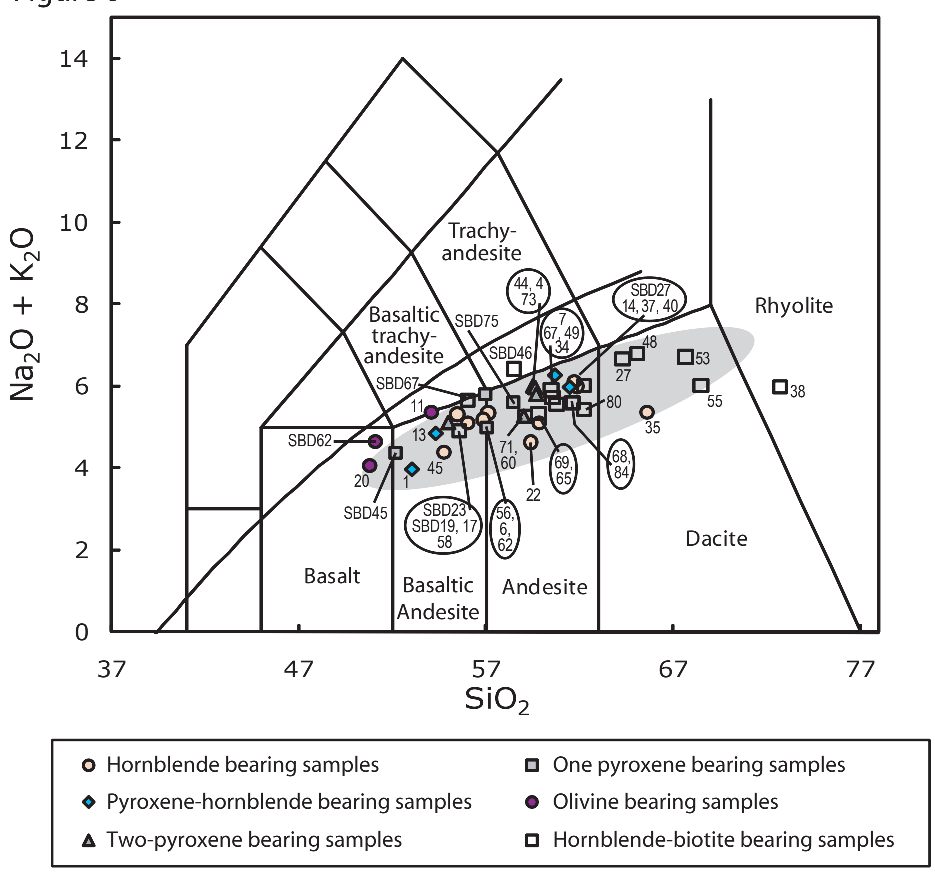


Figure 7

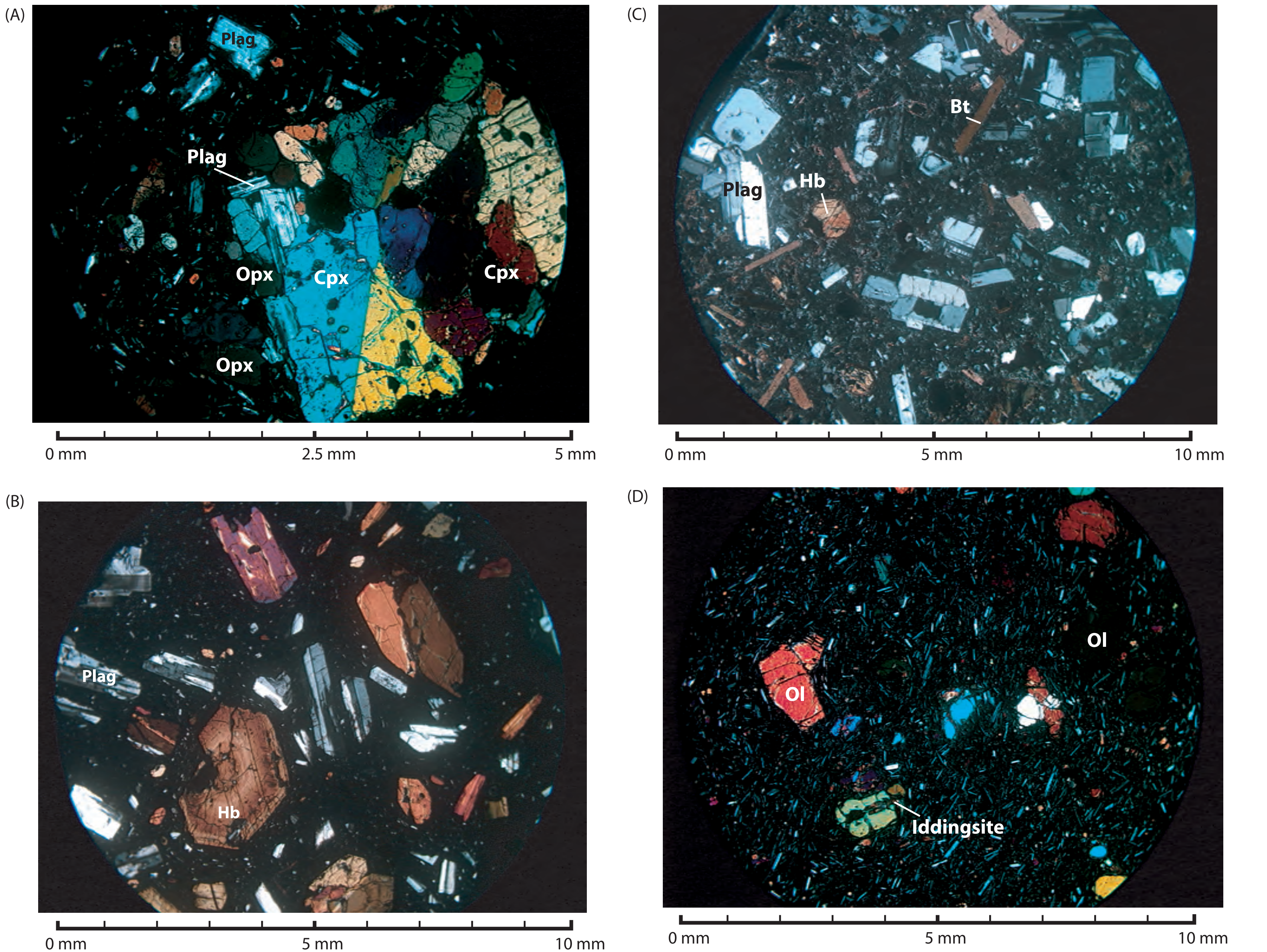
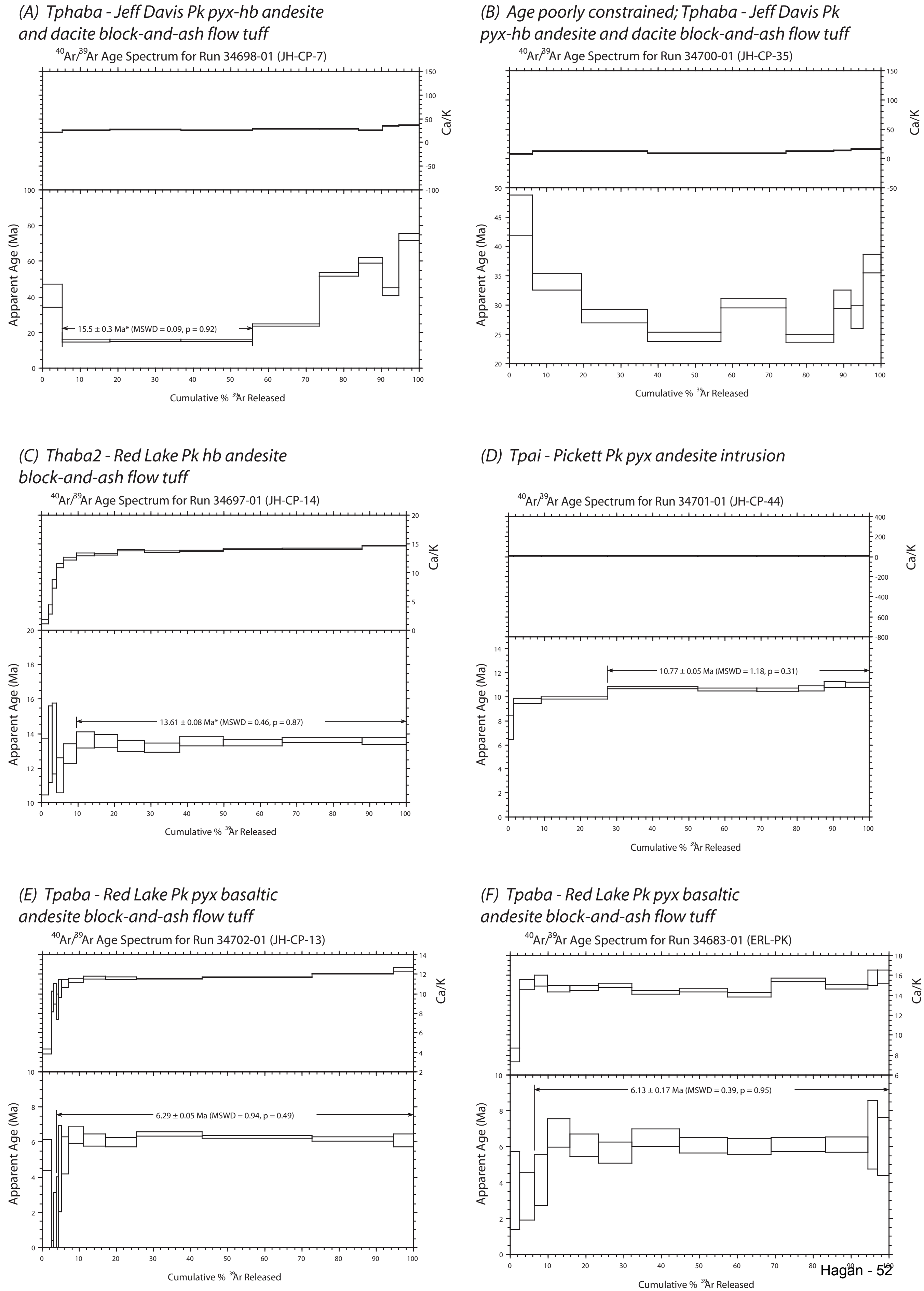

(A)
Plag
Plag
Opx
Cpx
Cpx
Opx
0 mm
2.5 mm
5 mm
(C)
Bt
Plag
Hb
0 mm
5 mm
10 mm
(B)
Plag
Hb
0 mm
5 mm
10 mm
(D)
Ol
Ol
Iddingsite
0 mm
5 mm
10 mm

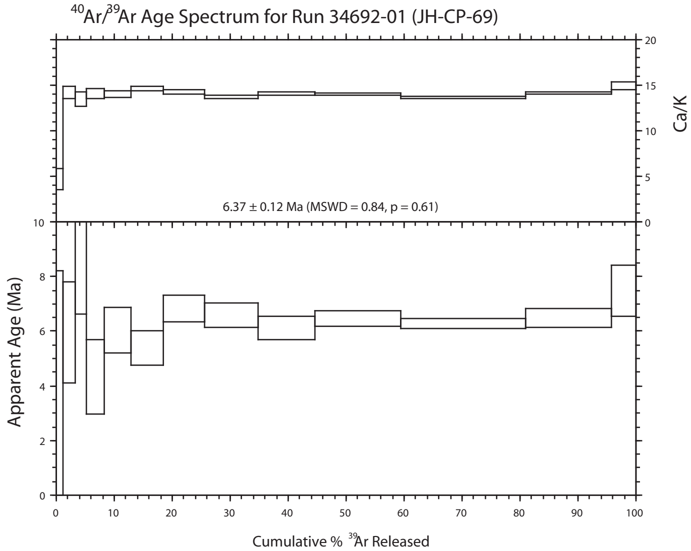
Figure 8



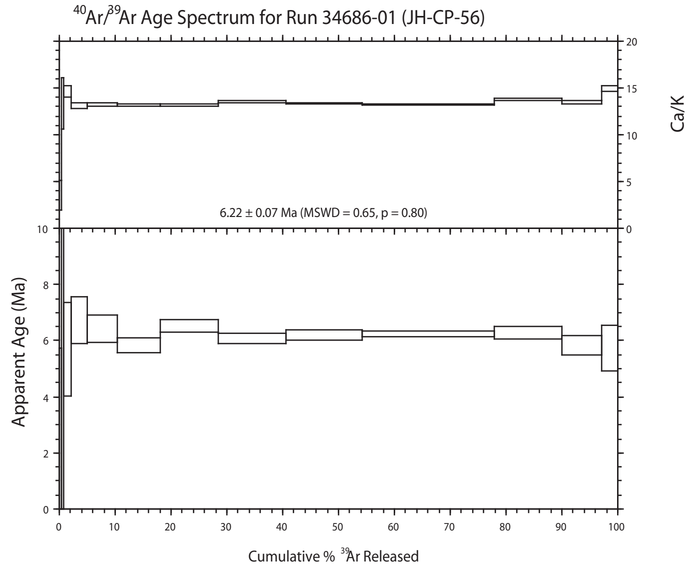
(A) Tphaba - Jeff Davis Pk pyx-hb andesite and dacite block-and-ash flow tuff
40Ar/39Ar Age Spectrum for Run 34698-01 (JH-CP-7)
Ca/K
Apparent Age (Ma)
15.5 ± 0.3 Ma* (MSWD = 0.09, p = 0.92)
Cumulative % 39Ar Released
(B) Age poorly constrained; Tphaba - Jeff Davis Pk pyx-hb andesite and dacite block-and-ash flow tuff
40Ar/39Ar Age Spectrum for Run 34700-01 (JH-CP-35)
Ca/K
Apparent Age (Ma)
Cumulative % 39Ar Released
(C) Thaba2 - Red Lake Pk hb andesite block-and-ash flow tuff
40Ar/39Ar Age Spectrum for Run 34697-01 (JH-CP-14)
Ca/K
Apparent Age (Ma)
13.61 ± 0.08 Ma* (MSWD = 0.46, p = 0.87)
Cumulative % 39Ar Released
(D) Tpai - Pickett Pk pyx andesite intrusion
40Ar/39Ar Age Spectrum for Run 34701-01 (JH-CP-44)
Ca/K
Apparent Age (Ma)
10.77 ± 0.05 Ma (MSWD = 1.18, p = 0.31)
Cumulative % 39Ar Released
(E) Tpaba - Red Lake Pk pyx basaltic andesite block-and-ash flow tuff
40Ar/39Ar Age Spectrum for Run 34702-01 (JH-CP-13)
Ca/K
Apparent Age (Ma)
6.29 ± 0.05 Ma (MSWD = 0.94, p = 0.49)
Cumulative % 39Ar Released
(F) Tpaba - Red Lake Pk pyx basaltic andesite block-and-ash flow tuff
40Ar/39Ar Age Spectrum for Run 34683-01 (ERL-PK)
Ca/K
Apparent Age (Ma)
6.13 ± 0.17 Ma (MSWD = 0.39, p = 0.95)
Cumulative % 39Ar Released

Figure 8

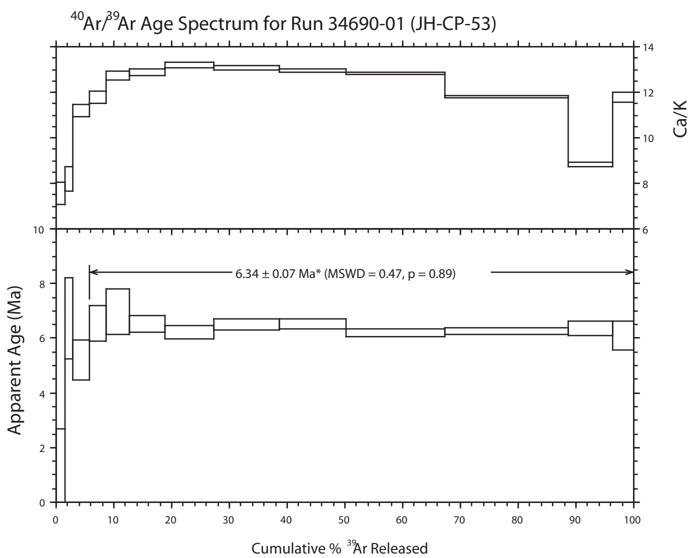
*(G) Thadp - Hb andesite dike of Markleeville Pk*




*(H) Thalu - Hb andesite lava flow, upper*




*(I) Thbdi - Markleeville Pk hb-bt dacite and andesite intrusions*




*(J) Thbdi - Markleeville Pk hb-bt dacite and andesite intrusions*

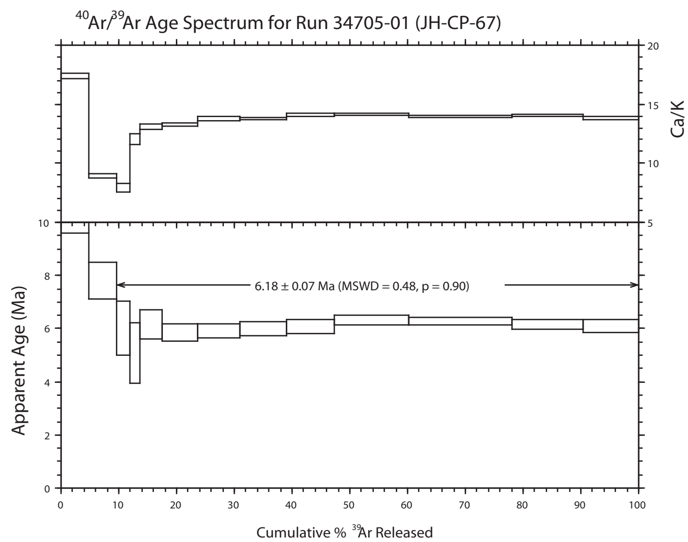
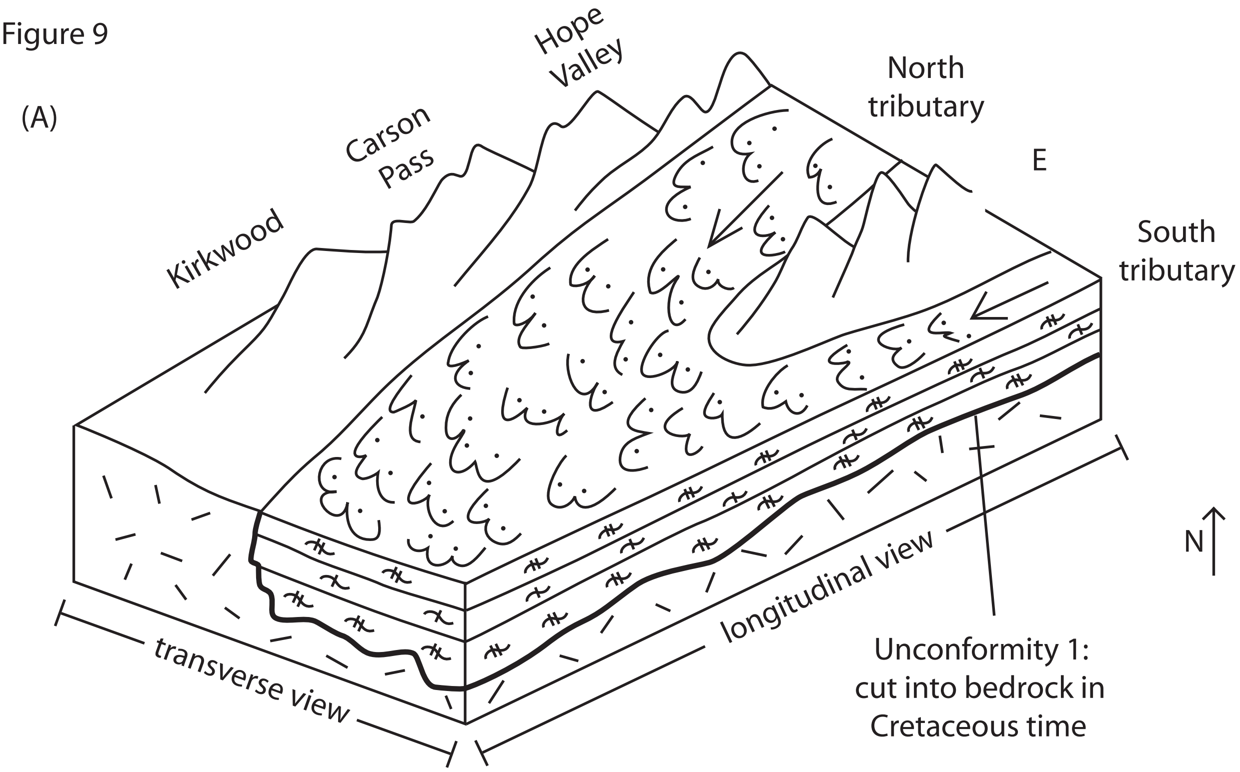
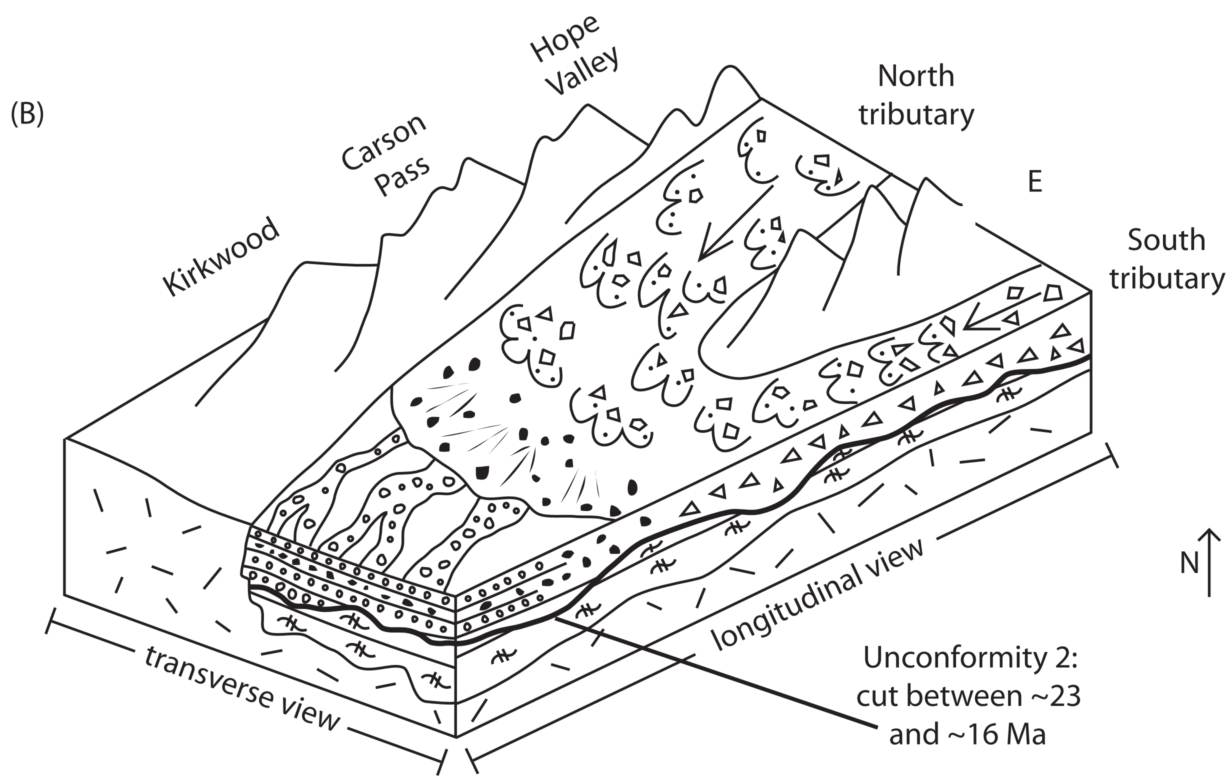


Figure 9

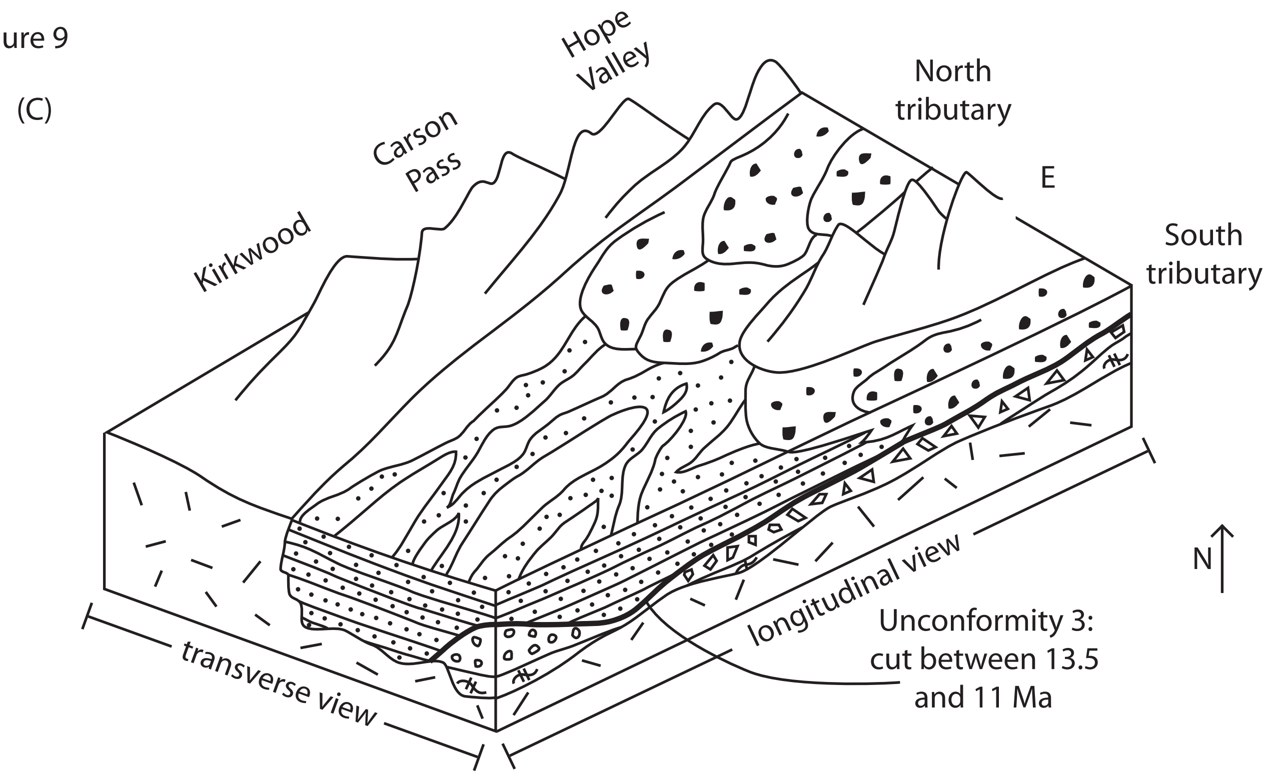



Sequence 1: Oligocene ignimbrites erupted in Central Nevada fill paleocanyon cut into Mesozoic bedrock.
(30-23 Ma)

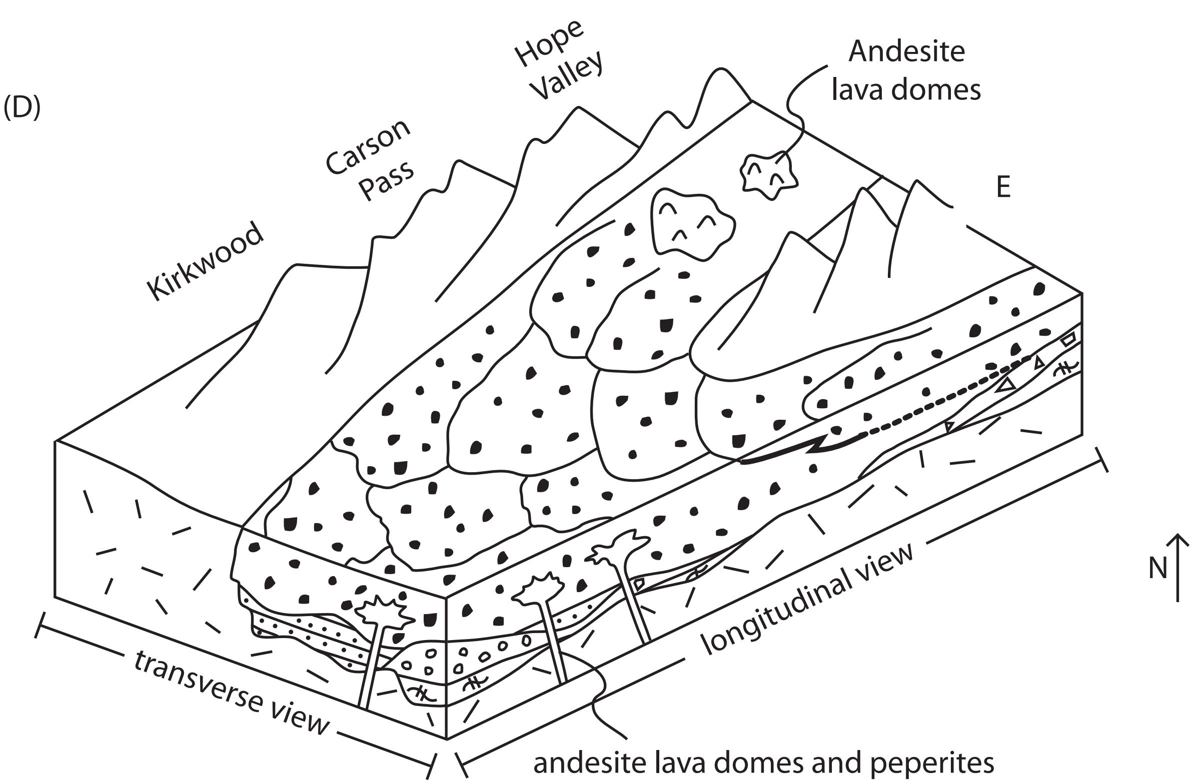



Sequence 2: Block-and-ash flow tuffs, generated by lava dome collapse, reworked down-canyon into debris flow and streamflow deposits.
(16-13.5 Ma)

Figure 9



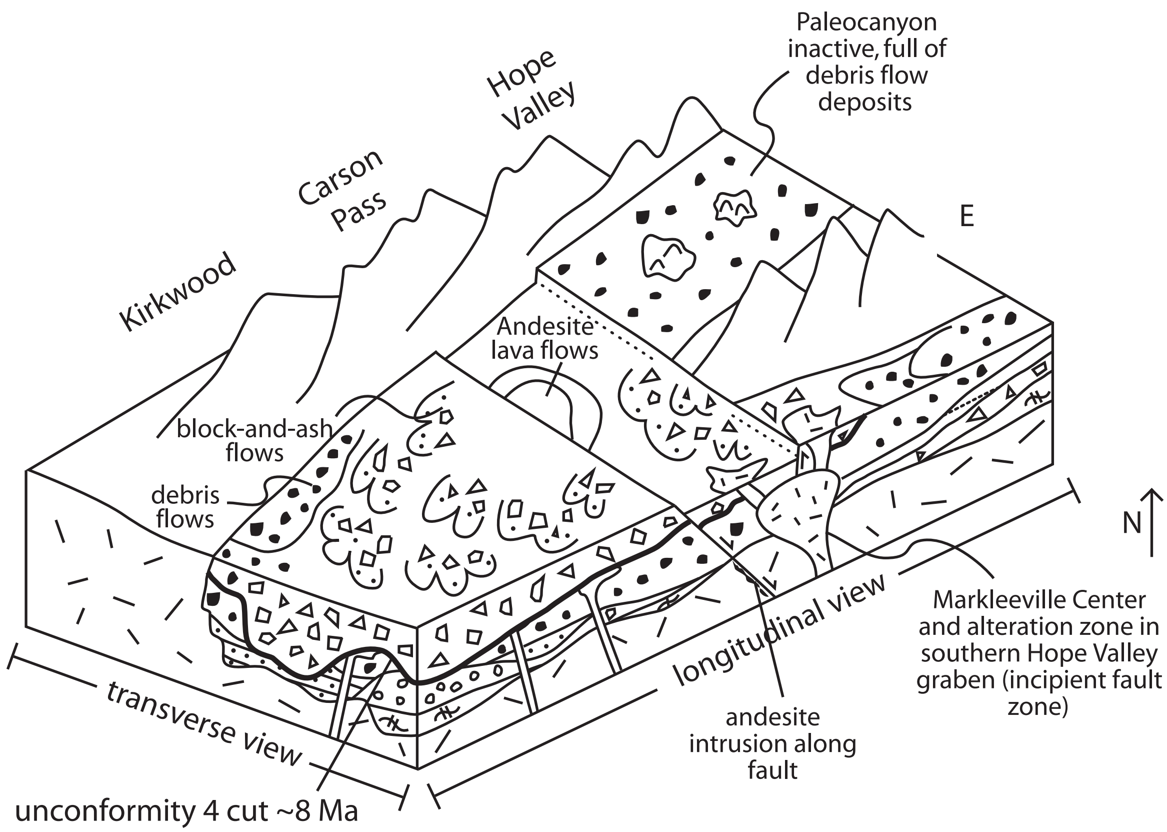

Sequence 3, Part I: Braided streams fed by debris flow lobes.
(~13.5-11 Ma)




Sequence 3, Part II: Debris flows, lava domes, peperitic intrusions and volcanic necks.
(~11-10.5 Ma)

Figure 9

(E)




Sequence 4: Basalt and andesite lava flows, andesite block-and-ash flow tuffs, andesitic to dacitic intrusions, and volcanic debris flow deposits.
(7-6 Ma)

**Table 1**

| | Unit Label | Field Description | Thin Section description |
|---|---|---|---|
| Sequence 4 | **Tri** - Rhyolite intrusion | Cream colored ryholite intrusion, with orange lysagang bands. Plagioclase, hornblende, and quartz visible in hand sample. Closely-spaced cleavage in three directions with highly variable orientations. Restricted to a single locality intruding the altered andesites (Taa). | Presence of quartz and K-spar phenocrysts and geochemistry suggests rhyolitic composition, but clay alteration precludes meaningful geochronologic or modal anlysis. |
| | **Thadp** - Hornblende andesite dike and plugs. 6.37 ± 0.24 Ma | Gray andesitic dikes and small plugs cutting Markleeville Pk dacite-andesite intrusions (Thbdi) and the altered andesite (Taa). Vertical platy fabric. Small phenocrysts of plagioclase and hornblende. | Phenocrysts of plagioclase > hornblende and local microcrystalline biotite; phenocrysts proportions and percentages vary from dike to dike. Plag laths aligned parallel to dike margins. |
| | **Thbdi** - Markleeville Peak hornblende-biotite dacite and andesite intrusions. Dacite dated at 6.34 ± 0.14 Ma, and andesite dated at 6.18 ± 0.14 Ma | Light gray to red biotite hornblende dacite to basaltic andesite. Hornblende commonly visible in hand sample, up to 2x4 mm. Biotite commonly visible, 1-2 mm, and euhedral. Some regions of intrusion are aphyric. Locally columnar jointed. Local horizontal joints spaced approximately 15 cm apart. | Phenocrysts: plagioclase > biotite > hornblende. Zoned plagioclase (1-2 mm) with clay replacement in interior; smaller crystals of hb (0.5-1 mm), some altered to clay and weathered out, leaving holes. Local apatite and biotite inclusions in plag, and local groundmass apatite. |
| | **Taa** - Altered andesite | Extremely altered hornblende and plagioclase rich lava flows, block-and-ash flow tuffs, and debris flow deposits. Varies in color from purple to blue to coppery-green with clasts frequently green, red or white. Most plagioclase altered to clay, with epidote crystallization in some locations. Minor copper mineralization in area visible as bright green veins in rocks; Charred and silicified wood visible in one probable block-and-ash flow tuff. | Phenocrysts: oxyhornblende rather than hornblende >> plagioclase which is partly or completely altered to sericite; abundance and size of phenocrysts vary; Modal analysis difficult to useless due to heavy presence of clay. |
| | **Tbi** - Basalt intrusion | Black basalt intrusions at Sierran Crest (in NW) and near Pickett Peak (in E). Has well-developed columnar joints at Pickett Peak, up to 40 cm wide, where it forms a large talus slope. Plagioclase and olivine (partially altered to iddingsite) visible in hand sample. | Phenocrysts: plagioclase > olivine >> pyroxene; minor iddingsite alteration of olivine; groundmass very fine-grained with plagiclase laths and olivine. |
| | **Thbai** - Horsethief Canyon hornblende-biotite andesite intrusion | Columnar jointed dark grey to black hornblende biotite andesite intrusion; columns ~1 m wide, with horizontal jointing radiating away from the joints. Large intrusion at peak that continues as an ~40 m (130 ft) wide dike at 310° to NW. Second dike of same composition and similar width and characteristics outcrops to N, also trending 310°. | Hornblende (up to 3 mm) and biotite (up to 1.5 mm) crystals, plagioclase slightly altered to clay. Biotite rims slightly oxidized, 60% of hornblende oxidized. |
| | **Thai** - Steven's Peak hornblende basaltic andesite intrusion | Large plug with abundant columnar jointing; very altered, with clay replacement of plagioclase, and bluish-grey hornblende. Dated by K/Ar at 5.2 ± 0.8 Ma (McKee oral comm. in Armin et al., 1984); too altered to sample for Ar/Ar dating. | Altered phenocrysts of hornblende up to 3mm >> plagioclase in a fine-grained plagioclase-rich plus cpx groundmass; clay makes up ~10% of the sample. |
| | **Tpaba** - Red Lake Peak pyroxene basaltic andesite block-and-ash-flow tuff; 6.29 ± 0.1 Ma, 6.13 ± 0.34 Ma | Dark gray to black andesite, with glassy blocks in a lapilli tuff matrix of the same composition, unsorted, and massive to very crudely stratified. Glomerocrysts of clinopyroxene. Two pyroxenes visible in hand sample. | Phenocrysts: plagioclase > hornblende > clinopyroxene > orthopyroxene; hornblende has thick oxidized rims. Both pyroxenes are euhedral, up to 3-4 mm; plagioclase has opaque inclusions. Groundmass glassy with square plagioclase microlites. |
| | **Tvdf2** - Volcaniclastic debris flow deposit; Little Round Top debris flow deposit of Busby et al., 2008A | Tan deposit composed of sub-rounded to sub-angular, pebble-boulder (up to 1.5 m) volcanic clasts in a coarse sand matrix. Clasts poorly sorted, unstratified, in a massive deposit. Clasts of hornblende-plagioclase andesite with minor mafic and granitic clasts. A mega-block of flow-banded lava (> 30 m wide) with similar geochemistry to unit Tpai found inside the upper debris flow E of Elephant's Back. | See Tvdf1. |

| | | | |
|---|---|---|---|
| | **Thalu** - Upper hornblende andesite lava flow. | Reddish-tan andesite lava flow, with a 4 m thick basal breccia and a 100 m (300 ft) thick coherent, columnar jointed interior. Abundant large hornblendes, up to 1 cm. Unaltered. Accidental clasts of other andesites mixed into basal breccia. A 10 m wide, 10 m thick lense of hornblende andesite block and ash flow tuff overlies this flow at one locality. | Similar composition and relative abundance of minerals as Thall, but hornblende crystals are slightly larger, up to 6 mm. |
| | **Thaba3** - Hornblende andesite block-and-ash-flow tuff | Purple to white hornblende andesite, with glassy blocks and lapilli (up to 50 cm), supported in a crystal and ash matrix of same composition, massive and unsorted. Forms a lense between the lower and upper andesite lava flows. Clasts sub-angular to angular, with bread crust texture, radial jointing, and *in situ shattering of blocks.* Matrix locally yellowish-green and purple. | Plagioclase > hornblende in a glassy groundmass with plag microlaths; 80% of hornblende is altered to oxy-hb or clay; only 3% of plagioclase is altered to clay |
| | **Thall** - Lower hornblende andesite lava flow: 6.22 ± 0.14 Ma | Reddish-tan hornblende andesite lava flow, lower of two flows. Generally smaller crystals than upper flow, especially hornblende. Very prominent bench marks cintact between lava flow and fluvial section below. Flow has basal breccia 1-3 m thick, and coherent interior at least 60 m (200 ft) thick, with columnar joints 20 cm wide. Flow- top breccia only ~1 m thick or not exposed; flow top marked by a prominent bench. | Euhedral plagioclase > hornblende, in unaltered microcrystalline groundmass. Hornblende rims altered. Plagioclase up to 6 mm; hornblende up to 4 m, common large = 1.5x3 mm and common small = 0.25-0.5 mm |
| | **Tbl** - Basalt lava flows | Black, glassy, aphyric to crystalline basalt lava flows. Up to 5 flows, each 2-3 m thick; aphyric to olivine- and plagioclase-phyric. Vesicular and/or brecciated horizons occur at the top of each flow. | Phenocrysts of iddingsitized olivine >> clinopyroxene and plagioclase; groundmass of plagioclase with minor olivine |
| Sequence 3 | **Tvf2** - Volcanic fluvial conglomerates and sandstones. | Tan to gray cliff-forming pebble to cobble conglomerate and pebbly sandstone, with sub-rounded to rounded clasts. Well-sorted, well stratified, thin to medium bedded, with planar lamination and trough cross lamination. Fills channels cut into underlying debris flow deposit (Tvdf 1), restricted to hills north of Charity Valley in SE. | Same as Tvf1 |
| | **Tpai** - Pickett Peak and Hawkins Peak pyroxene andesite intrusion: 10.77 ± 0.10 Ma | Dark gray to black andesite plugs that make up the peaks of Pickett and Hawkins Peak. Well-developed columnar joints throughout, up to 2 m wide. Plugs up to 350 m (1150 ft) wide, with 2-pyroxenes (both cpx and opx) visible in hand sample, and some cpx glomerocrysts. | Crystal-rich (35 - 50% crytsals). Plag > clinopyroxene = orthopyroxene. Round oxide crystals inside and surrounding cpx; sericite rims on plag. Some opx crystals have rims of microcrystalline cpx. Plag has inclusions of opx, and plag commonly grows in clusters around cpx (Figure 7A). Samples from the base of Hawkins Pk have same crystal intermixing of plag and pyx, but also contains hornblende (Figure 5, sample 71). |
| | **Tvdf1** - Volcaniclastic debris flow deposit; Age ≥10.72 ± 0.12 Ma (WR date on andesite dike with peperite margins, Busby et al., 2008). | Tan, poorly-sorted, matrix-supported, massive to indistinctly stratified cobble to boulder breccia with subrounded to angular clasts, in a pebbly sandstone matrix. Dominted by hornblende and pyroxene andesite clasts, up to 2 m in size, with minor olivine basalt and granitic clasts. | Thin section characteristics of debris flow sandstone matrix similar to that of sandstones in fluvial units. |
| | **Tvf1** - Volcanic fluvial conglomerates and sandstones. | Tan to grey, stratified, clast-supported cobble conglomerate and lesser pebbly/cobbly sandstone; moderately well-sorted with subangular to rounded clasts, in medium to thick beds with planar lamination and cut-and-fill structures. Unit commonly coarsens upward. Cliff-forming, especially at the Sierran crest, where it also has lesser debris flow deposits. Clasts include hornblende and pyroxene andesites, with minor granite and basaltic clasts, up to 50 cm in size. A sandstone-rich base passes gradationally upward into progressively coarser and less well-sorted conglomerates, with progressively more crude stratification, with fewer and more lenticular sandstone interbeds, and more angular clasts upsection. | Thin section characteristics of sandstone beds and sandstone matrix characteristics very similar to unit Tvs; Contains rounded clasts and crystals of probable Tertiary volcanic origin 0.2-0.5 mm |

| | | | |
|---|---|---|---|
| Sequence 2 | **Thaba2** - Red Lake Peak hornblende andesite block-and-ash-flow tuff. 13.5 ± 0.16 Ma | Angular and shattered blocks of light pink plag-and hornblende-phyric andesite with blocks in an ash matrix of the same composition. Massive and unsorted, generally matrix-supported. Blocks slightly vary in color from white to grey to pink, but retain same phenocryst assemblage. | Plagioclase > hornblende >> biotite > orthopyroxene in glassy groundmass; plagioclase has some hornblende and apatite inclusions. |
| | **Thaba1** - Carson Pass trachyandesite block and ash flow tuff and interstratified debris flow deposits; 15.01 ± 0.06 Ma (Busby et al., 2008A). | Blocks of white, glassy, hornblende + biotite andesite in an ash matrix of same composition. Massive and unsorted. Prismatic jointing and breadcrust texture on blocks, as well as charring of petrified wood, indicate hot deposition. | Phenocrysts: hornblende > plagioclase > biotite; groundmass: glass >> plagioclase microlites (Busby et al., 2008A). |
| | **Tphaba** - Jeff Davis Pk pyroxene-hornblende andesite and dacite block-and-ash-flow tuffs: 15.5 ± 0.6 Ma. | Reddish-tan plagioclase hornblende andesite block and lapilli fragments in a tuff matrix of the same composition. Massive and unsorted. Propylitically altered with some copper mineralization (aqua-green coating); commonly oxidized. | Plagioclase >> clinopyroxene > orthopyroxene > hornblende. Hb has oxy-hb rims. Groundmass holocrystalline (80% plag laths) to altered glass. |
| | **Tbai** - Round Top hornblende basaltic andesite; 13.4 ± 1.5 Ma (Morton et al., 1977) | Tan to gray cliff-forming intrusion. Hornblende crystals and hornblende glomerocrysts up to 1-2 cm, locally up to 10's of cm in size. Locally vesiculated horizons. | Hornblende > plagioclase; trace clinopyroxene and oxides. Hb has thin oxy-hb rims. Holocrystalline groundmass. Larger plagioclase phenocrysts resorbed. |
| | **Tsb** - Elephant's Back stratified cobble breccia-conglomerate. | Black to gray, moderately well sorted, crudely-stratified, subangular to subrounded, clast-supported pebble- to small cobble breccia/conglomerate. Minor interbedded sandstone and siltstone. Clasts of andesite to basalt. | No sandstone matrix (clast-supported). |
| | **Tvs** - Volcanic fluvial sandstones. Elephant's Back sandstone in Busby et al. (2008A), but extends across the Hope Valley area. Intruded by Round Top basaltic andesite intrusion (13.4 ± 1.5 Ma, Morton et al., 1977). | Pebbly volcanic sandstone, tan, with largely andesite clasts but includes Valley Spring Fm ignimbrite clasts at Horsethief Canyon (in NE) and just west of the Sierran Crest (in NW). Sandstone matrix, coarse-grained and lesser medium-grained, with volcanic rock fragments and lesser grains of quartz, plagioclase and biotite. Predominately medium- to thin-bedded, locally massive, with cut-and-fill structures, planar lamination and medium- to large-scale trough cross lamination. | Sandstone matrix dominated by intermediate-composition volcanic rock fragments. Minor mineral grains of probable Tertiary volcanic origin include sub-euhedral quartz, sub-euhedral plagioclase, and rounded pyroxene. Minor mineral grains of probable granitic basement provenance include rounded quartz, and rounded potassium feldspar. Opaque minerals locally abundant and aphyric basaltic clasts. |
| Sequence 1 | **Ti** - Valley Springs Formation; Age dated from 28.2 (Mosier, 1991) to 23 Ma (Busby et al., 2008A). | Welded to nonwelded ignimbrite with sanidine, quartz, biotite, hornblende; flattened pumice and lithic rock fragment including rhyolite in an ash matrix; percentage of clasts and phenocrysts variable. | Euhedral quartz and sanidine, ± biotite and/or hornblende. Bubble-wall shards, glassy throughout sample. |

**Table 2**

| Unit | Pheno | Sample # | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | Cr (ppm) | $P_2O_5$ | sum | Rock Name | Lat (°N) | Long (°W) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thai | hb | JHCP-17 | 55.44 | 0.91 | 19.11 | 8.07 | 0.1 | 3.45 | 7.48 | 3.19 | 2.02 | 20.5 | 0.355 | 100.127 | basaltic andesite | 38.73492 | 119.98086 |
| Tvdf2 [1] | hb | JHCP-65 | 59.1 | 0.79 | 18.55 | 6.51 | 0.07 | 2.66 | 6.26 | 3.39 | 2.17 | 1.6 | 0.269 | 99.7692 | andesite | 38.68648 | 119.97732 |
| Tvdf2 [2] | hb | JHCP-22 | 59.41 | 0.81 | 19.23 | 6.56 | 0.07 | 2.46 | 6.5 | 2.64 | 2.01 | 15.9 | 0.269 | 99.9606 | andesite | 38.69024 | 119.97776 |
| Thall | hb | JHCP-56 | 57.12 | 0.8 | 18.31 | 7.09 | 0.09 | 3.54 | 7.21 | 3.45 | 1.91 | 49.5 | 0.334 | 99.859 | andesite | 38.69089 | 119.97985 |
| Thalu | hb | JHCP-6 | 56.85 | 0.85 | 18.14 | 6.97 | 0.1 | 2.65 | 9.18 | 3.4 | 1.79 | 115.6 | 0.315 | 100.257 | basaltic andesite | 38.68447 | 119.97476 |
| Tphaba | hb | JHCP-35 | 65.52 | 0.695 | 16.025 | 5.655 | 0.16 | 0.84 | 5.185 | 3.19 | 2.35 | 10 | 0.2735 | 99.8895 | dacite | 38.64393 | 119.90493 |
| Tvdf1 [1] | hb | JHCP-45 | 54.78 | 1.11 | 17.95 | 8.17 | 0.1 | 5.2 | 7.97 | 2.71 | 1.7 | 77 | 0.298 | 99.9957 | basaltic andesite | 38.75189 | 119.89188 |
| Tvdf1 [3] | hb | JHCP-37 | 61.85 | 0.62 | 18.08 | 5.4 | 0.05 | 2.95 | 5.16 | 3.61 | 2.39 | - | 0.232 | 100.342 | andesite | 38.63137 | 119.89163 |
| Tbai | hb | SBDCP23 | 55.47 | 0.94 | 18.46 | 7.6 | 0.09 | 3.99 | 7.67 | 3.82 | 1.5 | 0 | 0.3 | 99.84 | basaltic andesite | 38.66756 | 120.00164 |
| Taba2 ** | hb | SBDCP27 | 61.73 | 0.56 | 18.37 | 5.42 | 0.04 | 1.58 | 5.73 | 4.09 | 2.02 | 0 | 0.329 | 99.869 | andesite | 38.41180 | 120.03382 |
| Thaba2 | opx-hb-bt | JHCP-14 | 61.46 | 0.73 | 17.39 | 5.25 | 0.06 | 3.47 | 5.72 | 3.29 | 2.7 | 60.3 | 0.265 | 100.341 | andesite | 38.71842 | 119.98533 |
| Tphaba | 2pyx-hb | JHCP-7 | 60.67 | 0.81 | 18.09 | 5.52 | 0.04 | 2.84 | 5.98 | 4.02 | 2.26 | 27.7 | 0.301 | 100.534 | andesite | 38.64326 | 119.90369 |
| Tpaba | 2pyx-hb | JHCP-1 | 53.05 | 1.23 | 19.11 | 8.93 | 0.5 | 3.13 | 10.06 | 2.65 | 1.34 | 40.9 | 0.322 | 100.321 | basaltic andesite | 38.71388 | 119.98658 |
| Tpaba | 2pyx-hb | JHCP-13 | 54.32 | 1 | 19.46 | 7.51 | 0.09 | 3.13 | 8.82 | 3.05 | 1.81 | 49.2 | 0.36 | 99.5549 | basaltic andesite | 38.71224 | 119.98561 |
| Tpai | 2pyx | JHCP-44 | 59.49 | 0.87 | 17.2 | 6.21 | 0.06 | 3.95 | 6.35 | 3.51 | 2.49 | 38 | 0.316 | 100.45 | andesite | 38.75435 | 119.89691 |
| Tpai | 2pyx | JHCP-4 | 59.6 | 0.84 | 17.28 | 6.19 | 0.06 | 3.81 | 6.33 | 3.44 | 2.52 | 40.8 | 0.31 | 100.384 | andesite | 38.75678 | 119.90254 |
| Tpai | 2pyx | JHCP-73 | 59.66 | 0.89 | 17.52 | 6.11 | 0.06 | 3.58 | 6.32 | 3.34 | 2.46 | 48.7 | 0.315 | 100.26 | andesite | 38.73818 | 119.87119 |
| Tpai | 2pyx | JHCP-71 | 58.3 | 0.82 | 18.21 | 6.8 | 0.1 | 3.16 | 6.58 | 3.33 | 2.08 | 33 | 0.297 | 99.6803 | andesite | 38.73956 | 119.87576 |
| Taba3 ** | 2pyx | SBDCP19 | 54.95 | 1.05 | 18.12 | 7.7 | 0.09 | 3.69 | 8.63 | 3.27 | 1.85 | 19.3 | 0.289 | 99.6409 | basaltic andesite | - | - |
| Tvdf2 [3] ** | pyx | SBDCP63 | 56.94 | 0.96 | 17.57 | 6.57 | 0.09 | 3.6 | 6.95 | 3.16 | 2.64 | 24.3 | 0.334 | 98.8164 | andesite | 38.71470 | 120.02381 |
| Tpaba | cpx | SBDCP45 | 52.18 | 1.2 | 18.36 | 9.09 | 0.21 | 3.72 | 10.32 | 3.1 | 1.28 | 40.7 | 0.327 | 99.7911 | basaltic andesite | 38.71406 | 119.98744 |
| Taba3 ** | cpx | SBDCP75 | 58.43 | 0.82 | 17.91 | 7.07 | 0.09 | 3.07 | 6.43 | 3.31 | 2.3 | 4.3 | 0.271 | 99.7014 | andesite | 38.70183 | 120.10372 |
| Tvdf2 [3] ** | pyx | JHCP-62 | 57.01 | 0.96 | 18.27 | 7.47 | 0.08 | 3.52 | 7.32 | 3.13 | 1.85 | 13.5 | 0.312 | 99.9234 | andesite | 38.73349 | 120.03360 |
| Tbi | cpx-Ol | JHCP-11 | 54.04 | 1.12 | 19.28 | 8.09 | 0.09 | 4.08 | 7.41 | 3.43 | 1.93 | 23.2 | 0.275 | 99.7473 | basaltic andesite | 38.76260 | 119.90861 |
| Tbi | ?px-Ol | JHCP-20 | 50.81 | 1.12 | 15.83 | 9.09 | 0.11 | 8.91 | 9.59 | 2.32 | 1.76 | 424.4 | 0.322 | 99.9044 | basalt | 38.74205 | 119.97841 |
| Tbl | cpx-Ol | SBDCP62 | 51.11 | 1.03 | 15.71 | 8.99 | 0.12 | 8.58 | 9.36 | 2.96 | 1.7 | 0 | 0.328 | 99.888 | basalt | 38.71008 | 120.01867 |
| Thbai | hb-bt | JHCP-80 | 62.21 | 0.9 | 18.21 | 5.9 | 0.05 | 2.35 | 5.1 | 3.13 | 2.32 | 57.1 | 0.267 | 100.443 | andesite | 38.81280 | 119.86133 |
| Thbdi | hb-bt | JHCP-58 | 55.54 | 1 | 18.54 | 7.6 | 0.1 | 3.695 | 8.255 | 3.1 | 1.82 | 26.55 | 0.323 | 99.9757 | basaltic andesite | 38.65911 | 119.89582 |
| Thbdi | hb-bt | JHCP-40 | 62.23 | 0.6 | 18.37 | 5.18 | 0.04 | 1.72 | 6.1 | 3.84 | 2.18 | - | 0.284 | 100.544 | andesite | 38.64469 | 119.89967 |
| Thbdi | hb-bt | JHCP-48 | 65.08 | 0.46 | 17.97 | 3.93 | 0.07 | 1.38 | 4.49 | 4.11 | 2.7 | 2.1 | 0.248 | 100.438 | dacite | 38.67296 | 119.91543 |
| Thbdi | hb-bt | JHCP-53 | 67.64 | 0.34 | 17.24 | 3.1 | 0.07 | 0.95 | 3.76 | 4.08 | 2.65 | - | 0.152 | 99.982 | dacite | 38.65813 | 119.92328 |
| Thbdi | hb-bt | JHCP-67 | 59.73 | 0.72 | 18.16 | 5.66 | 0.09 | 2.88 | 6.23 | 3.67 | 2.27 | 12 | 0.297 | 99.7082 | andesite | 38.65995 | 119.89956 |
| Thbdi | hb-bt | JHCP-60 | 59.015 | 0.805 | 18.665 | 6.2 | 0.07 | 2.58 | 6.785 | 3.52 | 1.89 | 6.3 | 0.307 | 99.8326 | andesite | 38.66105 | 119.89695 |
| Thadp | hb-bt | JHCP-68 | 60.79 | 0.67 | 18.44 | 5.25 | 0.06 | 2.16 | 6.08 | 4.4 | 1.88 | 1.8 | 0.287 | 100.017 | andesite | 38.66332 | 119.89796 |
| Thadp | hb-bt | JHCP-69 | 58.73 | 0.74 | 18.91 | 6.19 | 0.07 | 2.22 | 6.69 | 4.16 | 1.9 | - | 0.29 | 99.8999 | andesite | 38.66440 | 119.89472 |
| Taa | hb-bt | JHCP-34 | 60.75 | 0.71 | 17.68 | 6.11 | 0.08 | 3.27 | 5.68 | 3.65 | 1.91 | 19.7 | 0.285 | 100.127 | andesite | 38.63979 | 119.93361 |
| Taa | hb-bt | JHCP-55 | 68.48 | 0.37 | 17.09 | 4.09 | 0.06 | 0.55 | 3.04 | 3.74 | 2.3 | - | 0.242 | 99.962 | dacite | 38.66626 | 119.96749 |
| Taa | hb-bt | JHCP-27 | 64.26 | 0.41 | 18.14 | 4.27 | 0.12 | 1.26 | 4.59 | 4.33 | 2.35 | - | 0.267 | 99.997 | dacite | 38.66667 | 119.96321 |
| Taa | hb-bt | JHCP-84 | 61.07 | 0.79 | 19.04 | 6.35 | 0.03 | 2.3 | 4.19 | 4 | 1.79 | - | 0.204 | 99.7638 | andesite | 38.66578 | 119.97672 |
| Taa | hb-bt | JHCP-49 | 60.51 | 1 | 16.65 | 6.97 | 0.09 | 2.83 | 6.21 | 3.17 | 2.57 | 4.3 | 0.508 | 100.508 | andesite | 38.63720 | 119.92142 |
| Tri | hb-bt | JHCP-38 | 72.7 | 0.21 | 15.85 | 1.75 | 0.08 | 0.26 | 2.62 | 3.5 | 2.49 | - | 0.105 | 99.565 | rhyolite | 38.66458 | 119.95439 |
| Thaba1 | hb-bt | SBDCP46 | 58.43 | 0.85 | 17.05 | 6.04 | 0.05 | 3.08 | 6.02 | 3.88 | 2.56 | 29.6 | 0.433 | 98.396 | trachyandesite | 38.70489 | 119.99347 |
| Tfdf ** | hb-bt | SBDCP67 | 55.98 | 1.06 | 17.75 | 7.36 | 0.05 | 3.85 | 8.05 | 3.68 | 1.98 | 0 | 0.248 | 100.008 | basaltic andesite | 38.70703 | 120.10581 |

**Table 3**

| | | | | | | | Nominal Age (Ma)[1] | | Preferred Age (Ma)[2] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sample | Map Unit | Geochem | Mineral dated | Lat (°N) | Long (°W) | **Age** | ± 2σ | **Age** | ± 2σ | Unit Name |
| Seq 2 | JHCP-7 | Tphaba | Andesite | plagioclase | 38.6433 | 119.9037 | 15.4 | 0.6 | **15.5** | **0.6** | Jeff Davis Pk pyx-hb andesite and dacite block-and-ash-flow tuff |
| | SBDCP30 | Thaba1 | Trachy-andesite | biotite | 38.7014 | 120.0003 | 14.91 | 0.06 | **15.01** | **0.06** | Carson Pass hornblende trachyandesite block-and-ash-flow tuff (Recalculated from Busby et al., 2008a) |
| | JHCP-14 | Thaba2 | Andesite | hornblende | 38.7184 | 119.9853 | 13.51 | 0.16 | **13.61** | **0.16** | Red Lake Pk hb andesite block-and-ash-flow tuff |
| Seq 3 | JHCP-44 | Tpai | Andesite | hornblende | 38.7544 | 119.8969 | 10.70 | 0.10 | **10.77** | **0.10** | Pyroxene andesite intrusion of Pickett Pk |
| Seq 4 | SBDCP62 | Tbl | Basalt | whole rock | 38.7101 | 120.0187 | 6.90 | 0.20 | **6.95** | **0.20** | Basalt lava flow (Recalculated from Busby et al., 2008a) |
| | JHCP-69 | Thadp | Andesite | hornblende | 38.6644 | 119.8947 | 6.33 | 0.24 | **6.37** | **0.24** | Hornblende andesite dike of Markleeville Pk |
| | JHCP-53 | Thbdi | Dacite | hornblende | 38.6581 | 119.9233 | 6.30 | 0.14 | **6.34** | **0.14** | Markleeville Pk hb-bt dacite and andesite intrusions |
| | JHCP-67 | Thbdi | Andesite | hornblende | 38.6600 | 119.8996 | 6.14 | 0.14 | **6.18** | **0.14** | Markleeville Pk hb-bt dacite and andesite intrusions |
| | JHCP-13 | Tpaba | Bas. And. | hornblende | 38.7122 | 119.9856 | 6.25 | 0.10 | **6.29** | **0.10** | Red Lake Pk pyroxene basaltic andesite block-and-ash-flow tuff |
| | ERLPk | Tpaba | NA | hornblende | 38.7158 | 119.9857 | 6.09 | 0.34 | **6.13** | **0.34** | Red Lake Pk pyroxene basaltic andesite block-and-ash-flow tuff |
| | JHCP-56 | Thalu | Andesite | hornblende | 38.6909 | 119.9799 | 6.18 | 0.14 | **6.22** | **0.14** | Lower hornblende andesite lava flow |

Notes:
[1]Nominal age is calculated using 28.02 Ma for the FCs standard (Renne et al., 1998)
[2]Preferred age is calculated using 28.201 Ma for the FCs standard (Kuiper et al., 2008)

**Table 4**

| Sample | Map Unit | Geochem | Mineral dated | Lat (°N) | Long (°W) | Original Age (Ma)[0] **Age** | ± 2σ | Nominal Age (Ma)[1] **Age** | ± 2σ | Preferred Age (Ma)[2] **Age** | ± 2σ | Unit Name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBD-CP-29 | Trt | - | single sanidine | 38.70768 | 120.02590 | 22.9 | 0.1 | 23.2 | 0.1 | **23.4** | **0.1** | Reworked pumice lapilli tuff |
| SBD-CP-29 | Trt | - | single sanidine | 38.70768 | 120.02590 | 23.2 | 0.1 | 23.6 | 0.1 | **23.7** | **0.1** | " |
| SBD-CP-29 | Trt | - | fusion of several grains | 38.70768 | 120.02590 | 23.4 | 0.1 | 23.4 | 0.1 | **23.9** | **0.1** | " |
| SBD-CP-30 | Taba1 | trachy- | biotite | 38.70140 | 120.00030 | 14.69 | 0.06 | 14.91 | 0.06 | **15.01** | **0.06** | Trachyandesite block-and-ash-flow tuff of |
| SBD-CP-30 | Taba2 | andesite | plagioclase | 38.70140 | 120.00030 | 14.1 | 0.7 | 14.3 | 0.7 | **14.4** | **0.7** | Carson Pass |
| SBD-CP-20 | Tvdf1 | - | plagioclase | 38.68548 | 120.06170 | 10.49 | 0.12 | 10.65 | 0.12 | **10.72** | **0.12** | Peperite dike in volcanic debris flow deposits of Kirkwood Valley |
| SBD-CP-62 | Tbl | basalt | whole rock | 38.71008 | 120.01867 | 6.80 | 0.20 | 6.90 | 0.20 | **6.95** | **0.20** | Basalt lava flows of Carson Pass |
| SBD-CP-61 | Taba3 | andesite | plagioclase | 38.69210 | 120.08658 | 6.05 | 0.12 | 6.14 | 0.12 | **6.18** | **0.12** | Andesite block-and-ash-flow tuff of the Sentinels |

Notes:

[0]Original age age is calculated using 27.60 Ma for the FCs standard as reported by Gans (Busby et al., 2008b)

[1]Nominal age is calculated using 28.02 Ma for the FCs standard (Renne et al., 1998)

[2]Preferred age is calculated using 28.201 Ma for the FCs standard (Kuiper et al., 2008)