SIERRA CREST GRABEN: A MIOCENE WALKER LANE PULL-APART IN THE ANCESTRAL CASCADES ARC AT SONORA PASS

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INTRODUCTION

This paper was prepared for the National Association of Geoscience Teachers Far Western Section Fall Conference, High Sierra Institute, Baker Station, Sierra Nevada September 7 - 9, 2012. The maps and map interpretations in this document (Figures 1, 2, 3, 4, 5) form about a fourth of a much larger map and manuscript that have been peer reviewed by David John of the U.S. Geological Survey and Elizabeth Miller of Stanford University (Busby et al., in prep). The material presented here focuses on geologic maps and map interpretations for the Sonora Pass area, in the hope that this will be a resource to teachers who would like to bring students to Sonora Pass for future geologic mapping exercises. The Sonora Pass area forms a relatively accessible part of the Sierran crest, because Highway 108 runs through it (Figure 3). This paper describes all of the Sonora Pass area, which took us several years to map in its entirety, while the one-day field trip will be a single traverse between Sonora Pass and Sonora Peak (Figure 4A).

In addition, I have posted a pdf file of my lecture powerpoint online. This provides a full set of color figures geologic setting and geology of the region, which are too costly to print, along with bullet point interpretations. These are available at: http://www.geol.ucsb.edu/faculty/busby/NAGT2012

GEOLOGIC SETTING

A review of the geologic setting of Sonora Pass is beyond the scope of this paper, but is explained in the lecture powerpoint posted as a pdf file, with figures. In summary (see posted figures):

The transtensional eastern boundary of the Sierran microplate (Walker Lane rift) represents the northernmost extension of the Gulf of California rift, and it forms an onland analog in several ways. It formed at the same time (about 12 Ma), by a similar mechanism: transtension within the thermally- and structurally-weakened axis of a subduction-related arc. The two segments show similar structural trends: NE oblique slip normal faults (Walker Lane) or seafloor spreading centers (Gulf of California), connected by long NNW strike slip faults. However, the process of continental rupture has not yet been completed in the Walker Lane, so the structural controls on transtensional rift volcanism can be directly observed on land. For the past ~11-12 Ma, the biggest arc rift and continental rift volcanic centers or fields have been sited on major releasing fault stepovers on the trailing edge of the Sierran microplate. These large transtensional arc volcanic fields/centers are, from south to north (oldest to youngest):

(1) A ~11 – 9 Ma arc volcanic field that lies along the Sierran crest and rangefront in the Sonora Pass – Bridgeport area of the central Sierra Nevada. Its transtensional structural setting and its size (~ 50 X 50 km) had not been appreciated prior to my field efforts with students, although a modest-sized caldera in this volcanic field had long been

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recognized ("Little Walker caldera" of Priest, 1979). At this center, "flood andesites" were erupted from 6–8 km long fault-controlled fissures and ponded in grabens, to thicknesses of 400 m, with single flows up to 25 km^3 in volume. Total volume is difficult to estimate due to Pleistocene glacial erosion, but it is >200 km^3.

(2) The Ebbetts Pass center, which formed at ~5–4 Ma (dating in progress with Paul Renne, BGC). This large center had not been recognized prior to our mapping; it appears to be a complex central volcano with a large footprint (>16 km diameter, glacially eroded). Its original volume may be better estimated after its collapse deposits are mapped and dated, because it appears to have repeatedly collapsed into range-front half grabens.

(3) The active Lassen arc volcanic center, which formed at <3.5 Ma in a transtensional environment "favorable to the development of major volcanic centers" (Muffler et al., 2008, EOS 8-53).

Transtensional rift volcanic fields include: (10 the Cosos volcanic center, which lies in a large-sacale transtensional dextral releasing step over (Pluhar er al., 2006), and (2) the Long Valley rift volcanic field, which also formed in a releasing bend in the Walker Lane transtensional rift (since ~4.5 Ma); the structure of this field (Jayko and Bursik, 2012) is remarkably similar to that of the ~11-9 Ma arc rift volcanic field at Sonora Pass (Busby, 2012).

STRATIGRAPHY OF THE SONORA PASS REGION

The oldest strata in the Sonora Pass area consist of Oligocene rhyolite ignimbrites of the Valley Springs Formation (Tvs, Figure 2; Slemmons, 1953). Oligocene ignimbrites were erupted from calderas in eastern Nevada and flowed through paleochannels westward across the northern and central Sierra Nevada (Henry, 2008; see posted lecture pdf); in the map area, these are preserved in paleochannels (Figure 1). They consist of light-colored silicic welded and nonwelded ignimbrites with centimeter-scale pumice/fiamme and lithic clasts, and crystals of quartz, sanidine, biotite, hornblende, and plagioclase set in an ash matrix. Due to repeated reincision events within the paleochannels, ignimbrites are preserved as thin deposits on paleochannel floors and walls.

The Oligocene ignimbrites are overlain in erosional unconformity (unconformity 2, Figure 2) by Early Miocene (>10.4 Ma) arc volcaniclastic and volcanic rocks of andesitic composition, with minor olivine basalt and dacite lava flows (Relief Peak Formation, Trp, Figure 2). At Sonora Pass, the Relief Peak Formation consists mainly of andesitic debris flow deposits (Trpdf) and much lesser interstratified block-and-ash-flow tuffs (Trpba), with increasing proportions of fluvial deposits to the west (Trpf). The block-and-ash flow tuffs (Trpba) consist of monomict, angular, blocks set in an unsorted ash matrix of the same composition. These are formed from lava dome collapse and were not transported far from vent areas (*cf* Busby et al., 2008a). The debris flow deposits (Trpdf) are composed of heterogeneous, variably rounded clasts of andesitic composition, set in a sandstone matrix; they are dark tan colored, unsorted, and matrix-supported, with pebble- to boulder-sized clasts. Debris flow deposits pass down-paleochannel into fluvial deposits (Trpf), which consist of stratified sub-rounded to well-rounded andesitic conglomerate and sandstone. Basement granitic clasts are rare. Some units in the Relief

Peak Formation are mapped as undifferentiated (Trpu) due to difficulties in access, or altered (Trpa) because post-depositional alteration is too severe to permit accurate identification of primary features. Available age data indicate that andesitic volcanism of the Relief Peak Formation continued right up to the time of eruption of the Table Mountain Latite of the Stanislaus group (Figure 2), because an andesitic block-and-ash-flow tuff that lies below the TML yielded a date of 10.39±0.18 Ma, which overlaps with the basal TML flow (within analytical error; Busby et al., 2008a; Busby and Putirka, 2009).

The Relief Peak Formation is overlain in erosional and angular unconformity (unconformity 3) by high-K volcanic rocks of the Stanislaus Group, with dates of 10.4 to 9.3 Ma. The basal formation of the Stanislaus group, the Table Mountain Latite (Figure 2), consists largely of trachyandesite lava flow; these extend from the California-Nevada border to the east, to the Sierra Nevada foothills to the west (Figure 1). The TML contains 23 lava flows on Sonora Peak; the basal flow of the TML there yielded an Ar^{40}/Ar^{39} age of 10.41±0.08 Ma, and the uppermost flow yielded an age of 10.36±0.06 Ma (Busby et al., 2008a). The Table Mountain Latite (TML) lava flows are easily recognized in the field by their clinopyroxene and large (~1 cm) skeletal plagioclase phenocrysts. Geochemical analyses from the TML at Sonora Peak shows that it ranges in composition from trachyandesite (latite) to basaltic trachyandesite (shoshonite); we follow previous workers by referring to these as latites (Busby et al. 2008a). New mapping described here shows that black, olivine-phyric basaltic lava flows and olivine-plagioclase-phyric basaltic-andesite lava flows (Tstmlb, Figures 4, 5) are locally interstratified with the TML flows, which lack phenocrystic olivine.

The middle formation of the Stanislaus group, the Eureka Valley Tuff (EVT), consists largely of nonwelded to densely welded ignimbrite that ranges in composition from trachydacite to dacite (Putirka and Busby, 2007). These ignimbrites include (from base to top): the largely welded Tollhouse Flat member, with abundant phenocrystic biotite; the largely welded By-Day Member, which lacks phenocrystic biotite; and the Upper member, which is generally white and nonwelded. Busby et al. (2008a) reported Ar^{40}/Ar^{39} dates 9.42±0.04 and 9.43±0.02 Ma, on the By-Day and Upper members of the EVT at the reference section. The Tollhouse Flat Member is the most voluminous and widespread of the three ignimbrite members (Noble et al., 1974), and previously unmapped occurrences are still being found; similarly, previously unmapped lava flows of the Lava Flow Member of the EVT are still being found (Hagan, 2010).

The upper formation of the Stanislaus group, the Dardanelles Formation, is a single very thick (60 m) black, nearly aphyric shoshonite lava flow with very sparse pyroxene, olivine and resorbed hornblende (Koerner et al., 2009). This distinctive lava flow has so far only been found on the Bald Peak - Red Peak ridge and on the ri*f*dge that extends SE from there to St Mary's Pass (Figures 4, 5) and in a very small (8 X 16 m) outcrop on Dardanelles Cone (Figure 1).Dalrymple (1964) reported a single whole rock K-Ar date of 9.3±0.4 for the Dardanelles Formation, obtained on a sample described as an aphyric basalt lava flow at an elevation of 9,230' on Bald Peak (Figure 1). Our mapping (Figure 5, described below) confirms that this distinctive lava flow is indeed Dardanelles Formation, because it overlies the Upper Member of the EVT further east along the same ridge (Koerner et al., 2009). However, our geochemical data show that Dardanelles

Formation is shoshonite, not a basalt as reported by Dalrymple (1964; Koerner et al., 2009).

The resistant lava flows of the Stanislaus group form the top of the stratigraphic section at Sonora Pass. However, we assign hornblende plagioclase andesite plugs and dikes that cut the Stanislaus group to Disaster Peak Formation (Slemmons, 1966; Koerner et al., 2009; Figure 2). One of these plugs was dated at 7.28±0.06 Ma by Busby et al. (2008a).

THE SIERRA CREST GRABEN PART I: LITHOSTRATIGRAPHY

We propose the term "Sierra Crest graben" to describe a region of ponded TML, underlain largely by avalanche deposits, that is bounded on the west by east-dipping normal faults (Kennedy Creek fault zone - Seven Pines fault, Figures 3, 4, 5) and on the east by the west-dipping East Carson fault (Figures 3, 4). The faults on the west side of the graben were previously mapped by Slemmons (1953). Cenozoic strata to the north and northwest of the Kennedy Creek fault zone contain Stanislaus Group lava flow sections up to 400 m thick, but west and southwest of the Kennedy Creek fault zone there are no Stanislaus Group lava flows, although the distribution of older Cenozoic units shows that a paleocanyon existed there (unpublished mapping by Slemmons; Roelefs, 2004; and mapping by Busby et al., in prep). This shows that the lavas were entirely ponded within the Sierra Crest graben along this segment of it. However, in the next segment to the north, along the Seven Pines fault, a <80 m thick section of Stansilaus Group lava flows extends westward from the western margin of the Sierra Crest graben (Figure 3) as paleocanyon fill, and erosional remnants of the lava-filled paleocanyon extend all the way to the Sierra foothills (Figure 1; e.g. Gorny et al, 2009; see posted lecture powerpoint pdf). This indicates that some lava flows escaped the Sierra Crest graben along the Seven Pines segment and flowed down the paleochannel. The Seven Pines Fault maps directly northward into the newly-recognized Disaster Creek fault (not shown in this paper; Busby et al., 2008a and in prep). Like the Seven Pines Fault, the Disaster Creek Fault is also an east-dipping normal fault with ponded Stanislaus group lava flows on its hanging wall; no flows escaped westward from this segment, but there was no pre-existing paleocanyon at this segment (which would be marked by older strata filling a surface cut into the basement; Busby et al., 2008a, and in prep).

The stratigraphy of the Sierra Crest graben is the most complex in the region, because it contains vent facies for lava flows of the Stanislaus Group, which are by nature lenticular, as well as intrusive equivalents, which interrup the strata. To add to this complexity, we estimate that >90% of the deposits below the Stanislaus group in the Sierra Crest graben are debris avalanche deposits, with <10% represented by *in situ* strata or intrusions.

Debris Avalanche and Minor *In Situ* Deposits Beneath Stanislaus Group (Relief Peak Formation)

The Relief Peak Formation in the Sierra Crest graben is largely mapped as undifferentiated on Figures 4 and 5, because it is not entirely clear how much of it represents *in situ* deposits, and how much can be mapped separately as debris avalanche deposits, but we estimate the proportion of *in situ* deposits to be very low.

The debris avalanche deposits consist of a chaotic mixture of mega-blocks of a wide variety of Relief Peak Formation rocks types, of widely varying colors, with unaltered rocks juxtaposed against highly altered rocks, and locally mixed together with slabs of Valley Springs Formation. Many mega-blocks have internal stratification, with dips that vary widely from mega-block to mega-block. Strata that may represent *in situ* deposits are identified by consistent low westward dips (concordant with regional dips), but these are restricted to a few small areas of the Sierra Crest graben.

Possible *in situ* Relief Peak Formation includes the altered breccias that form the ridge east of Leavitt Lake (in the SE corner of Figure 4B); these breccias are heavily altered but appear to have relict horizontal stratification, as well as Valley Springs Formation, in its correct stratigraphic position at the base of the section (Tvs, Figure 4B) with horizontal welding compaction fabric. However, the possibility remains that this is slide block of Valley Springs Formation, because at nearby Sardine Falls, slide blocks of Valley Springs Formation that are large enough to map individually lie within chaotic deposits of Relief Peak Formation (Tvs and Trpu, Figure 4B). There may be a relatively thin (<10's of meters) section of *in situ* deposit at the top of the Relief Peak Formation, at one locality < 1 km south of Sardine Falls and another ~0.6 km south of Sonora Pass, because in both places, a 4 m thick flat-lying mafic lava flow can be mapped (Trpl, Figure 4B). Another small *in situ* area of Relief Peak Formation lies in a narrow, deep paleocanyon cut into basement rocks west of Sonora Peak, at the north end of the St. Mary's Pass fault (Figure 4A). That is filled with subhorizontal fluvial and debris flow deposits that are probably *in situ* (Trpf and Trpu, Figure 4A).

The biggest area of possible *in situ* Relief Peak Formation lies along the western third of the ridge that extends west from Leavitt Peak (Trpu, Figure 4B). There, stratification in the Relief Peak Formation dips gently west. Exposures are very poor on the SW side of the ridge above Kennedy Creek (Figure 4B), due to cover by talus, but a 20 m thick, ignimbrite there (Trpig, Figure 4B) shows flat compaction fabric. The ignimbrite is purplish to greenish white, with hornblende plagioclase and sparse biotite, and may be correlative with an "ash flow tuff" that Roelofs (2004) described within fluvial deposits of the Relief Peak Formation on the opposite side of Kennedy Creek. Along the NE side of the same ridge that extends west from Leavitt Peak, west of Blue Canyon (Figure 4B), the Relief Peak consists of horizontally stratified (likely *in situ*) fluvial and debris flow deposits, which pass upward into massive debris flow deposits with interstratified block-and-ash-flow tuffs near the top. Block-and-ash-flow tuffs are also interstratified with debris flow deposits at the top of clearly *in situ* Relief Peak Formation west of the maps shown here, at the Dardanelles (location shown in Figure 3); perhaps they are correlative, but modal analysis, geochemistry and dating are needed to determine this. Also west of Blue Canyon, discontinuous lenses of light-colored rock at the base of the section are mapped as *in situ* Valley Springs Formation (Tvs, Figure 4B). This interpretation is supported by the fact that a lense of *in situ* Valley Springs Formation with horizontal compaction underlies the Relief Peak Formation directly to the north across Deadman Creek at Chipmunk Flat, although it is topographically lower (by 180 m), and it is not clear that the overlying Relief Peak Formation is *in situ*. However, we have not succeeded in accessing the lenses on the south side of Deadman Creek (west of Blue Canyon), nor is it clear that previous workers did; those include Slemmons (1953) who mapped the unit as Valley Springs Formation, and Roelefs (2004) who mapped the unit as fluvial deposits within the Relief Peak Formation. Lastly, a coherent andesite makes up a ~1 km^2 unmapped area within the debris avalanche deposits south of the Sonora Pass highway in the southern end of the Sonora Pass fault zone. This body is important because it is indurated enough to display fault kinematic indicators, described below. It appears to have a chilled margin against the breccias at one locality, so it may be an *in situ* intrusion into the debris avalanche deposit; alternatively, it may lie within a larger slab.

The largest mega-block we have been able to map as a separate unit is the megablock at the south foot of Sonora Peak, mapped as interstratified andesitic debris flow deposits and block-and-ash-flow tuffs (Trpba, Figure 4A). This ~2 km long megablock was first described by Busby et al. (2008a); we consider it to be one slide block because the dips within it are relatively consistent (25°NE, Figure 4A). The block-and-ash-flow-tuff dated at 10.39 +/- 0.18 Ma (Figure 3A; Busby et al., 2008a) was sampled from this slide block before we realized it was not *in situ*. The largest landslide slab of Valley Springs Formation within the debris avalanche deposit occurs as white tuff at the base of Sardine Falls, and is about 200 m long. This white tuff has broken crystals of sanidine, quartz, and biotite, in a matrix of glass shards and small pumices, typical of Valley Springs Formation, and is thin- to medium-bedded, with planar lamination and trough cross-lamination, indicative of fluvial reworking. Other, smaller blocks of Valley Springs Formation are common in this area. Four separate hornblende pyroxene intrusions that lie within ~1.5 km of each other on the east and west side of Blue Canyon have peperitic margins, indicating they were intruded at very shallow levels into a wet sediment host; after consolidation of the host, the intrusions and surrounding host rock became incorporated into the debris avalanche, so the intrusions may have originally been one contiguous body disrupted by the avalanching (Trpvf, Figure 4).

Finally, primary volcanic rocks are abundant at a stratigraphically high position within the undifferentiated Relief Peak Formation in the St. Mary's Pass region, similar to *in situ* primary deposits in this stratigraphic position at the Dardanelles (described above), so it is possible that these are *in situ*. These include a glassy plagioclase- biotite-hornblende dacitic (?) lava flow with flow breccia and a cm-scale glass hydration fracture pattern at St. Mary's Pass, and a block-and-ash-flow tuff with 20% hornblende crystals and glomerocrysts beneath the TML west of St. Mary's Pass. Petrified wood fragments are abundant in debris flow deposits at the latter locality. The Relief Peak Formation-granitic basement contact drops rapidly in elevation (300 m) from St. Mary's Pass to Chipmunk Flat, probably representing the SE side of a ENE-WSW trending paleocanyon wall; there the Relief Peak Formation consists of debris avalanche deposits with megablocks of hornblende-plagioclase-pyroxene-phyric block-and-ash-flow tuff, flow breccia, and coherent andesite.

Table Mountain Latite Lava Flows, Vent Facies Deposits and Feeder Dikes

The thickest preserved sections of TML lava flows lie within the Sierra Crest graben on Sonora Peak and Stanislaus Peak, on either side of Sonora Pass along the modern range crest (Figure 4). The Sierra Crest graben also contains TML vent facies, described here from the Sonora Peak to Stanislaus Peak area; the graben and its vent facies also extends north of the area described here, through Disaster Creek (Figure 1; Busby et al., this volume). In this section we also describe feeder dikes for the TML, as well as olivine basalt lava flows at the base of the TML.

The section of TML lava flows on Sonora Peak (Figure 4A) was measured and described by Busby et al. (2008a). It consists of 23 flows, for a total preserved thickness of 405 m (top eroded). The section is mainly composed of normal-polarity lava flows, but contains two reverse-polarity zones, each represented by a single lava flow (Busby et al, 2008a; Pluhar et al., 2009). The lower reversed flow, flow 14, exhibits what we call the "Classic Table Mountain" remanence direction; this flow extends to the Sierra foothills at Knight's Ferry (Pluhar et al., 2009; Gorny et al., 2009).

The section of TML on Leavitt Peak contains over 30 lava flows (Koerner, 2010). A single ~ 7 m thick olivine basalt lava flow lies at the base of the TML about 600 m south of Sardine Falls (Tstmb, Figure 4). Similarly, a thin (3 m) discontinuous (30 m long) olivine basalt lies at the base of the TML on the east wall of Blue Canyon (Tstmb?, Figure 4B); this is overlain by about 24 latite lava flows of relatively uniform thickness (about 15 m each). Further west, on the north face of Night Cap Peak, the unconformity at the base of the TML (unconformity 3) on Relief Peak Formation is striking, with >80 m of relief over a distance of <1 km. The TML lava flows there show anomalous dips of 8° to the north-northeast (Figure 4B), and basal flows have interstratified debris flow deposits with dominantly angular latite clasts, sub-angular hornblende andesite clasts, and minor granitic pebbles. Along the north-facing cliffs ENE of Night Cap Peak (Figure 4B), a prominent sharp boundary can be seen from a distance, which appears to separate the Table Mountain Latite lava flows into two sections (unmapped in Tstml, Figure 4). Much of this boundary is inaccessible, but at its western end, it appears to be a bedded latite tuff within the TML (Koerner, 2010). The conical Night Cap Peak is a single 30 m thick Table Mountain Latite lava flow with a 5 m thick basal flow breccia. On the cliffs directly north of the Kennedy Lake pack trail, the TML consists of >24 subhorizontal latite lava flows.

To the west of St. Mary's Pass fault, on the south and east side of By Day Flat, there are 5 – 9 latite lava flows preserved beneath EVT (Tstml, not mapped individually, Figure 4A); however, on the west side of By Day Flat, the TML thickens rapidly into a paleo-low cut into Relief Peak Formation (unconformity 3, Figure 2) and has >10 lava flows. Geochemical analysis of a small erosional remnant of TML ~1.6 km SSW of St. Mary's Pass shows it is a basaltic-trachyandesite (sample JHSP41 of Hagan, 2010). For more detailed descriptions of individual lava flows in this section, see Koerner (2010).

On Stanislaus Peak at the northern end of the map area (Figure 4A), the TML has only three lava flows. This is because the TML was deposited across substantial paleo-relief in the Stanislaus Peak area, where the basal contact of the TML rises 100 m, and the TML rests directly on granitic basement. Paleorelief between the underlying Relief Peak Formation and the granitic basement is even more dramatic along this paleocanyon wall (~300 m). The TML lava flows interfinger with vent facies deposits on the east face of Stanislaus Peak (Figure 4A).

The 0.6 km long sheer eastern face of Stanislaus Peak (Figure 4a) exposes a 40 m thick deposit of red, unstratified TML scoria bomb deposits with dense TML blocks up to several meters in size (Tstmvf, Figure 4). This interfingers with TML lava flows (Tstml, Figure 4A) on the SE side of Stanislaus Peak; the lava flows are mapped continuously around the west side of Stanislaus Peak and continue both north and south along the

Sierran crest. For these reasons, we interpret the east face of Stanislaus Peak is to preserve a vent facies deposit for the TML. The map pattern of the vent deposits suggests they are part of a cinder rampart, rather than a cinder cone deposit. A second locality of TML vent facies deposits lies about 1 km southeast of Stanislaus Peak (Tstmlvf) on another east-facing cliff, immediately south of the Stanislaus Peak fault (Figure 4A). This vent facies deposit is also composed mainly of scoria and bombs with skeletal plagioclase typical of TML, but it lacks the dense megablocks of the Stanislaus Peak vent facies, and is crudely stratified rather than massive. A third locality of TML vent facies deposits is mapped on the south face of Sonora Peak (400 m from the peak). These deposits resemble the Stanislaus Peak deposits, because they form an up to 50 m thick massive red deposit, with dense-clast TML megablocks up to 3 m in size. These pass laterally into what is by far the thickest flow on Sonora Peak, lava flow19, which is 92 m thick (the rest are < 22 m thick, see Figure 10 of Busby et al., 2008a, 2008b). These vent facies deposits also lie directly upsection from a latite dike that cuts up through Relief Peak Formation 1 km south of Sonora Peak (sample PC-AD, Busby et al., 2008a; Putirka et al., in review; Figure 4a). We interpret this to be a TML feeder dike.

Another TML feeder dike is identified ~3 km southeast of Leavitt Peak, cutting the Relief Peak Formation along the Sierran crest near the Pacific Crest trail (080° striking purple line, Figure 4B).). This dike has the skeletal plagioclase typical of the TML.

Olivine basalt vent facies deposits and an associated lava flow rests upon TML in the Stanislaus Peak area; these are mapped as undifferentiated Stanislaus Group (Tsbvf and Tsb, Figure 4A) because we cannot prove that they form part of the TML, since we have recognized basalt vent facies and lava flows that overlie Tollhouse Flat Member in the Sierra Crest graben (assigned to Lava Flow Member of EVT, described below). The Tollhouse Flat Member, is regionally the most widespread Miocene volcanic unit (Figure 1), but it is is laterally discontinuous on the map scale (Figures 4, 5), and in the absence of dates, that unit must be present to distinguish TML lava flows from Lava Flow Member lava flows (Figure 2). We prefer the interpretation that the basalts lie within the TML, because many more TML flows are preserved topographically higher on the ridge southward toward Sonora Peak (Figure 4A). However, the other TML two olivine basalts (near Sardine Falls and in Blue Canyon, described above) lie at the base of the TML section (Tstmb, Figure 4B), so the possibility remains that this is a Lava Flow Member unit whose topographically-low position (relative to the top of TML nearby) resulted from infilling of an erosional surface cut into the TML.

Regardless of which olivine basalt vent facies deposits belong to TML and which belong to EVT, they are important for demonstrating that Stanislaus Group lava flow vents occur along the Sonora peak – Stanislaus Peak ridge. The olivine basalt vent facies deposits and associated lava flows lie along the crest on both the north and south side of Stanislaus Peak, and also directly to the south across Stanislaus Peak fault (1.3 km SE of Stanislaus Peak), with eroded tops. In all three places, TML lava flows are overlain by olivine basalt scoria fall deposits, which are in turn overlain by an olivine basalt lava flow. At Stanislaus Peak these are mapped together as basalt vent facies (Tsbvf), while south of the Stanislaus Peak Fault, the basalt vent facies and lava flow are mapped separately (Tsbvf and Tsb). The olivine basalt vent facies consists of red, orange and black stratified to massive deposits of bombs and scoria, including agglutinated scoria fall and spindle bombs. The olivine basalt lava has a basal flow breccia, crude columnar joints, subhorizontal platy parting, and <10% olivine.

A unit of diverse breccias overlies the basalt vent facies on Stanislaus Peak (Tsu, Figure 4A), and are assigned to the Stanislaus Group because primary deposits in it (flow breccia and block-and-ash-flow tuff) bear plagioclase and pyroxene, although debris flow deposits in it bear hornblende. The primary breccias could represent additional Stanislaus group vent facies deposits.

Summary of TML Vents, Sonora Peak to Stanislaus Peak: Eastern Side of Sierra Crest Graben

Slemmons (1966) outlined a 27 X 6 km^2 WNW-trending region that encompassed the entire Sierra crest to the Bald Peak area (geography shown in Figure 3), and proposed that latite "intrusives" occurred throughout this area. However, he did not describe any vents or give specific locations for them, and the only rocks we have found so far that might be called "latite intrusives", with the diagnostic skeletal plagioclase, are the two dikes described here (although below we tentatively assign nearly aphyric dark colored plugs in the Sierra Crest graben to the Dardanelles Formation). Instead, we find vent facies eruptive products; presumable, additional feeder dikes for TML lie buried beneath these.

The TML vent facies on Stanislaus Peak lie along the same NNW trend as the vent facies on the south side of Stanislaus Peak (Tstmlvf, Figure 4A), and the latite feeder dike at Sonora Peak has the same strike; furthermore, the basalt vents lie along this line (Figure 4A). We therefore infer that additional TML vents lie buried beneath the TML lava flows along the intervening part of the Sierra crest, and that the TML was erupted from a >5.5 km long fissure. This proposed fissure parallels the St. Mary's Pass fault (described below) and the newly mapped East Fork Carson fault to the east (Figure 4A). It thus lies inside the eastern edge of the Sierra Crest graben (Figure 3). Later, Disaster Peak andesite intrusions were emplaced along the inferred TML fissure (Figure 4A).

A second system of aligned Stanislaus Group vent deposits and subvolcanic intrusions forms another NNW-trending ridge, parallel to the vents on the Sonora Peak – Stanislaus Peak ridge, but this ridge lies inside the western edge of the Sierra Crest graben (Figure 5). It was an eruptive source for Stanislaus group lava flows younger than the TML, including the Lava Flow Member of EVT, and the Dardanelles Formation, described in the next section.

Eureka Valley Tuff, Including Lava Flows and Associated Vent Facies Deposits

The EVT in the Sierra Crest graben includes previously unrecognized lava flows that range in composition from latite (Tsell) to olivine basalt (Tselb) to trachydacite (Tselt), as well as previously unrecognized latite and olivine basalt vent facies deposits (Tselvf; Tselbvf) and vent-proximal deposits (latitic block-and-ash-flow tuff, Tselba). These occur along a NW-trending ridge that extends from By Day Flat (Figure 4A) through Peak 10244' to Peak 9798' (Figure 5B). The Tollhouse Flat Member of the EVT rests upon, and is overlain by, latite lava flows at three localities along the ridge, described from south to north. The first locality, on the north-northwest edge of "By-Day Flat" (Figure 4A), consists of a 13 m thick, 275 m long lense of biotite-phyric welded ignimbrite. The second locality, which lies along the ridge about halfway between By

Day Flat and peak 10244' (Figure 5), is a very small (~10m by 4 m area) exposure of nonwelded biotite-phyric ignimbrite; lithologically, it could be confused with the Upper Member, but By Day Member lies upsection from it. The third locality is at the north end of peak 9798', and forms a thicker, more laterally continuous exposure of welded biotite-phyric ignimbrite (Figure 5). In all three localities, it is only the presence of lenses of Tollhouse Flat Member that allows us to map EVT Lava Flow Member lava flows separately from TML lava flows, even though they apparently differ in age by at least 780 Ka (Figure 2A); they are lithologically the same.

The basal part of the Lava Flow Member of the EVT in the Sierra Crest graben has olivine basalt lava flows (Tselb), and a vent facies deposit for the flows, consisting of the erosional remnant of an olivine basalt cinder cone intruded by coherent olivine basalt (Tselbvf, Figures 4A and 5B). The olivine basalt cinder cone (Tselbvf) superficially appears in map view to cross cut the TML but that is because it supports a pinnacled ridge that juts out over the top of the TML, which underlies it (SE face of peak 10244, Figure 5B). The latite lava flows of the Lava Flow Member of the EVT (Tsell) onlap the sides of the cinder cone, and the By-Day Member of Eureka Valley Tuff directly overlies it (Figures 5, 12F). The cinder cone is bright red, with black and red stratified scoria fallout layers that dip ~30-50°. The cinders are locally agglutinated and contain large volcanic bombs (~2m). A relatively thick (15 - 20 m) basalt lava flow crops out on the NW and NE side of the same peak, and was probably erupted from the cinder cone. Another erosional remanant of this lava flow lies ~ 0.5 km to the north, also at the base of the Lava Flow Member. At that locality, it is lies topographically higher than the nearby Tollhouse Flat Member, although the contact is not preserved (Figure 5B). In addition, two ~ 4m thick olivine basalt lava flows with flow-top breccias lie at the base of Lava Flow Member on the southwestern face of By-Day Flat (Figure 4A).

The Lava Flow Member of the EVT has three latite lava flows along the ridge from By-Day Flat to peak 10244' (Tsel1, Tsel2, Tsel3, Figure 5; for full description, see Koerner, 2010). The lowest (Tsel1) is crystal poor, with small crystals compared to the other two; it has spindle bombs in its flow-top breccia. The middle flow (Tsel2) has more pyroxene than the other flows, has thin, highly contorted flow bands, and also has spindle bombs on top. The top flow (Tsell 3) exhibits platy parting on horizontal surfaces. A 75 m thick erosional remnant of a latite cinder cones lies within the Lava Flow Member along the ridge-top about 1.2 km east of peak 10244' (Tselvf, Figures 5, 12C). This red scoria-rich section contains abundant spindle bombs and blocks up to 1 m in size. To the north of the peak 10244' exposures, the Lava Flow Member lava flows are not mapped separately but the section contains at least two, separated by a debris flow deposit (Tseldf, Figure 5). A laterally discontinuous block-and-ash-flow tuff lies between lava flows 2 and 3 around peak 10244' (Tselba, Figure 5). The block-and-ash-flow tuff weathers white and contains plagioclase, clinopyroxene and biotite, similar to the EVT trachydacite ignimbrites, but this unit is a trachyandesite (sample PC065, Busby et al., 2008a). The outcrop mapped as block-and-ash-flow tuff adjacent to the Seven Pines Fault consists of reworked equivalents.

The By Day Member of the EVT (Tseb, Figure 5) is better represented in the Sierra Crest graben than it is in other parts of the Sierra, and thus preserves more welding zonations than are typical for the unit in the Sierra (for details, see Koerner, 2010). The Upper Member of the EVT (Tseu, Figure 5) is a bright white nonwelded ignimbrite, with white sub-rounded pumice, abundant euhedral biotite phenocrysts, and pebble-sized volcanic lithic fragments. It is very soft, and is preserved only in small channels cut into the By Day Member welded ignimbrite (see Tseu, mapped 500 m NE of peak 10244', and also mapped <500 m east of peak 10244'). At both localities, it is overlain by a dark-colored, nearly aphyric lava flow that is distinctive of Dardanelles Formation.

A Stanislaus Group unit of uncertain origin lies along the ridge that projects east from peak 10244'. It has 40-50% skeletal plagioclase, with irregular joints that are vertical in the center and horizontal along the sides, suggestive of an intrusive origin (Tsi?, Figure 5B). Slemmons (1953) also mapped an intrusion here. However, the By-Day Member of the EVT ramps up over it, and is not cross cut by it, which suggests it was deposited on top of it. Furthermore, there are no post-By-Day Member latites that we are aware of, making it unlikely that it intrudes By-Day Member. Therefore, it could be a Lava Flow Member Lava flow, or a very shallow level Lava Flow Member intrusion that was unroofed by erosion prior to deposition of the By-Day Member.

Dardanelles Formation and Possible Intrusive Equivalents

The stratigraphic position of the distinctive single black, nearly aphyric Dardanelles Formation lava flow (Tsdl) is well constrained on the north and southeast sides of peak 10244', where it rests on Upper Member EVT, which in turn rests on By Day Member EVT (Figure 5). A small (~40 m wide and 400 m long) erosional remnant of the Dardanelles Formation lava flow rests on By-Day Member of the EVT at By Day Flat, and an even smaller erosional remnant also rests on By Day Member on the ridge between peaks 10244' and 9798' (Figure 4A). They contain the typical very sparse plagioclase, pyroxene, olivine and resorbed/oxidized hornblende. Another erosional remnant along the ridgecrest lies in a channel cut into TML lava flows and Relief Peak Formation debris flow deposits (Tsdl?, Figure 4A); the assignment to Dardanelles Formation is queried because no EVT units intervene, and the flow is not as glassy as Dardanelles Formation typically is, although it is otherwise identical. That lava flow has columnar joints that radiate inward from the side and base of this flow, due to cooling against the floor and wall of the small channel it fills.

Intrusions that are lithologically identical to the Dardanelles Formation lava flow, but cross cut units as young as By Day Member, are mapped here as Dardanelles intrusions; however, this interpretation must be tested by future dating and geochemical work. These intrusions lie along the western boundary of the Sierra crest graben, on either side of the Seven Pines Fault (Tsdi, Figure 5B), Figure 5). The largest plug lies on peak 9798', east of the fault; in addition, two smaller plugs and two dikes of identical lithology (shown as purple line with hatches, Figure 5B) lie west of the fault, on the Red Peak horst block. Another lithologically identical NNW-striking dike lies about 2 km west of St. Mary's Pass, well within the Sierra Crest graben (Figure 4A).

The southern part of the Sierra Crest graben (Figure 4B) does not preserve the Dardanelles Formation lava flow, but dikes that lithologically resemble the distinctive lava flow are present (each dike shown as a purple cross-hatched line, Figure 4B). Two of these dikes cut TML near Night Cap Peak, and one cuts Relief Peak Formation along the range crest south of Leavitt Lake; these dikes strike NW, parallel to the Kennedy Creek Fault Zone (Figure 4B). A fourth NW trending dike lies along the St. Mary's Pass Fault, about 500 m southwest of Sonora Pass (Figure 4B). All of these dikes are black and nearly aphyric, with very sparse plagioclase, +/- hornblende (commonly oxidized), +/- pyroxene phenocrysts +/-olivine microcrysts. Their correlation with the Dardanelles Fomration lava flow must be tested by geochemical and geochronological work.

A Dardanelles Formation unit of uncertain origin lies in the northern part of the Sierra Crest graben, just inside its west margin, on the north side of peak 10244' (Tsdi?, Figure 5B). Slemmons (1953) mapped this body as an undifferentiated intrusion. However, if this is an intrusion, it is a Dardanelles plug intruding the Dardanelles lava flow, so it must not have vented, because we have found only one lava flow in the Dardanelles Formation. One alternative interpretation is that this body represents a megablock in the debris avalanche deposit that forms the highest peak in the western Sierra Crest graben fill (peak 10244'); this erosional remnant may therefore may have been much more extensive originally (Tsdda, discussed below). The erosional remnant of the Dardanelles Formation lava flow on the southeast side of the peak 10244' is depositionally overlain by the debris avalanche deposit (Tsdda, Figure 5).

Stanislaus Group (?) Debris Avalanche Deposit in the Sierra Crest Graben

The erosional remnant of a debris avalanche deposit preserved on peak 10244' is assigned to the Stanislaus Group, rather than the Disaster Peak Formation, because it contains abundant megablocks of Upper Member EVT nonwelded ignimbrite that are very irregularly shaped and deformed between other block types. This indicates that the avalanche occurred before the nonwelded tuff became lithified. The debris avalanche deposit consists of mega-blocks (meters to tens of meters in size) of both Relief Peak Formation and Stanislaus Group rock types, including debris flow deposits, Upper Member EVT, flow breccia, andesitic block-and-ash flow tuff, and olivine basalt. There are no primary pyroclastic rocks interstratified with the deposit (only avalanche slabs of tuff). The position of the debris avalanche deposit on the downthrown block of the Seven Pines fault may indicate an origin by fault scarp collapse, rather than volcano sector collapse.

Summary of the Western Side of the Sierra Crest Graben

The NNW trending topographic ridge that lies east of the Seven Pines Fault is on the hanging wall of the Seven Pines Fault, which is a NNW-striking, east-dipping fault (described below). The Stanislaus Group on the ridge has intrusions, vent deposits and vent-proximal deposits aligned roughly NNW, parallel to the Seven Pines fault but on its hangwall. Furthermore, the TML dramatically thickens on the east side of the ridge, relative to the west side of the ridge (Figure 5). This suggests that the Stanislaus Group vents were located along a NNW-striking, east-dipping normal fault strand of the Seven Pines normal fault, which got buried under eruptive products, and has not been reactivated since. In contrast, the Seven Pines fault (described below) was clearly reactivated after eruption of the Stanislaus group. We infer that intrusion and venting of magmas along the inferred buried fault strand prevented its postvolcanic reactivation.

Both the east and the west margins of the Sierra Crest graben are marked by ridges with intrusions, vent deposits, and vent-proximal deposits. These ridges presumably resisted erosion because they have a higher proportion of lava flows and intrusions than surrounding areas, which have a higher proportion of volcaniclastic rock.

Disaster Peak Formation Strata, Sierra Crest Graben

There are very few Disaster Peak Formation strata in the Sonora Pass area, although there are many hornblende-bearing plugs and dikes that cut Stanislaus Group, and are assigned to Disaster Peak Formation (Figures 4, 5). One of these plugs, on Bald Peak (Figure 3) yielded the date of 7.28 +/- 0.06 Ma shown on Figure 2A (reported in Busby et al., 2008a).

Only two very small patches of Disaster Peak Formation volcaniclastic channel deposits lie above Stanislaus Group, occupying a <20 m wide channel cut into By-Day Member of the EVT on By Day Flat (Tdpf, Figure 4A). The channel fill consists of sandstone and conglomerates as well as reworked silicic white tuff. Clasts include a variety of andesitic rocks with hornblende, which is why it is included in Disaster Peak formation rather than Stanislaus Group. Clasts also include white tuff with hornblende, feldspar, and quartz, similar to the reworked tuffs. The Disaster Peak Formation further north in the Sierra Crest graben (Disaster Peak area, Figure 1, not mapped here) has similar, abundant white tuffs, reworked tuffs and tuff clasts (Busby et al., in prep).

Two primary volcanic rocks units that we assign to Disaster Peak Formation occur along the ridgecrest NW of Leavitt Peak, within the SW boundary of the Sierra Crest graben near the Kennedy Creek Fault. The lower of the two primary volcanic rocks is a white-green ignimbrite that lies within channels cut into the TML (Tdput, on the south and NW sides of peak 11,200', Figure 4B; the latter locality was mapped by binoculars because it is inaccessible). The white-green ignimbrite is unwelded to incipiently welded, and contains pumice lapilli and pebble-sized accidental volcanic lithic fragments and sparse polycrystalline quartz lithic fragments; these are set in a matrix of glass shard and broken crystals, including (in order of abundance) sieve-textured plagioclase, bladed hornblende/amphibole with oxidized rims, and sparse euhedral orthopyroxene and clinopyroxene. This ignimbrite is assigned to the Disaster Peak formation because it (and the overlying lava flow) contains hornblende and lacks biotite, unlike ignimbrites of the EVT. Above the ignimbrite lies a more extensively-preserved >100 m thick lava flow, which forms the tall cliff and jagged peaks that dominate the NW-trending ridgeline NW of Leavitt Peak (Tdpl, Figure 4B). Previous workers have assigned this unit to the Disaster Peak Formation (Slemmons, 1953) or the Dardanelles Formation (Giusso, 1981). The rock is distinctive because it contains two pyroxenes in addition to hornblende; these together with plagioclase phenocrysts, constitute ~25–30% of the rock, so it is also crystal rich for a lava flow. The plagioclase phenocrysts appear similar to those of the TML, because they are large (7 mm) and skeletal, but the TML has no hornblende. The unit also does not appear to be a Lava Flow member unit because those may contain very sparse hornblende (<1%) but this unit contains ~10% hornblende. It is far too crystal rich to be Dardanelles Formation. Therefore, we follow Slemmons (1953) in assigning it to the Disaster Peak Formation. This unit has a basal flow breccia and appears to have a horizontal base, so it is probably a lava flow (and not an intrusion), although much of the unit is inaccessible. A breccia of uncertain origin that we assign to Disaster Peak Formation lies on the same ridge as the ignimbrite and the lava flow (Tdpu, Figure 4B) and is mineralogically similar to them.

Disaster Peak Formation Intrusions

Disaster Peak Formation intrusions inside the Sierra Crest graben are generally similar to those outside the graben, although they are more abundant in the graben and along the Red Peak and Bald Peak faults to the west (Figure 5) than they are further west in the range or to the east in the range front (Busby et al., in prep). They are small hypabyssal intrusions and dikes that do not vary much in character. Most contain hornblende (Koerner, 2010).

THE SIERRA CREST GRABEN PART II: STRUCTURE

In this section, we give describe and interpret faults of the Sierra Crest graben. We start with the NNW-striking East Fork Carson fault on the northeast graben boundary (Figure 4A), then moving westward to adjacent, smaller faults within the graben (Stanislaus Peak, and Sonora Pass Faults, Figure 4A, and the St. Mary's Pass Fault, Figures 4A, 4B). This leads to a discussion of a fault within the southeast part of the graben (Blue Canyon Fault, Figure 4B), and parallel faults at the southwestern margin of the graben (Kennedy Creek Fault, Figure 4B). Faults of the western graben boundary are then tracked up through the Chipmunk Flat Fault Zone (Figures 4A, 4B), into the Seven Pines Fault. (Figure 5).

East Fork Carson Fault

This fault controls the trace of a very straight, deep, narrow river valley on the northeast side of the Sierra Crest Graben (Figure 3), with very obvious west--dipping facets cut into the granite on its eastern wall. The spectacular White Canyon segment of the Pacific Crest trail follows the base of this fault scarp, on the valley floor. The segment of the East Fork Carson Fault shown on Figure 4A forms only the southern third of the fault; its northern segment drops TML down to the west (Busby et al., in prep), and its facets indicate that it remains active today.

There is no Relief Peak Formation below TML on the footwall block of the East Fork Carson fault (Figure 4A, and Busby et al., 2008a and in prep). However, *in situ* Relief Peak Formation reappears on the hanging wall side of the next fault to the east (the east-dipping, down –to-the-east Chango Lake Fault; Hagan, 2010). Only TML lies on top of the horst block to the northeast of the East Fork Carson fault (Figures 3, 4A). We infer that much of the very thick Relief Peak Formation-derived debris avalanche deposit below the TML in the Sierra Crest graben was derived from this horst. Therefore, the fault was active before eruption of the TML.

Stanislaus Peak Fault

The northeast-striking Stanislaus Peak fault has apparent left-lateral separation, separating the lavas and vent facies of the TML and a basalt lava flow by at least 300 m (Tstmlvf, Tstml, Tsb, Tsbvf, Figure 4A). In this region, the Cretaceous granite is highly sheared and jointed with northeast-oriented fractures. This fault is conjugate to the NW-striking East Fork Carson fault and the St. Mary's Pass Fault, and its sinistral offset is like that of the NE-striking Sonora Pass fault zone.

Sonora Pass Fault Zone

The northeast-striking Sonora Pass fault zone (Figure 4A) was mapped in its eastern third by Slemmons (1953), where it clearly cuts TML (Busby et al., 2008a). A series of faults is also very well exposed at the SE end of the fault zone (south of Highway 180), where a competent coherent hornblende andesite lies. There, NE-striking fault surfaces dip >80° southeast. The fault surfaces have slickenlines that plunge 45-20° NE; making the reasonable assumption that the dip slip component is normal (since there are no reverse-slip faults in the region), the slickenlines indicate a sinistral component of slip. The fault zone can be traced north of the pass by mapping joints and calcite veins in the incompetent Relief Peak Formation debris avalanche deposits (shown as a solid line, Figure 4A).

The central segment of the Sonora Pass fault zone is queried (Figure 4A) because it does not appear to offset the map trace of the TML, although it appears to cut the large avalanche block of interstratified block and ash flow tuffs and debris flow deposits (Trpdb). However, the slide block may have been disrupted during the avalanching process, not by the fault. At that locality, the TML has lava flows on either side of the fault, and a flow breccia over the projected trace of the fault, so it cannot be determined whether individual lava flows were offset by the fault.

A north-striking, steeply west-dipping fault that offsets the Table Mountain Latite lava flows on the east side of Sonora Peak may represent a splay off the Sonora Pass fault zone, although its trace becomes lost southward in the Relief Peak Formation debris avalanche deposits before it reaches the Sonora Pass fault (Figure 4A). About 1.1 km south of Sonora Peak, this fault is marked by a zone of sheared Relief Peak Formation, and it drops the base of the TML down to the west (<10 m, which does not show at the scale of this map, Figure 4A). The north end of this fault drops the base of the TML 30 m down to the west (Figure 4A).

St. Mary's Pass Fault

The St. Mary's Pass fault is a NNW-striking normal fault that dips east ~70°, and traces through St. Mary's Pass and Sonora Pass, displacing both the Relief Peak Formation and the Table Mountain Latite (Figures 4A, 4B). The southern end of the fault was previously mapped by Slemmons (1953, as Leavitt Peak fault) and Roelofs (2004), and the trace was extended to the north through St. Mary's Pass by Busby et al. (2008a). The fault trace cuts straight through topography and its steep dip is directly observable where it cuts competent rocks of the TML (Figure 4B). Hanging wall TML lava flows are rotated ~8–15° west, toward the fault, with tilting increasing southward from Sonora Pass toward Leavitt Lake (Figure 4). Similarly, vertical separation of the contact between Relief Peak Formation and TML increases southward, from ~70 m along the northern segment near Sonora Pass to ~130 m along the southern segment near Sardine Falls. The fault becomes difficult to map at its north and south ends, where there is no competent TML to expose fault planes or act as a strain marker.

There is some weak stratigraphic evidence for growth faulting on the St Mary's Pass fault during deposition of the Relief Peak Formation and the TML. The Relief Peak Formation doubles in thickens abruptly (by about 50 m) onto the hanging wall block at St. Mary's Pass. The TML also thickens from ~200 m on the footwall, to >400 m on the hanging wall at St. Mary's Pass, but the TML has been eroded away in the saddle along the fault, so an abrupt change in thickness cannot be demonstrated (Figure 4A). We previously made an erroneous estimate of 146 m minimum vertical displacement on the fault prior to eruption of the TML, because we mapped landslide deposits at the top of the Relief Peak Formation on the hangingwall but not the footwall (Busby et al., 2008a; Hagan, 2010). However, more field work in 2010 (with Graham Andrews) convinced Busby that none of the Relief Peak Formation along the St. Mary's Pass fault is *in situ*, except in the fluvial channel fill at the northern mapped end of the fault, described above (Trpf, Figure 4A). The chaotic nature of the Relief Peak Formation thus makes estimates of any pre-TML slip on the St. Mary's Pass Fault impossible.

Although there is syn(?)- to post-TML normal offset along the St. Mary's Pass fault, it also accommodated dextral strike-slip separation. Obliquely-plunging lineations and Riedel shears are present in Relief Peak Formation near Sardine Falls and Sonora Peak (Busby et al., 2008a). A 1 km long, NW-striking (320°) splay of the fault at Sonora Pass (shown by red dextral arrows, Figure 4A) dips ~65–70° west and has slickenlines that plunge obliquely (~25°) to the NW; assuming normal displacement (rather than regionally unlikely reverse displacement), the slickenlines indicate right-oblique-slip (Koerner, 2010). Additionally, at the northern end of the mapped fault (which may continue further north), the paleochannel axis cut into granitic basement and filled with Relief Peak Formation fluvial deposits is offset right laterally ~500 m on either side of the Clark Fork valley (Trpf; Figure 4A).

Blue Canyon Fault

The Blue Canyon Fault is a minor fault that parallels the much more important Kennedy Creek Fault (Figure 4B; Koerner, 2010). It strikes WNW (~300°) and is subvertical. This fault shows 30 m of apparent dextral offset of a biotite dike 1 km north of Deadman Lake (shown as a blue line with boxes, Figure 4B). Two splays off this fault are mapped N of Blue Canyon Lake. The southern of these two splays strikes NW, and is marked by abundant NW-striking surfaces; it clearly drops TML >80 m down to the southwest against Relief Peak Formation (Figure 4B). Along this NW-striking normal fault are also N-striking, steeply west-dipping undulatory surfaces (not mapped at the scale of Figure 4) with slickenlines that plunge 35° to the north; this suggests that the normal fault also accommodates dextral slip. Where the southern splay meets the Blue Canyon fault, on the north side of the Blue Canyon fault, lies a 100 m long north-striking fault (Figure 4B) that strikes ~015°, dips steeply east, and contains slickenlines that plunges south ~75–90°. If this is a normal fault like the rest of the faults in the region, the slickenlines indicate a dextral component of slip. It thus appears that the more oblique, N-striking fault has a greater component of normal slip relative to the less oblique, NW-striking splay, supporting the interpretation that the WNW-striking Blue Canyon fault accommodates dextral strike slip offset (Koerner, 2010).

Kennedy Creek Fault Zone

The Kennedy Creek fault zone was first mapped by Slemmons (1953), who did not estimate the magnitude of slip. It forms the southwestern margin of ponded TML (up to 400 m thick), and none escaped into the paleochannel to the west, as defined by Valley Springs and Relief Peak Formation filling a paleocanyon carved into the basement there (Slemmons, unpublished mapping; see mapping by Roelefs, 2004; Busby et al., 2008a, and in prep). The Kennedy Creek Fault therefore had had at least 400 m of normal slip before or during the extrusion of the TML. A minor strand of the Kennedy Creek fault zone offsets one of the intrusions of the cluster in the granitic basement, east of the confluence of Kennedy and Deadman Creeks (Figure 4B). It is subvertical and strikes ~320, with about 30 m of apparent right-lateral separation.

Slemmons (1953) connected the Kennedy Creek fault zone northward, to the westernmost fault of the Chipmunk Flat fault zone (Figure 4B), across a NE striking transfer fault that he mapped in the dramatic steep, narrow gorge of Deadman Creek. We concur (Figure 4B).

Chipmunk Flat Fault Zone

Slemmons (1953) mapped the eastern and western faults but not the central fault of the Chipmunk Flat fault Zone, which is smaller (Figure 4). The eastern fault strikes ~330° and dips relatively gently (~60° west) compared to other faults of the Sonora Pass area; accordingly, the fault makes a "V" on topography, and TML lava flows on the hanging wall are tilted eastward ~5° toward the fault, opposite the regional shallow west dip. The eastern fault vertically separates the contact between the Valley Springs ignimbrite and the Relief Peak Formation ~200 m, but it only drops the base of the TML down to the west ~100m, and the Relief Peak Formation thickens from ~160 m on the hanging wall to ~250 m on the footwall. This indicates growth faulting.

The central fault of the Chipmunk Flat fault zone (Figure 4A) strikes 340° and dips east, and drops the base of the Relief Peak Formation to the east about 60 m, but the Valley Springs Formation is absent. This may represent an antithetic fault.

The western fault of the Chipmunk Flat fault zone (Figure 4A) is subparallel to the other faults and dips east, bringing up granitic basement against Relief Peak Formation. As noted above, Slemmons (1953) connected this fault with the Kennedy Creek Fault ~4 km to the south, via a transfer fault. We infer that it forms the western margin of the Sierra Crest graben (Figure 3).

We connect the westernmost fault of the Chipmunk Flat Fault Zone with the Seven Pines Fault via a stepover between these two faults (which both dip east). We infer that the fault stepover is accommodated by a fault followed by a very narrow, straight creek with a NE trend similar to many other faults in the Sonora Pass area (Figures 4, 5; Hagan, 2010), including the nearby transfer fault to the south in Deadman Creek (described above). A Quaternary landslide deposit, with abundant megablocks, lies in this fault valley (Figure 4A).

Seven Pines Fault

The segment of the Seven Pines fault that crosses the ridge east of Red Peak was also mapped by Slemmons, as a down to the east normal fault (1953, referred to as the Iceberg fault). We trace it 4 km farther to the south (Figure 5), where we infer that it transfers to the Kennedy Creek Fault via the westernmost Chipmunk Flat fault, as described above (Figure 4). We also trace it continuously northward, where it becomes the Disaster Creek Fault (Busby et al., in prep); similarly, Slemmons (1953) inferred that it may "have a northern extension up Disaster Creek" (p. 149). North of that, we trace it continuously to the Nobel Canyon Fault of Curtis (1951), for a total strike length of 55 km (Busby et al., in prep).

The Seven Pines Fault strikes 340°, dips east ~60°, and has a normal sense of displacement. The base of the TML is down-dropped to the east ~50–80 m across the fault, both east of Red Peak (Figure 6A) and west of peak 10244' (Figure 5B). Drainages follow the fault trace both north and south of Douglas Creek, and calcite is common along the fault. Paleorelief on the contact between basement and Relief Peak Formation (merged unconformities 1 and 2), as well as the contact between the Relief Peak Formation and the TML (unconformity 3), is too great to determine whether or not any of the slip predated deposition of the TML. As noted above, the TML does not thicken dramatically onto the hangingwall of the Seven Pines Fault, but it does thicken dramtically across the ridge that is buried in younger Stanislaus Group vent deposits and flows of the EVT and Dardanelles Formation. Therefore, we infer that a buried strand of the Seven Pines Fault formed the main graben boundary, and that it was healed by intrusions, so that post-Stanislaus Group fault slip was concentrated on the strand that maps out at the surface. The Disaster Peak fault to the north clearly ponds TML onto its hangingwall (Busby et al., in prep).

DISCUSSION

Unlike other parts of the Sierra Nevada, significant faults are not restricted to the modern range front (i.e. east of the modern crest). At Sonora Pass, faults with 100 – 400 m offset or more extend 12 – 15 km into the so-called "stable Sierran block", which is widely viewed as unfaulted (except in the southern Sierra; see Saleeby et al., 2009). Slemmons (1953) recognized faults west of the modern Sierra Nevada range crest, but proposed that offset is greatest on down-the-east normal faults on the eastern range front. However, pre- to syn-TML offset is much harder to recognize than post-TML offset, and in fact, no previous workers have recognized it anywhere. This is because the effects of paleo-relief can only be separated from the effects of syndepositional faulting through detailed, modern volcanic lithofacies mapping of the kind described here. Modern detailed volcanic lithofacies mapping is also required to identify volcanic vents and infer structural controls on them. To summarize our detailed findings:

(1) This paper describes the southern two-thirds of a previously unrecognized graben that we name the Sierra Crest graben. It is a wide (~6 – 10 km) full graben, so strata are not tilted in either direction. In contrast, the previously recognized down-to-the-west half grabens on the eastern range front (not described here) are narrower (~2 – 4 km), with strata westward tilted up to 45° (Hagan, 2010).

(2) The east-dipping Kennedy Creek fault on the SW margin of the Sierra Crest graben must have slipped >400 m before 10 Ma, in order to pond TML on what is now the Leavitt Peak – Night Cap Peak ridge. Similarly, the newly-recognized west-dipping East Fork Carson fault on the NE margin of the graben contains up to 730 m (2,400') of pre-TML debris avalanche deposits on its footwall at Sonora Pass, while TML rests upon granite on its hangingwall. This requires pre- to syn-TML slip on Sierra Crest graben faults that is of similar magnitude to post-TML faulting on the Sierran range front here (the latter described by Hagan, 2010).

(3) Paleochannel fill deposits can be distinguished from graben fill deposits in both faulted and unfaulted parts of the Sonora Pass area, by the following features: presence of *in situ* (i.e. not avalanche slab) Valley Springs Formation ignimbrite; presence of *in situ* (ditto) Relief Peak Formation fluvial deposits; presence of fluvial deposits interstratified

with lava flows of the TML and Lava Flow Member; west-directed paleocurrents in sedimentary rocks; E-W (rather than NNW-SSE) stretching of vesicles in lava flows; kuppaberg jointing on the tops of lava flows; lateral accretion of lava flow breakout lobes, due to emplacement in channels with easily eroded walls of sediment; and phreatomagmatic tuffs and pepritic bases on lava flows.

(4) The general lack of post-Stanislaus Group strata in the region described here suggest that accommodation was not provided by either extension or paleochannel reincision after about 9 Ma.

(5) The segment of the Sierra Cest graben mapped in this paper has earlier (TML) high-K lava flow vents, feeder dikes and vent-proximal deposits along the eastern side, and later (Lava Flow Member and Dardanelles Formation) high-K lava flow vents, feeder dikes and vent-proximal deposits along its western side. Olivine basalts lava flows and vent deposits are interstratified with both the TML and the Lava Flow Member high-K lava flows.

(6) We infer that a buried strand of the Seven Pines Pines fault formed an important NW boundary to the segment of the Sierra Crest graben described in this paper, but it is not exposed to view because it was not reactivated postvolcanically, possibly due to stitching by Lava Flow Member and Dardanelles Formation intrusions.

(7) The St Mary's Pass fault, which lies within the Sierra Crest graben, may have initiated displacement before eruption of the TML, but this cannot be quantified, due to the chaotic nature of the underlying debris avalanche deposits. Hanging wall TML lava flows are rotated ~8–15° west, toward the fault, with tilting increasing southward from Sonora Pass toward Leavitt Lake; similarly, vertical separation of the contact between Relief Peak Formation and TML also increases southward, from ~70 m near Sonora Pass to ~130 m near Sardine Falls.

(8) The TML is thickest, with the most flows, in the Sierra Crest graben (>400 m, top eroded), and thinnest to the west in the Cataract paleochannel (~ 80 m), but it is also ponded to thicknesses of up to 400m in the eastern rangefront half grabens (Hagan, 2010; Busby et al., in prep). This is in marked contrast with TML just east of the range front, directly across highway 395 (Figure 1), where the TML is <150 m thick (commonly much thinner), and consists of only 1- 5 flows (King et al., 2007; Pluhar et al., 2009). We attribute this to synvolcanic extension in what is now the Sierra Nevada range crest and range front.

(9) Kinematic indicators and apparent offsets are suggestive of a right slip component on the NNW normal faults. These include Riedel shears and obliquely-plunging lineations on the St. Mary's Pass fault; dextral offset of the narrow paleochannel cut into granitic basement and filled with Relief Peak Formation at the northern mapped end of the St. Mary's Pass fault; slickenlines on a strand of the Sonora Pass fault; dextral offset of a dike on the Blue Canyon fault and dextral slickenlines along its splays; and dextral offset of dikes in the Kennedy Creek fault zone.

(10) Preliminary data are suggestive of a sinistral component on the NE faults; these include apparent sinistral offset of TML on Stanislaus Peak fault and Sonora Pass fault zone, and as well as kinematic indicators on the latter.

(11) More convincingly, the map-scale pattern of the interaction between NE and NNW faults is indicative of dextral transtension, because the NE faults appear to accommodate right steps along in the NNW faults. So, although we have no kinematic

indicators on the two NE-trending faults on the western margin of the Sierra Crest graben (in Deadman Creek and the next creek to the north, Figure 3), the fault pattern strongly suggests they have a sinistral component. A similar right step on the eastern margin of the Sierra Crest graben (Figure 3), accommodated by the Sonora Pass fault zone (Figure 4) has kinematic indicators consistent with the interpretation of sinistral motion, as noted in (12).

The most important result of this paper is that preservation of the vast majority of the Miocene volcanic-volcaniclastic section at Sonora Pass was accommodated by syndepositional faulting, not by one or more paleochannels as previously assumed by others. NNW normal faults (likely with a dextral component of slip) and NE faults (with a likely sinistral component of slip) record dextral transtension, beginning by 10.6 Ma (age of oldest dated TML). These faults controlled the positions of vents for effusive rocks of the Stanislaus Group, and controlled the development of the Little Walker caldera.

CONCLUSIONS

Prior to significant development of Basin and Range or Walker Lane faults, Oligocene ignimbrites were erupted from calderas in eastern Nevada and flowed through paleochannels westward across the northern and central Sierra Nevada; in the map area, these are preserved in paleochannels carved into Mesozoic granitic basement (unconformity 1). These are overlain in erosional unconformity (unconformity 2) by Early Miocene (>10.4 Ma) arc volcaniclastic and volcanic rocks of andesitic composition, with minor olivine basalt and dacite lava flows (Relief Peak Formation). The earliest stages of extension accompanied this volcanism (not discussed in this guidebook), so while some early Miocene strata were accommodated by the Cataract paleochannel, grabens also provided some accommodation space. These are overlain in erosional and angular unconformity (unconformity 3) by high-K volcanic rocks of the Stanislaus Group, with dates of 10.4 to 9.3 Ma.

The most voluminous unit of the Stanislaus Group, the basal Table Mountain Latite (TML), consists largely of trachyandesite lava flows that extend from the California-Nevada border to the east, to the Sierra Nevada foothills to the west. In the map area, this unit rests upon debris avalanche deposits up to 700 m thick, derived from the Relief Peak Formation and deposited in part of a 28 km long, 6 – 10 km wide full graben we name the "Sierra Crest graben", the southern two-thirds of which is described here. The modern Sierran range crest lies just within the eastern boundary of the Sierra Crest graben, and has vent deposits and feeder dikes for the TML. The TML was ponded to a thickness of ~400 m in the Sierra Crest full graben, and was also ponded to thicknesses of ~200 – 400 m in narrower (~2 – 4 km wide) down-to-the-east half grabens on the Sierra range front, but some TML overtopped the western edge of the Sierra Crest graben to flow westward down the paleochanel, where it is >80 m thick.

An overall dextral transtensional regime is indicated by NNW normal faults with a dextral component of slip, and NE faults with a sinistral component of slip. At least half the slip on faults of the Sierra crest and range front occurred before or during eruption of the TML, with slip increasing southward in the rangefront system (Busby et al., in prep); we infer that this controlled the siting of the Little Walker Caldera, from which the overlying Eureka Valley Tuff ignimbrites were erupted (Putirka and Busby, 2007). However, eruption of lava flows continued in the Sierra Crest graben throughout deposition of the Stanislaus Group, switching to vents straddling its western margin, including Lava Flow Member of the Eureka Valley Tuff (EVT), and the Dardanelles Formation, which we show here to be a single distinctive lava flow that overlies Upper Member of the EVT. At Sonora Pass, the record of post-Stanislaus andesite arc volcanism is mainly restricted to intrusions.

To summarize, the vast majority of the Miocene section at Sonora Pass was deposited in syn-volcanic grabens and half grabens that formed within the axis of the Ancestral Cascades arc.

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This work is dedicated to Burt Slemmons, whose pioneering work at Sonora Pass is truly heroic in its scope, depth and longevity.

FIGURE CAPTIONS

Figure 1. Distribution of high-K volcanic rocks of the central Sierra Nevada (Stanislaus Group), modified from King et al., 2007; Pluhar et al., 2009; and Hagan, 2010. The volcanic rocks flowed from east to west down “paleochannels” defined by the gray fingers. Mapped areas outlined in black boxes (Figures 4, 5). Inset shows physiographic setting: B&R, Basin and Range; CR, Coast Ranges; GV, Great Valley; KM, Klamath Mountains; SCM, Southern Cascade Mountains; SN, Sierra Nevada.

Figure 2. (A) LEFT Composite stratigraphy of Cenozoic rocks of the Sonora Pass region, central Sierra Nevada, California, modified from Busby et al. (2008a), Koerner et al. (2009), Koerner (2010), and Hagan (2010). Thicknesses of units are extremely variable and are not shown to scale. Ages are recalculated from Busby et al. (2008a); see Busby and Putirka (2009). (B) RIGHT Formations and members divided by lithofacies and intrusions types; this serves as the map key to Figure 4.

Figure 3. Generalized Cenozoic rocks of the Sonora Pass area, from the modern range crest westward to The Dardanelles, showing the spatial distribution of geologic maps presented in Figure 4A, 4B and Figure 5B of this guidebook. The modern range crest is indicated by the brown dotted line, and the red line shows Highway 108.

Figure 4. (A = NORTH HALF, B = SOUTH HALF) Geologic Map of the Stanislaus Peak - Leavitt Lake - Night Cap Peak area, northern Emigrant Wilderness, central Sierra Nevada, California. Mapping by Koerner (in 2008, 2009), Rood (unpublished 2003 USGS EDMAP map), Busby (unpublished 2003 – 2010), and Slemmons (1953). Location given on Figures 1, 3; key to map units is given in Figure 2.

Figure 5. Geologic map of the eastern half of the area boxed in as "Figure 5" on Figure 3 (St. Mary's Pass - Red Peak - Bald Peak area,). Mapping by Koerner (in 2008, 2009), Rood (unpublished 2003 USGS EDMAP map), Busby (unpublished 2003 – 2010), and Slemmons (1953). Key to map units is given in Figure 2. Red lines (A', D') indicate positions of cross sections not shown here but presented in Koerner (2010) MS thesis.

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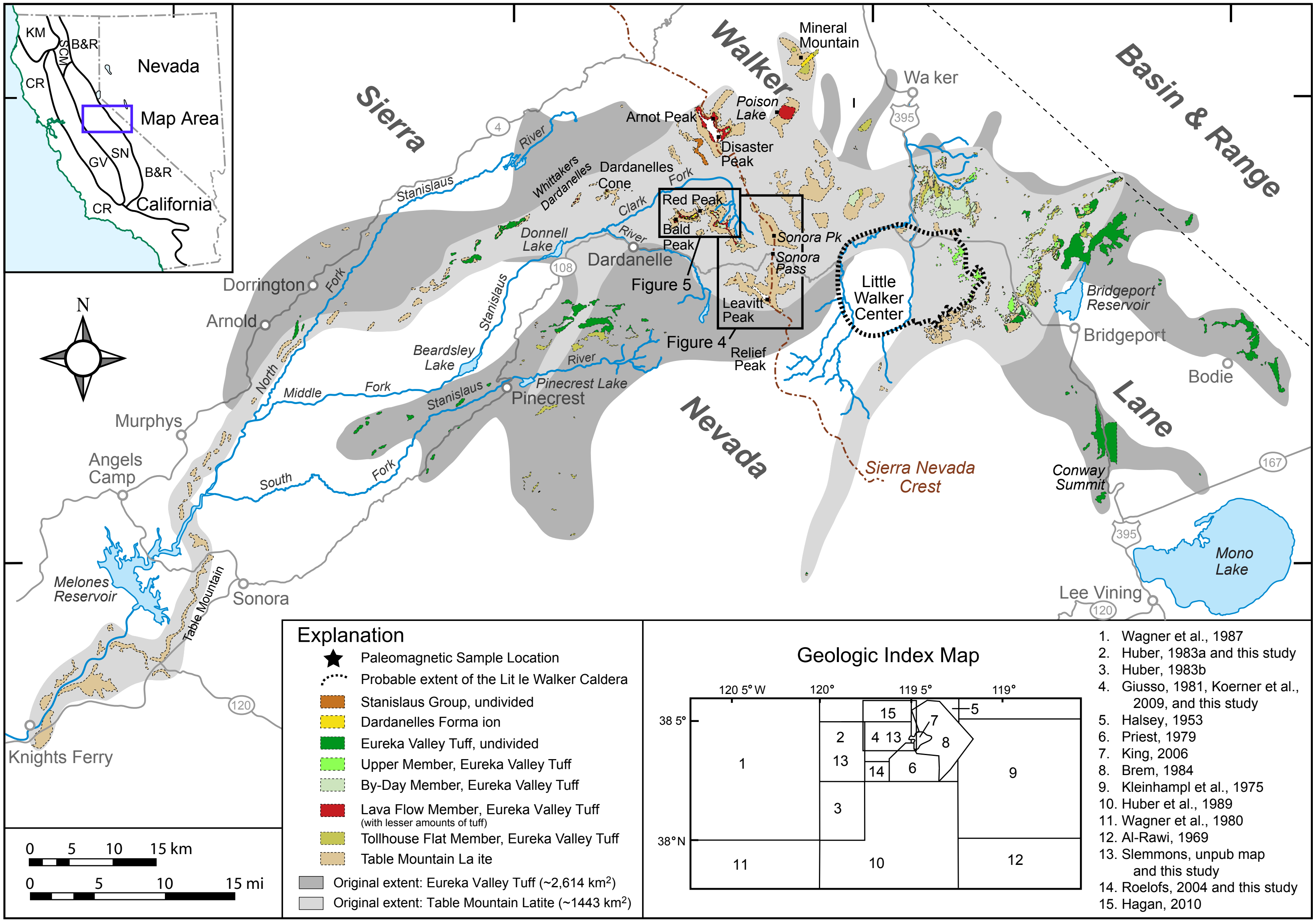
Figure 1



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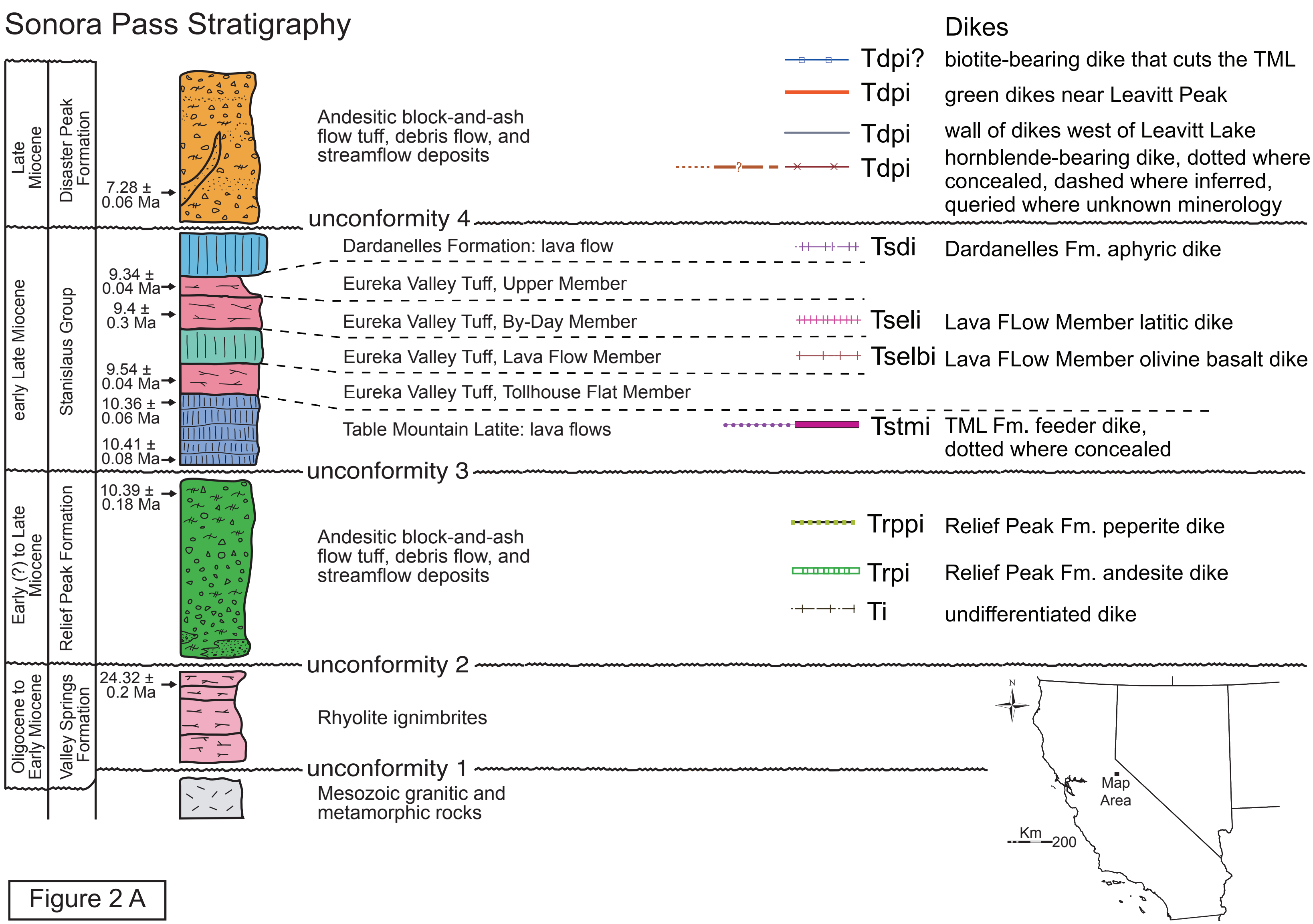

Figure 2 A

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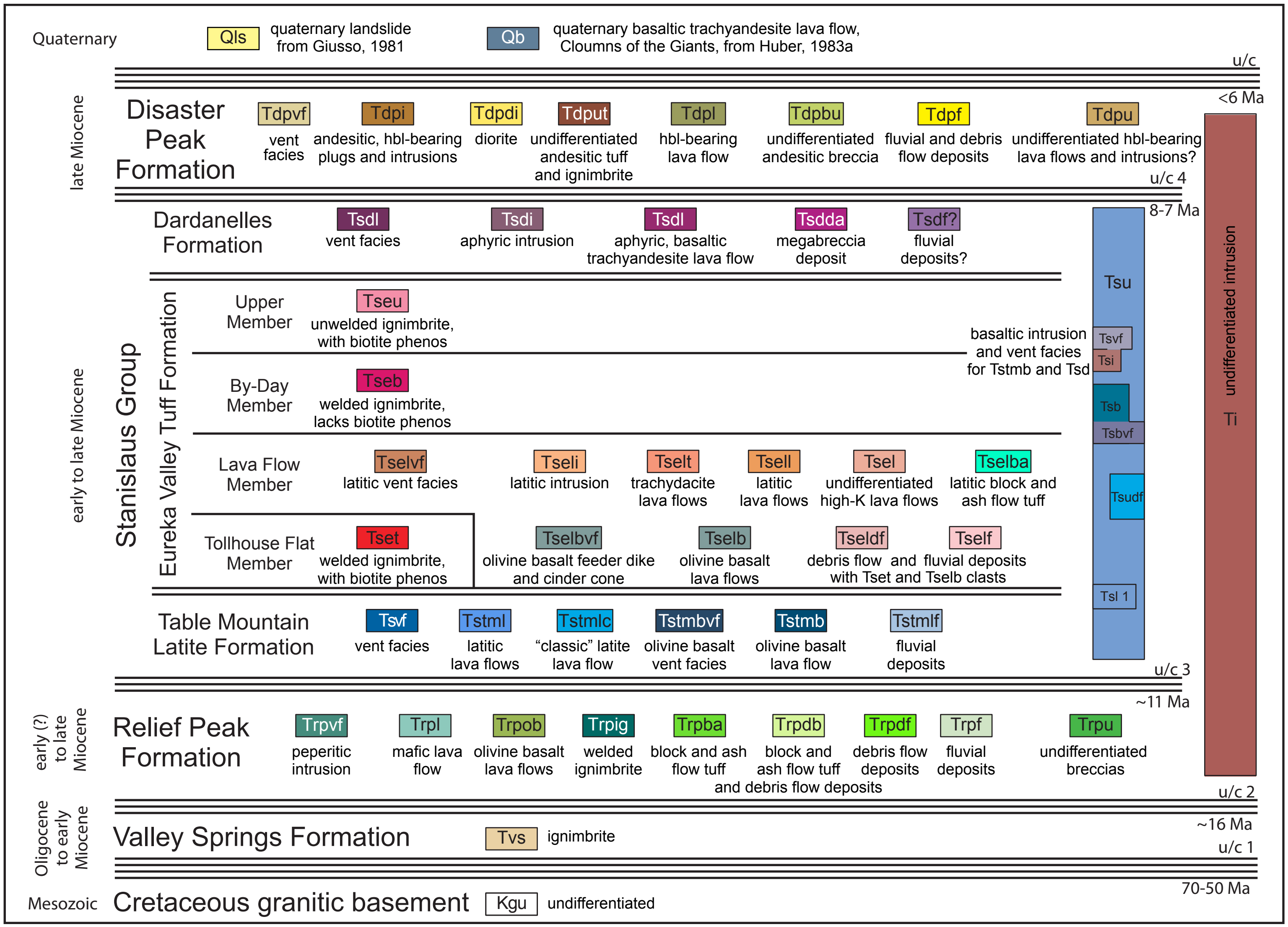

Figure 2B

BUSBY, Cathy J., KOERNER, Alice, HAGAN, Jeanette, and ANDREWS, Graham, 2012, Sierra Crest graben: a Miocene Walker Lane Pull-apart in the Ancestral Cascades Arc at Sonora Pass, in, N. Hughes and Garry Hayes (eds), Geological Excursions, Sonora Pass Region of the Sierra Nevada, Far Western Section, National Association of Geoscience Teachers field guide, p. 8-36.

FIGURE 3

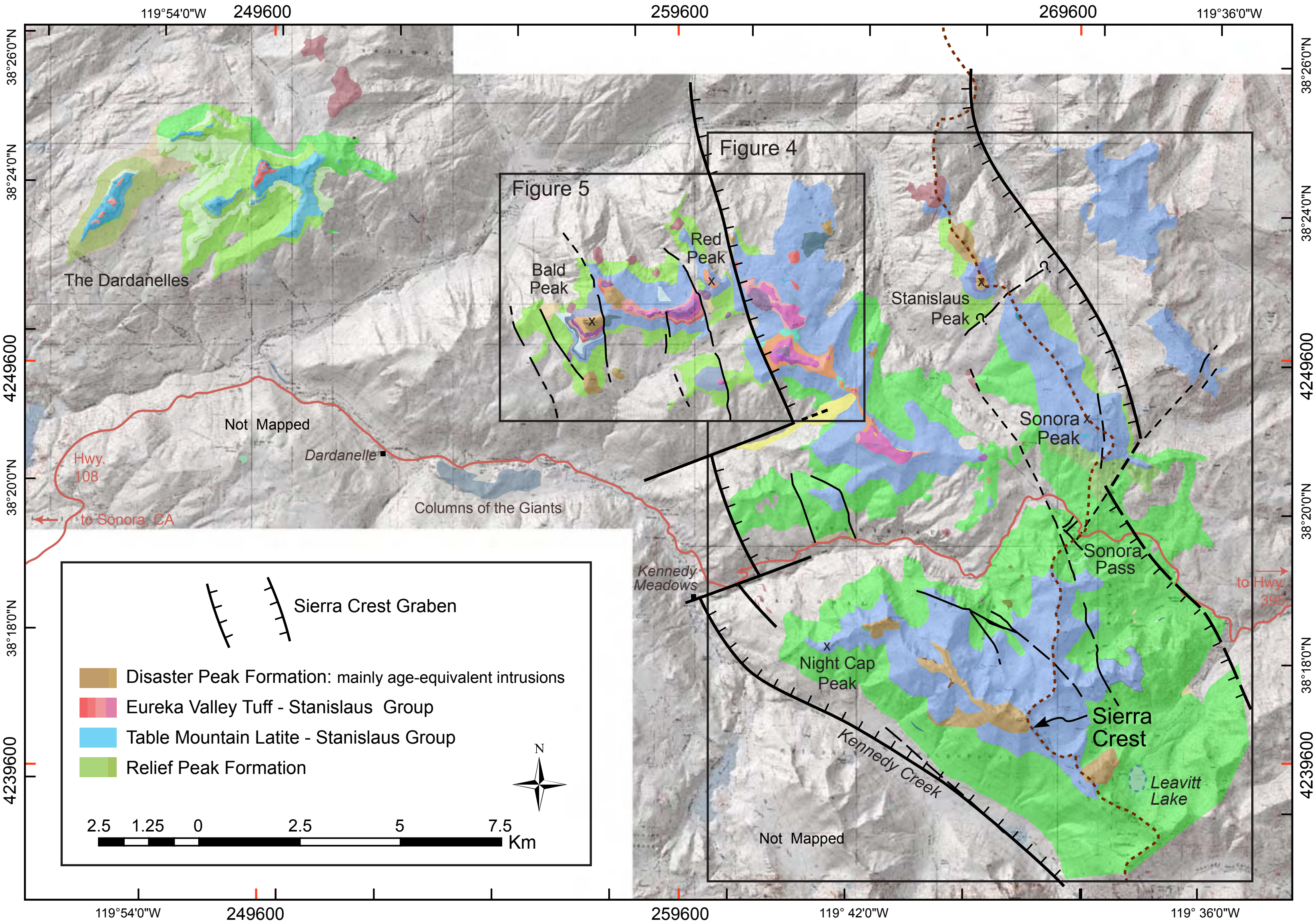

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FIGURE 4A

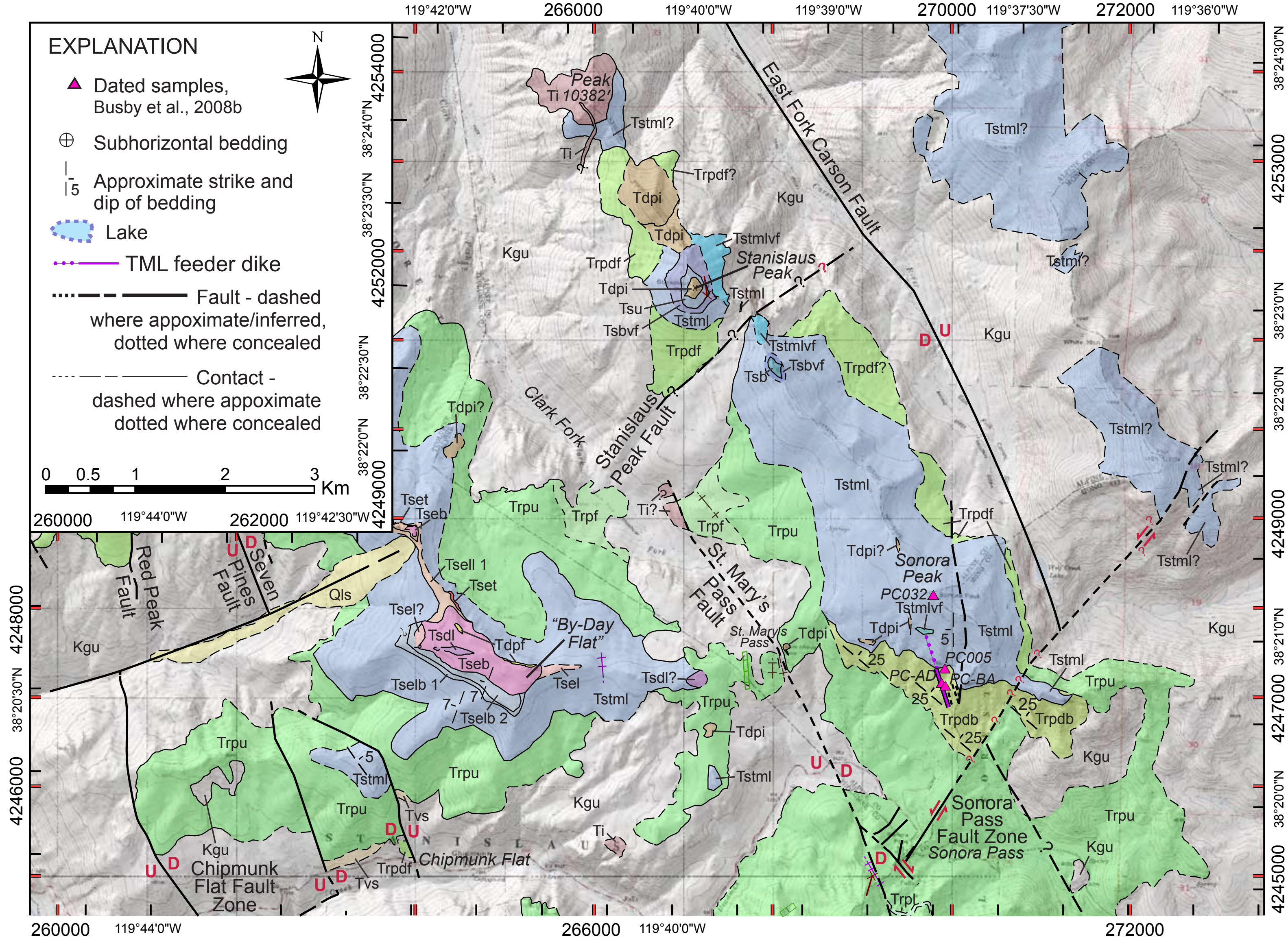

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FIGURE 4B

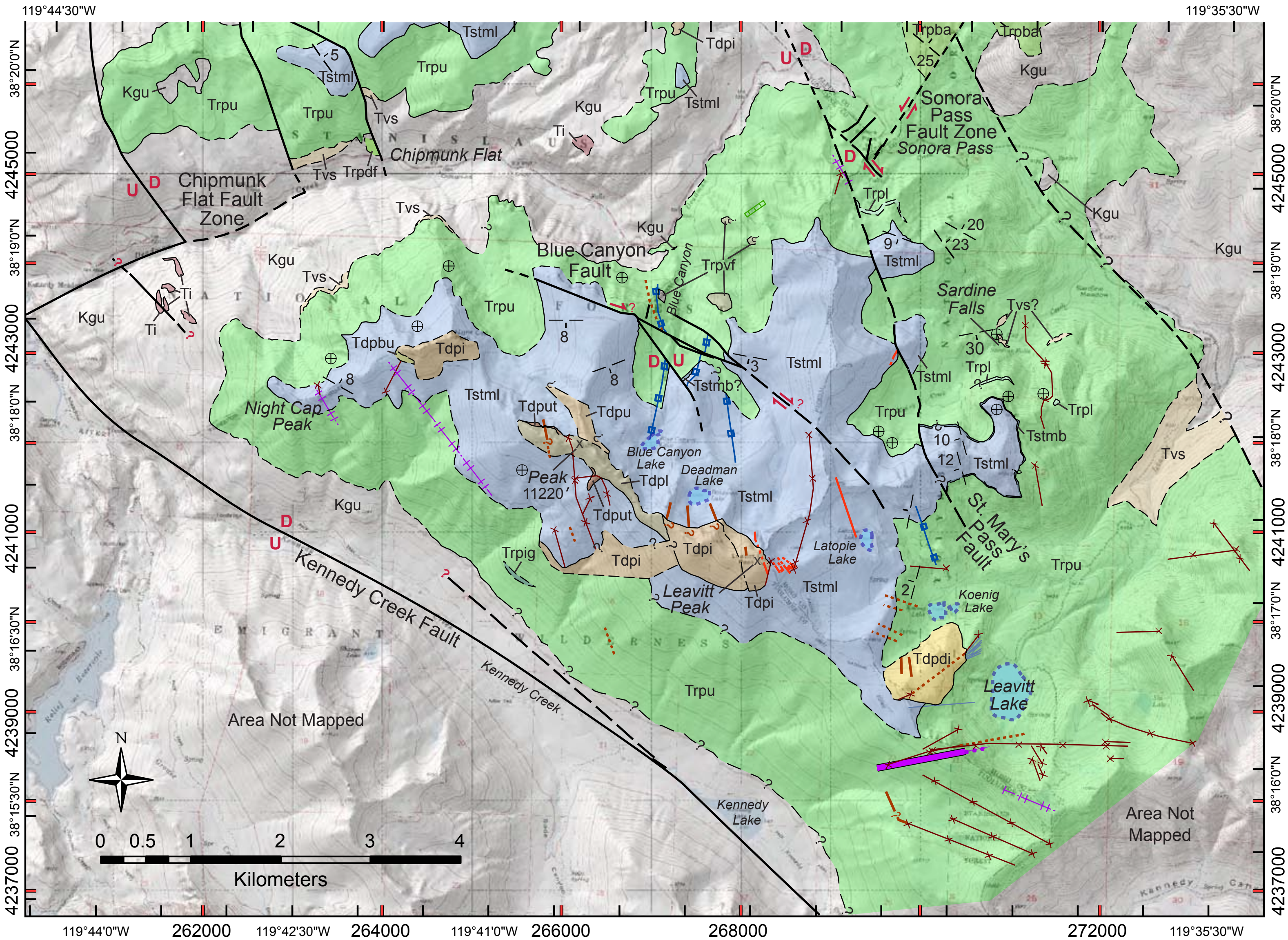

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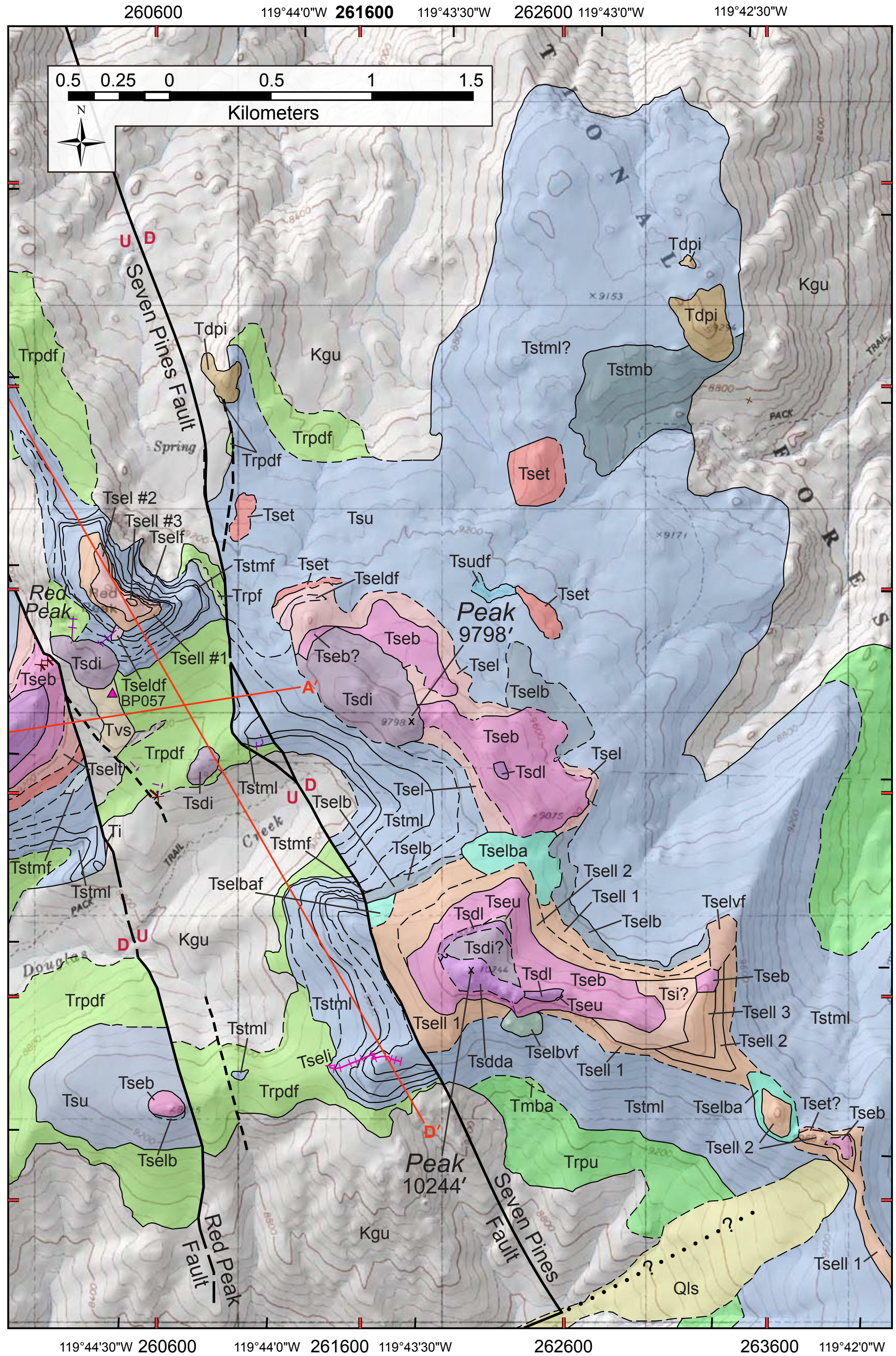
FIGURE 5



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