Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Geosphere

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Geosphere published online 26 June 2013;
doi: 10.1130/GES00670.1

Notes

THE GEOLOGICAL SOCIETY OF AMERICA

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Sierra Crest graben-vent system: A Walker Lane pull apart within the ancestral Cascades arc

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ABSTRACT

We show here that transtensional rifting along the eastern boundary of the Sierra Nevada microplate (Walker Lane rift) began by ca. 12 Ma in the central Sierra Nevada (USA), within the ancestral Cascades arc, triggering voluminous high-K intermediate volcanism (Stanislaus Group). Flood andesite (i.e., unusually large-volume effusive eruptions of intermediate composition) lavas erupted from fault-controlled fissures within a series of grabens that we refer to as the Sierra Crest graben-vent system. This graben-vent system includes the following.

1. The north-northwest–south-southeast Sierra Crest graben proper consists of a single 28-km-long, 8–10-km-wide full graben that is along the modern Sierra Nevada crest between Sonora Pass and Ebbetts Pass (largely in the Carson-Iceberg Wilderness). This contains fissure vents for the high-K intermediate lavas.

2. A series of north-northwest-south-southeast half-grabens on the western margin of the full graben, which progressively disrupted an ancient Nevadaplano paleochannel that contains the type section of Stanislaus Group (Red Peak–Bald Peak area). These Miocene half-grabens are as much as 15 km west of the modern Sierra Nevada crest, and vented high-K lavas from point sources.

3. Series of northeast-southwest grabens define a major transfer zone along the northeast side of the Sierra Crest graben. These extend as much as ~30 km from the modern range crest down the modern Sierra Nevada range front, in a zone ~30 km wide, and vented high-K lavas and tuffs of the Stanislaus Group from point sources. Range-front north-south and northeast-southwest faults to the south of that, along the southeast side of the Sierra Crest graben, did not vent volcanic rocks (although they ponded them); those will be described elsewhere.

We present evidence for a dextral component of slip on the north-northwest–south-southeast normal faults, and a sinistral component of slip on the northeast-southwest normal faults. The onset of transtension immediately preceded the high-K volcanism (within the analytical error of $^{40}Ar/^{39}Ar$ dates), and triggered the deposition of a debris avalanche deposit with a preserved volume of ~50 km^3. The grabens are mainly filled with high-K lava flows, ponded to thicknesses of as much as 400 m; this effusive volcanism culminated in the development of the Little Walker caldera over a relatively small part of the field. Trachydacite outflow ignimbrites from the caldera also became ponded in the larger graben-vent complex, where they interfingered with high-K lavas vented there, and escaped the graben-vent complex on its west margin to flow westward down two paleochannels to the western foothills.

The Sierra Crest graben-vent system is spectacularly well exposed at the perfect structural level for viewing the controls of synvolcanic faults on the siting and styles of feeders, vents, and graben fills under a transtensional strain regime in an arc volcanic field.

INTRODUCTION

The superjacent sequence of the Sierra Nevada (California, USA; Whitney, 1880) is a sequence of more or less flat-lying Cenozoic strata that overlie deeply eroded Mesozoic basement rocks (mainly the Sierra Nevada batholith). Basal Eocene strata were hydraulically mined in the nineteenth century for their placer gold, and the east-west system of Sierran paleochannels they are in were mapped at the turn of the twentieth century; it was then assumed that the Cenozoic paleochannels, which parallel the modern ones, had their heads within the Sierra Nevada, at what is now the modern range crest (Lindgren, 1911). At the turn of the nineteenth century, voluminous high-K lavas (Table Mountain Latite) were discovered within one of these paleochannels (Cataract paleochannel of Lindgren, 1991); these channel-filling lavas were mapped ~100 km from the central Sierra Nevada range crest westward to the foothills (Ransome, 1898; Fig. 1). Bateman and Wahrhaftig (1966) showed that the Sierra Nevada forms a west-tilted block, bounded by normal faults on its east side, and the range was inferred to be very youthful (younger than 6–3.5 Ma). For decades, workers inferred that Miocene Basin and Range extension had gradually encroached westward from Nevada into California, and that the modern Sierra Nevada range front forms the western edge of the Basin and Range province.

Two major paradigm shifts have occurred in the past decade. (1) The Sierra Nevada paleochannels have been shown to be the lower reaches of fluvial systems, the heads of which were far to the east in central Nevada, where the caldera sources for Oligocene–Early Miocene ignimbrites within the paleochannels lie (Henry, 2008; Henry et al., 2012). The paleochannels are inferred to have been carved into a plateau created by Cretaceous low-angle subduction, termed the Nevadaplano, and the Sierra Nevada is inferred to have been on the western shoulder of this broad uplift, prior to disruption of the Nevadaplano by Basin and Range extension (Wolfe et al., 1997; DeCelles, 2004; Henry et al., 2012). The youthfulness of the Sierra Nevada mountain range has also been called

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Geosphere; August 2013; v. 9; no. 4; doi:10.1130/GES00670.1; 15 figures; 2 supplemental files.
Received 4 February 2011 ♦ Revision received 10 March 2013 ♦ Accepted 12 March 2013 ♦ Published online 26 June 2013

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

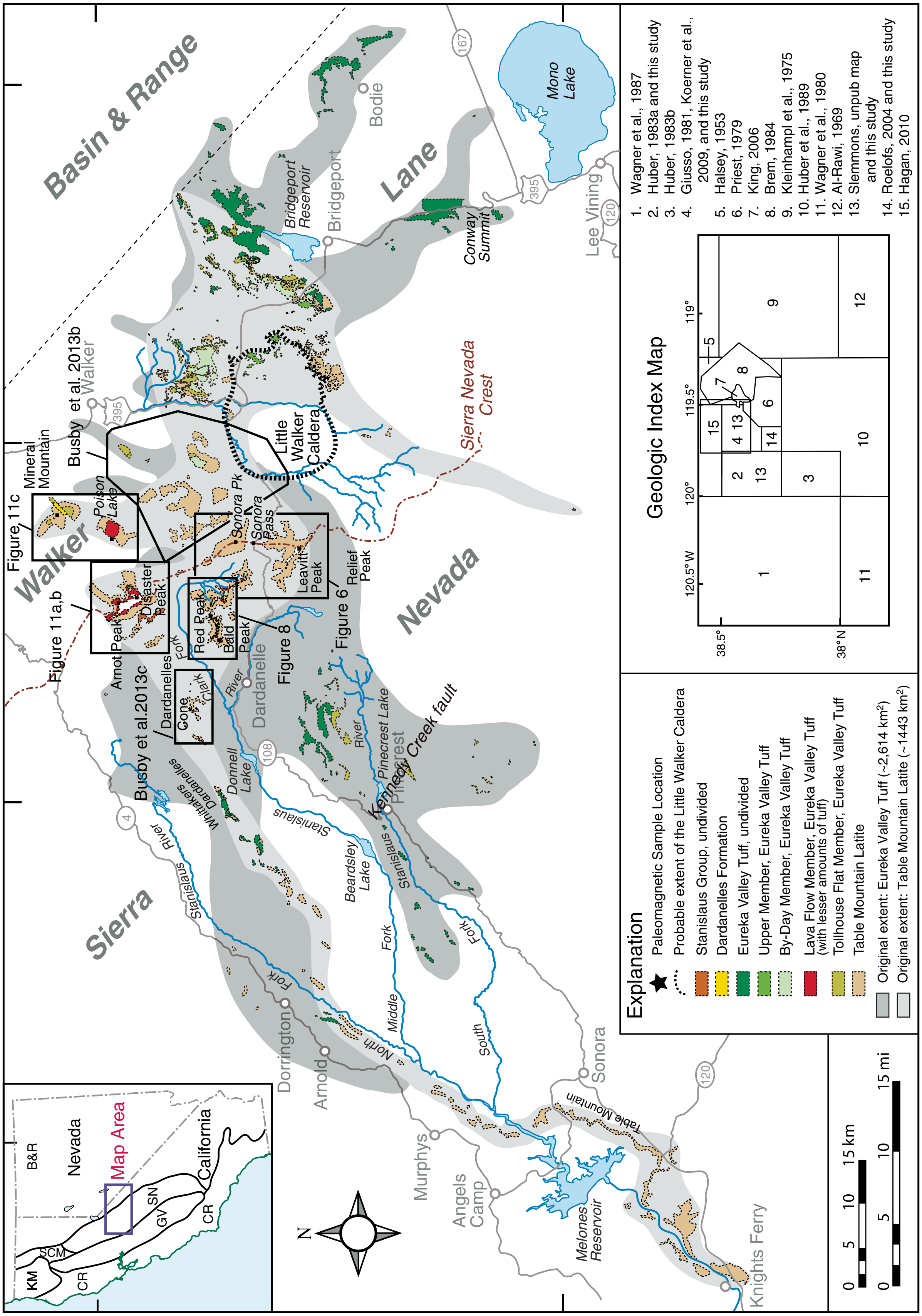

Figure 1.

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into question; many hypothesize that much of its present elevation was inherited from Cretaceous time (for discussion and references, see Wakabayashi, 2013). (2) Global positioning system and earthquake data showed that the eastern margin of the Sierra Nevada is currently a transtensional microplate boundary (not the western edge of the Basin and Range extensional province), taking up 20%–25% of the relative plate motion between the Pacific and North American plates (Unruh et al., 2003). This microplate boundary is now commonly viewed as the future plate boundary because it is assumed that the Sierra Nevada microplate will be transferred to the Pacific plate, as has Baja California. The eastern boundary of the Sierra Nevada microplate is a reasonable approximation to a classic plate boundary, because it is discrete relative to its north and west boundaries, which are diffuse and complex due to structural interleaving by compressional and transpressional tectonics, respectively. The eastern microplate boundary is thus ideal for determining when the microplate formed, and for identifying the timing of features that signal the birth of a microplate. The central Sierra Nevada range crest and range front offer superb exposure and abundant dateable Cenozoic volcanic rocks, suitable for reconstructing the Cenozoic geologic history of the region; however, the area has previously been given very little attention.

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). 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. This paper focuses on the Sierra Crest graben-vent system (mapped in Figs. 6, 8, and 11). We show here that the lavas, which flowed westward down paleochannels, indicated by the light gray fingers, erupted from a system of active grabens, referred to here as the Sierra Crest graben-vent system. Also shown is the area along the southeast side of the graben-vent system (mapping of Busby et al., 2013b), where half-grabens that step eastward down the range front were active during the high-K volcanism, but apparently do not contain vents for them. It was previously inferred that a releasing right step in the range-front faults controlled the siting of the Little Walker caldera (Putirka and Busby, 2007), which erupted ignimbrites of the Eureka Valley Tuff (dark gray fingers). The figure also shows the position of unfaulted paleochannel fill rocks at The Dardanelles (a prominent ridge, and unpublished map area also shown on Fig. 5; we will focus on the derangement of the paleochannels by transtensional faults of the Walker Lane belt elsewhere).

In this paper we present the results of a decade of detailed geologic mapping along the central Sierra Nevada range crest and range front area, between Sonora Pass and Ebbetts Pass (Fig. 1). The ~1000 km^2 area described herein is mainly within the Carson-Iceberg Wilderness, a roadless area with high relief (~1524–3505 m). Due to topographic inversion, the resistant volcanic rocks are along steep, generally inhospitable ridges, high above glacial and river valleys cut into the granitic basement. Most of the wilderness is under snow 8–9 mo/yr. Probably due to these access challenges, this area was last mapped more than 30 yr ago, mostly by helicopter, at a scale of 1:62,500 (Keith et al., 1982). Our mapping effort took a total of about 3 person years, and was done at scales of 1:6000–1:12,000, applying modern volcanic facies analysis techniques (as in Carson Pass area of the central Sierra Nevada; Busby et al., 2008b; Hagan et al., 2009). Geochemical and geochronological data show that ca. 16–4.5 Ma volcanic rocks of the central Sierra Nevada formed within the ancestral Cascades arc, a belt of subduction-related volcanic rocks that extended southward to the area of Las Vegas prior to northward migration of the Mendocino triple junction (Putirka and Busby, 2007, 2011; Busby et al., 2008a, 2008b; Hagan et al., 2009; Putirka et al., 2012).

We use our new detailed map data to describe a large (~50 × 50 km), previously unrecognized, volcano-tectonic structure we call the Sierra Crest graben-vent system, and show for the first time that it is the source of the voluminous Table Mountain Latite described by Ransome (1898) (for our estimate of its volume, see Supplemental File 1[1]). We demonstrate that the Sierra Crest graben-vent system formed ca. 11.5–9 Ma, along what is now the crest and range front of the Sierra Nevada, in the heart of the ancestral Cascades arc. Faults along the western boundary extend 30 km west of the modern range crest, but most of these faults were not previously recognized because they have generally not been reactivated since the graben-vent system formed (hence their position west of the modern range crest, which is held up by the graben-fill lavas). A synvolcanic history was not previously known for any of these faults. We also demonstrate for the first time that at least half the slip on faults along the eastern boundary of the graben-vent system, in the range front, occurred during the ca. 11.5–9 Ma arc volcanism (see also Busby et al., 2013b); this synvolcanic slip history is difficult to recognize because of Pliocene to Holocene reactivation. Previously workers proposed a two-phase history, wherein an arc thermal pulse preceded westward encroachment of Basin and Range faulting into what is now the eastern Sierra (Saltus and Lachenbruch, 1991; Surpless et al., 2002). We show that half or more of the faulting in the central Sierra range crest and range front occurred during, not after, arc magmatism.

From a tectonic perspective we demonstrate, using kinematic indicators, piercing points, and map-scale geometry of northwest oblique dextral-normal faults and northeast oblique sinistral-normal faults, that the Sierra Crest graben-vent system formed under a transtensional strain regime. These transtensional faults deranged the ancient Nevadaplano paleochannel system by ca. 12–11 Ma (shown herein; also Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). Thus, we infer that Walker Lane transtension exploited the active arc, and the resulting pull-apart structures controlled the siting of this unusually large arc volcanic field, which we show here is similar in structure and size to the modern Long Valley rift volcanic field. This ca. 12–11 Ma transtension is earlier than most have proposed for the onset of Walker Lane transtension at this latitude, but is not inconsistent with regional data (Busby et al., 2010).

In addition to tectonic implications, the Sierra Crest graben-vent system is interesting from a volcanic perspective. We show here that flood andesites (i.e., unusually large-volume effusive eruptions of intermediate composition) were erupted from 5–8-km-long fault-controlled fissures. These are unusual because intermediate-composition lavas are thought to be never large in volume (Hildreth, 2007), and fissure-fed eruptions are typical of flood basalt, not andesite, which normally erupts from point sources. We have been able to find only one other close analog, also in a subduction setting, i.e., a Miocene–Pliocene example in Japan, discussed herein. In this paper we take advantage of virtually 100% exposure, in three dimensions, to describe in detail the relationships between faults, feeder dikes and plugs, vent facies deposits, and graben fill in the Sierra Crest graben-vent system of the ancestral Cascades arc.

[1]Supplemental File 1. Minimum volume estimate for the Table Mountain Latite. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00670.S1 or the full-text article on www.gsapubs.org to view Supplemental File 1.

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PREVIOUS WORK

Our mapping builds on the pioneering mapping carried out by Slemmons (1953, 1966, and his maps archived at the California Geological Survey). Whitney (1880) and Lindgren (1911) recognized, in the broader region of the central and northern Sierra Nevada, that Cenozoic strata were deposited in paleochannels that flowed westward across the region. Lindgren (1911) referred to the paleochannel that is approximately followed by the modern North Fork Stanislaus River, from Sonora Pass to Knight's Ferry (Fig. 1), as the Cataract paleochannel. In the central Sierra Nevada, the oldest paleochannel fill deposits consist of several Oligocene nonwelded to welded rhyolite ignimbrites, first recognized as such by Slemmons (1953), who referred to them as Valley Springs Formation (Fig. 2A). More recent work has shown that these ignimbrites erupted from calderas in central Nevada and flowed westward down paleochannels across the present-day Sierra Nevada to the Sacramento Valley of central California (Garside et al., 2005; Henry, 2008; Henry et al., 2012). Slemmons (1953, p. 26) was also the first to recognize that after the rhyolite ignimbrites accumulated, "valleys were cut into the rhyolites along almost the same paths as those followed by the pre-rhyolite valleys," before the first andesites were deposited. More recent work shows that this unconformity can be correlated across the Sierra Nevada, and is Early Miocene (unconformity 2; Fig. 2; Busby et al., 2008a, 2008b; Busby and Putirka, 2009; Hagan et al., 2009).

Miocene andesitic volcanic and volcaniclastic rocks that overlie the Valley Springs Formation are referred to as Relief Peak Formation in the Sonora Pass region (Fig. 2A; Slemmons, 1966). Slemmons (1953) was the first to note that Miocene andesitic strata pass gradationally westward from primary volcanic deposits at the present-day Sierra Crest into reworked volcaniclastic deposits exposed along modern west-flowing drainages; this and paleocurrent indicators provide evidence for continued westward flow of material down the paleocanyons in Miocene time (Busby et al., 2008a, 2008b; Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). The Relief Peak

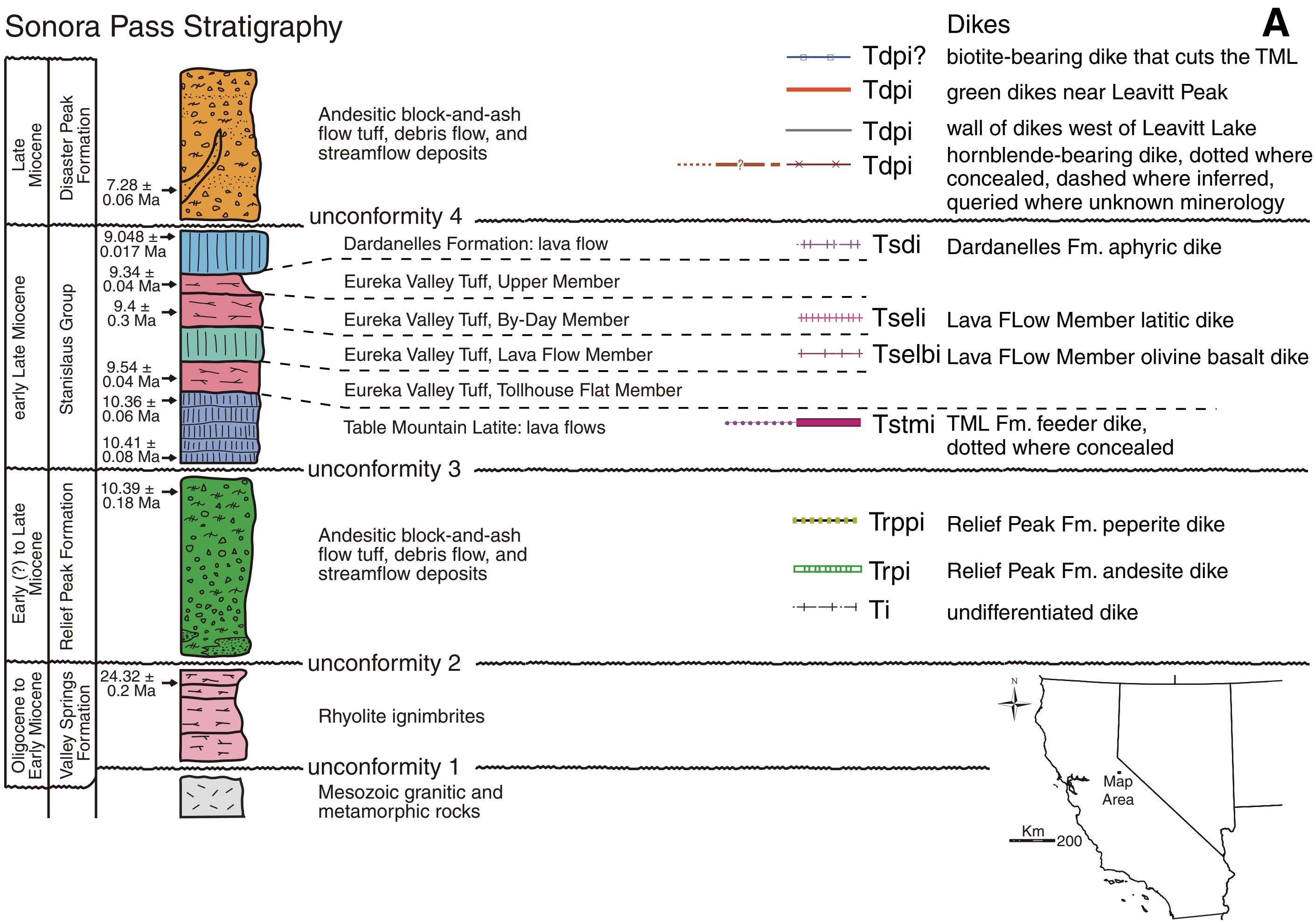

Figure 2 (*Continued on following page*). (A) Composite stratigraphy of Cenozoic rocks of the Sonora Pass region, central Sierra Nevada, California, modified from Busby et al. (2008a), Koerner et al. (2009), Koerner (2010), and Hagan (2010). Thicknesses of units are extremely variable and are not shown to scale. Ages are recalculated from Busby et al. (2008b); see Busby and Putirka (2009), except for the age of the Dardanelles Formation, which consists of a single lava flow $^{40}Ar/^{39}Ar$ whole-rock dated as 9.137 ± 0.017 (Busby et al., 2013a; complete age data will be available elsewhere). TML—Table Mountain Latite. (B) Formations and members divided by lithofacies and intrusion types; this serves as the map key to Figures 6 and 8 and the cross sections in Figure 9. Red stars are added to Stanislaus Group vent facies map units to make them easier to find on the geologic maps (Figs. 6, 8). Abbreviations: hbl—hornblende; u/c—unconformity; phenos—phenocrysts.

Formation is as young as 10.39 ± 0.18, and is separated from overlying high-K volcanic rocks of the overlying Stanislaus Group by a third erosional unconformity recognized across the central Sierra Nevada (Fig. 2; Busby et al., 2008a, 2008b). At Sonora Pass, Slemmons (1953, p. 41) first identified this unconformity as the "pre-latite erosion interval."

High-K volcanic rocks of the central Sierra Nevada were first described by Ransome (1898, p. 64); he recognized that these potash-rich volcanic rocks varied in silica content and mineralogy, but wanted to devise a term that would show how distinctive they are, relative to older and younger andesites in the region: compositionally, "an important group standing midway between the trachytes and the andesites." All subsequent workers have followed him in referring to these rocks of this composition in the Sierra as "latites." Ransome (1898) described latite lava flows (Table Mountain Latite, TML) overlain by biotite augite latite, in turn overlain by the Dardanelles flow. The "biotite augite latite" referred to by Ransome (1898) was recognized as welded and unwelded ash-flow tuffs (ignimbrites) by Slemmons (1953), who referred to them as the Eureka Valley Member of the Stanislaus Formation (later elevated to Eureka Valley Tuff [EVT] and members; Fig. 2A). Slemmons (1953, 1966) grouped all the high-K volcanic rocks (TML, EVT, and Dardanelles flow) into the Stanislaus Formation (later elevated to Stanislaus Group and formations; Fig. 2A), and designated the Bald Peak–Red Peak area (Fig. 1) as the type section, although a measured section was not made of the type section. Slemmons (1953) was the first to distinguish basalts from latites in the Stanislaus Group, on the basis of conspicuous olivine and/or lower silica percentage.

Slemmons (1953) first recognized that TML lava flows form a much thicker, more extensive section, with many more flows, for an ~32-km-wide distance on either side of the Sierra Crest (approximately the area extending from Bald Peak in the west to Highway 395 in the east; Fig. 1), relative to the thinner, much less extensive TML in the Cataract channel to the west at Dardanelles Cone and westward to Knights Ferry (Fig. 1). This approximately corresponds to the area that we herein show TML became ponded in synvolcanic grabens and half-grabens. Slemmons (1953) mapped north-northwest normal faults and northeast faults, some of which we map similarly, but he inferred that all faulting was postvolcanic, while we show here that it was mainly synvolcanic. Slemmons (1966) reported latite lava flows within the Eureka Valley Member in the type section at Bald Peak–Red Peak, but their exact location was not identified, and later reports were not made of them in the central Sierra Nevada, until the work of Koerner et

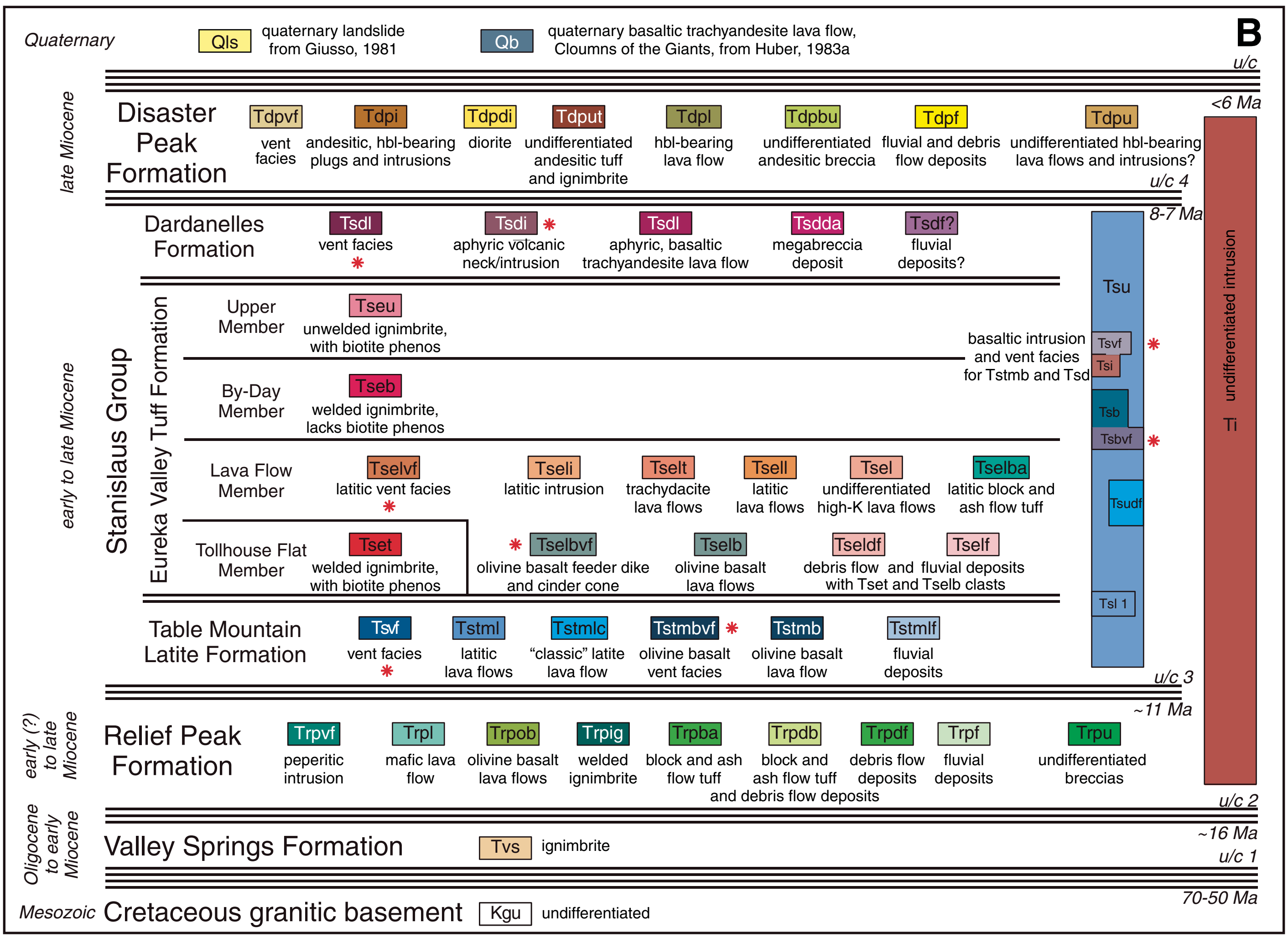

Figure 2 (*Continued*).

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

al. (2009), where they were referred to as the "Lava Flow Member of the EVT" (Fig. 2A).

Noble et al. (1974) identified three distinct ignimbrites within the Eureka Valley Member, and it was raised to formational status, the Eureka Valley Tuff (EVT), subdivided into the Tollhouse Flat, By-Day, and Upper members (Fig. 2A). This subdivision required elevation of the Stanislaus Formation to group status (Fig. 2A; Noble et al., 1974). Nonetheless, Noble et al. (1974; and, e.g., Priest, 1979; Slemmons, 1966; King et al., 2007) continued to use the term "Eureka Valley Tuff" not "Eureka Valley Tuff Formation"; similarly, they use the term "Table Mountain Latite" not "Table Mountain Latite Formation." Therefore, we follow their terminology, while emphasizing that the TML has mappable units that are not latite (e.g., olivine basalts, sandstones, debris flow deposits; Fig. 2B; Busby et al., 2008a), and EVT has a member that is not tuff (Lava Flow Member; Koerner et al., 2009; Pluhar et al., 2009).

Because of difficulty of access to the type section for the Stanislaus Group at Bald Peak–Red Peak, Noble et al. (1974) proposed a reference section ~20 km to the east of the type section, directly across the Little Walker River from Highway 395, close to the north end of the high-K Little Walker caldera (Fig. 1; first identified as a caldera by Noble et al., 1969). The reference section does not include the Dardanelles Formation, nor does it contain the latite lava flows interstratified with EVT that Slemmons (1953) reported from the type section (Noble et al., 1974, 1976; see measured section in King et al., 2007).

Prior to the work presented in Koerner et al. (2009), it had not been proven, with maps or measured sections, that the Dardanelles Formation is younger than all of the units of the EVT Formation (Fig. 2A). Instead, many workers (e.g., Slemmons, 1953, 1966; Giusso, 1981; Huber, 1983a) mistakenly assigned plagioclase-phyric latite lava flows to Dardanelles Formation, because they were upsection from Tollhouse Flat Member of the EVT, the most extensive of the three EVT ignimbrites. However, our mapping has shown that wherever a latite lava flow is preserved above the Upper Member of the EVT, it consists of a single, distinctive, black, nearly aphyric lava flow (Koerner et al., 2009; Fig. 2B). In addition, it was shown that plagioclase-phyric latite flows that are above the Tollhouse Flat Member are overlain by the By-Day Member (EVT), and are not part of the Dardanelles Formation (see fig. 5 of Koerner et al., 2009). Priest (1979), Brem (1977), and Pluhar et al. (2009) reported latite lava flows in the same stratigraphic position (within EVT) close to the Little Walker caldera, and referred to them as the "Latite Flow Member" of the EVT. However, geochemical work has shown that some of these lava flows are trachydacites (Koerner et al., 2009; Hagan, 2010; Koerner, 2010); we therefore refer to the unit by the more general name Lava Flow Member of the EVT (Fig. 2B). We also show that olivine basalt lava flows are within the Lava Flow Member of the EVT (Fig. 2B). The Stanislaus Group is overlain by Late Miocene andesitic volcanic and volcaniclastic rocks of the Disaster Peak Formation (Keith et al., 1982), separated by unconformity 4 (Fig. 2; Busby et al., 2008a, 2008b; Busby and Putirka, 2009). High-K volcanic rocks of the Stanislaus Group are very useful as regional strain markers, because they are distinctive and widespread.

GENERAL STRATIGRAPHY OF THE SONORA PASS REGION

Here we describe features of the stratigraphy that apply to the Sonora Pass area in general (Fig. 2A). In the following discussions, we refine the stratigraphy by describing the stratigraphic variation between a series of fault-bounded blocks in order to reconstruct slip histories on the faults. Photographs of typical rock types are shown in Figures 3 and 4.

The oldest strata consist of Oligocene rhyolite ignimbrites of the Valley Springs Formation (Tvs; Fig. 2; Slemmons, 1953). These consist of light colored silicic welded and nonwelded ignimbrites with centimeter-scale pumice and/or 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 paleochannel, ignimbrites are preserved as thin deposits on paleochannel floors and walls. These are overlain by the Relief Peak Formation (Trp), which at Sonora Pass consists 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 (see outcrop photos in Fig. 3). The block-and-ash flow tuffs (Trpba) consist of monomict, angular, blocks set in an unsorted ash matrix of the same composition (Figs. 3A, 3B). 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 in a sandstone matrix; they are dark tan colored, unsorted, and matrix supported, with pebble- to boulder-sized clasts (Fig. 3C). Debris flow deposits pass down the paleochannels into fluvial deposits (Trpf), which consist of stratified subrounded to well-rounded andesitic conglomerate and sandstone (Fig. 3D). 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 postdepositional alteration is too severe to permit accurate identification of primary features. Available age data indicate that andesitic volcanism of the Relief Peak Formation continued until the time of eruption of the TML of the Stanislaus Group, because an andesitic block-and-ash flow tuff that is below the TML yielded a $^{40}Ar/^{39}Ar$ age of 10.39 ± 0.18 Ma, which overlaps with the overlying basal TML flow at that locality (within analytical error; Fig. 2; Busby et al., 2008a; Busby and Putirka, 2009).

The basal formation of the Stanislaus Group, the TML, contains 23 lava flows on Sonora Peak; the basal flow of the TML there yielded a $^{40}Ar/^{39}Ar$ age of 10.41 ± 0.08 Ma, and the uppermost flow yielded an age of 10.36 ± 0.06 Ma (Fig. 2A; Busby et al., 2008a). The TML lava flows are easily recognized in the field by their large (~1 cm) skeletal plagioclase phenocrysts (Fig. 4A). Geochemical analyses from the TML at Sonora Peak show that it ranges in composition from trachyandesite (latite) to basaltic trachyandesite (shoshonite); we follow previous workers by referring to these as latites (Putirka and Busby, 2007; Busby et al., 2008a; Putirka et al., 2012). New mapping described here shows that black, olivine-phyric basaltic lava flows and olivine-plagioclase-phyric basaltic-andesite lava flows are locally interstratified with the TML flows (Tstmlb; Fig. 2B), which lack phenocrystic olivine.

The middle formation of the Stanislaus Group, the Eureka Valley Tuff, consists largely of nonwelded to densely welded ignimbrite that ranges in composition from trachydacite to dacite (Putirka and Busby, 2007; Putirka et al., 2012). 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 (typical outcrop photos in Figs. 4B–4E). In Busby et al. (2008a), $^{40}Ar/^{39}Ar$ dates of 9.42 ± 0.04 and 9.43 ± 0.02 Ma were reported on the By-Day and Upper Members of the EVT (respectively) 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 (described in the following). Similarly, previously unmapped lava flows of the Lava Flow Member of the EVT are still being found (described in the following); an outcrop photo of a lava flow from this unit is shown in Figure 4F.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

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 ridge between Bald Peak and Red Peak ridge, and as erosional remnants on the ridge that extends southeast from there to Saint Mary's Pass (Fig. 6A; described in the following); it also occurs in a very small (8 × 16 m) erosional remnant on Dardanelles Cone (Koerner and Busby, personal observs.). 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 2813 m on Bald Peak. Our mapping confirms that this distinctive lava flow is the Dardanelles Formation, because it overlies the Upper Member of the EVT farther east along the same ridge (Koerner et al., 2009). However, our geochemical data show that the Dardanelles Formation is shoshonite, not a basalt, as reported by Dalrymple (1964; Koerner et al., 2009).

The resistant lava flows of the Stanislaus Group generally form the eroded top of the stratigraphic section in the Sonora Pass segment of the Sierra Crest graben system (Fig. 1), but we assign hornblende plagioclase andesite plugs and dikes that cut the Stanislaus Group to the Disaster Peak Formation (Slemmons, 1966; Koerner et al., 2009; Fig. 2B). One of these plugs was dated as 7.28 ± 0.06 Ma (Busby et al., 2008a). Small erosional remnants of hornblende-bearing ignimbrite and lava flows, as well as andesite-clast debris and fluvial deposits, also occur in the Sonora Pass area (Figs. 2B, 6, and 8). Farther north, in the Disaster Peak–Arnot Peak–Mineral Mountain segments of the Sierra Crest graben-vent complex (Fig. 1), the Disaster Peak Formation is much thicker and more extensive at similar present-day elevations (described in the following).

Figure 3. Rock types typical of the Relief Peak Formation. (A) Typical block-and-ash flow tuff: gray monolithic breccia supported in a matrix of lapilli- to ash-sized material of the same composition (andesitic), formed by collapse of lava domes. (B) Close-up of a radially jointed andesite block, typical of block-and-ash flow tuffs; this is produced by cooling of a hot block, and indicates limited transport after cooling (or the block would fall apart along the joints). (C) Typical debris flow deposit, formed by reworking of andesitic block-and-ash flow deposits. This deposit differs from primary block-and-ash flow tuffs in that it contains a wide array of andesitic volcanic rocks types, some rounded, in a matrix of tan volcanic lithic pebbly sandstone. (D) Typical fluvial deposit, formed largely of andesite clasts, with rounding, sorting and stratification.

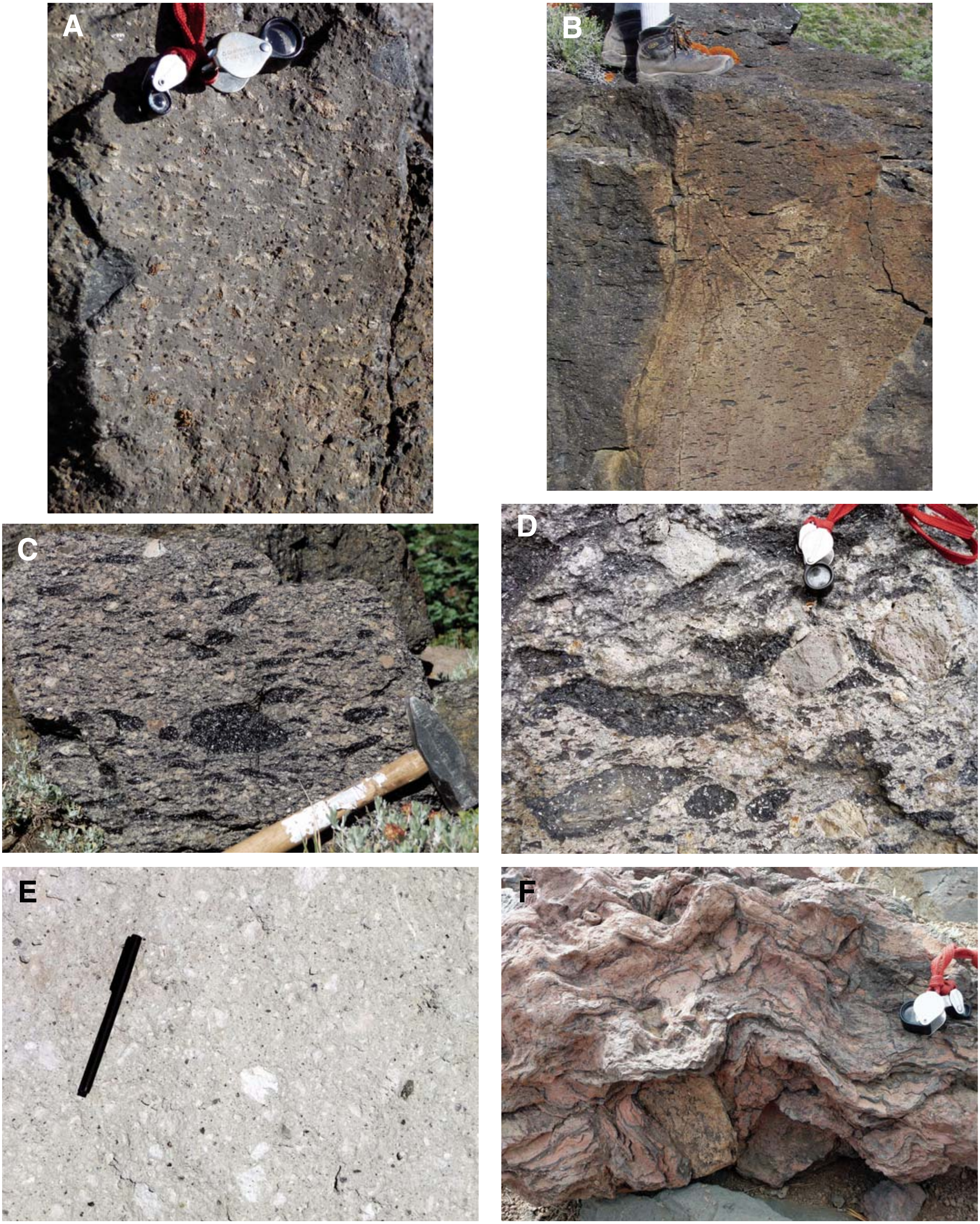

Figure 4.

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SIERRA CREST GRABEN-VENT SYSTEM

We use the phrase Sierra Crest graben-vent system to refer to a series of synvolcanic grabens and half-grabens with fault-controlled vents that erupted ca. 11.5–9 Ma, high-K volcanic rocks of the Stanislaus Group, described and interpreted for the first time here. The largest basin is the Sierra Crest full graben, a single 28-km-long, 8–10-km-wide, north-northwest–south-southeast–trending full graben that lies along the modern Sierra Nevada crest. This large graben extends from the Leavitt Peak area south of Sonora Pass, northward to the Disaster Peak–Arnot Peak area (Fig. 1). Exposures of this graben are divided into a northern and southern segment by the modern glacial valley of the Clark Fork River (Fig. 1), which cuts through the Cenozoic basin fill into Mesozoic granitic bedrock, but we infer that the northern and southern segments of the Sierra Crest graben were originally continuous. These southern and northern segments are referred to as the Sonora Pass segment and the Disaster Peak–Arnot Peak segment. Smaller basins in the Sierra Crest graben-vent system include (1) north-northwest–south-southeast half-grabens that extend as much as 6 km west of the western edge of the Sierra Crest graben, and (2) grabens in a 24 × 24 km northeast-southwest transfer zone that is on the northwest margin of the Sierra Crest graben.

Figure 4. Rock types typical of the Stanislaus group. (A) Typical appearance of the Table Mountain Latite, with large skeletal plagioclase weathered out against the groundmass. (B) The typical outcrop appearance of both Tollhouse Flat and By-Day Members of Eureka Valley Tuff is a dark colored rock with a prominent pumice compaction fabric; this produces a black sheet visible from great distances, because commonly, only the basal black vitrophyre is preserved. The eutaxitic fabric is flaggy and thus is readily weathered. (C) A less-compacted part of the sheet, which is less weathered, showing uncompacted to compacted glassy blocks and fiamme. (D) Close-up of lapilli-sized obvious volcanic rock fragments. These are ubiquitous in the Tollhouse Flat and By-Day Members of Eureka Valley Tuff, and are much less common in the Upper Member nonwelded ignimbrites. (E) The Upper Member of the Eureka Valley Tuff consists of a nonwelded ignimbrite with small (lapilli sized) pumices, prominent biotite, and minor lapilli-sized volcanic rock fragments. (F) The lava flow member of the Eureka Valley Tuff generally looks very similar to the Table Mountain Latite lava flows, except that it includes more silicic lava flows (trachydacite) as well as trachyandesite and trachybasaltic andesite lava flows, and includes aphyric lavas such as the one shown here with contorted flow banding (Tsell 3, on the top of Red Peak; see Fig. 8B).

Our description of the Sierra Crest graben-vent system is divided into the following sections:

Part I: Sierra Crest graben at Sonora Pass is subdivided into a stratigraphy section (IA) and a structure section (IB). This segment of the full graben is described first because our results from that region are the most detailed. A generalized map of the Sierra Crest graben at Sonora Pass area is shown in Figure 5, and detailed maps and photos are shown in Figures 6, 7, and 8.

Part II: Synvolcanic half grabens in the Cataract paleochannel on the western margin of the Sierra Crest graben describes a series of NNW fault-bounded half grabens that lie beyond the west margin of the full graben, in the Bald Peak-Red Peak area (Figs. 5, 8, 9, and 10). As discussed above, the Bald Peak-Red Peak ridge forms the type section of the Stanislaus Group (Slemmons, 1953). As shown here, these are paleo-channel deposits, which are thin relative to the full graben fill to the east, but the paleochannel was progressively disrupted into half grabens before and during deposition of the Stanislaus Group, and the faults controlled the siting of Stanislaus Group intrusions and vents.

Part III: Sierra Crest Graben at Disaster Peak-Arnot Peak, and range-front transfer zone basins describes the Disaster Peak-Arnot Peak segment of the Sierra Crest full graben, to the north of the Sonora Pass segment (Figs. 1, 11, 12, and 13). Similar to the Sonora Pass segment, this segment has more than one N-S fault along its western fault boundary, while the east boundary is formed by the same single fault that controls the east boundary of the southern segment (East Fork Carson fault, Fig. 11). However, the northeast part of the Disaster Peak-Arnot Peak segment is much more complicated, because the East Fork Carson fault passes northeastward into a 24-km wide transfer zone of NE-SW faults, connected by shorter ~N-S faults, mapped here for the first time (Fig. 11). These extend down the modern range front for a distance of 24 km northeast of the modern range crest (Fig. 11). As shown here, these faults formed basins that accommodated Stanislaus group deposits, and controlled the siting of Stanislaus group vents (as well as younger vents in the arc). For this reason, the NE-SW fault zone is described here as part of the "Sierra Crest graben-vent system." Similar NE-SW faults link longer ~N-S normal faults along the Sierra Nevada range front immediately to the south, at Sonora Pass, but these faults did not vent Stanislaus group rock (although they ponded them); for this reason, they are described in a separate paper (Busby et al., 2013b).

Our description of the Sierra Crest graben in the Sonora Pass area begins with its stratigraphy, and then examines its structure in the section after that.

PART IA: STRATIGRAPHY OF THE SIERRA CREST GRABEN AT SONORA PASS

The Sonora Pass segment of the Sierra Crest graben is bounded by north-northwest–south-southeast normal faults, with east-northeast– to northeast-striking transfer faults (Fig. 5). The graben is filled with ponded TML, underlain largely by avalanche deposits of the Relief Peak Formation (Figs. 5–8). It is bounded on the east by the west-dipping East Carson fault (Figs. 5–7), and on the west by east-dipping normal faults (Kennedy Creek fault zone–Seven Pines faults; Figs. 5, 8, and 9). Vent facies deposits for the TML are along the eastern margin of the graben, while younger Stanislaus Group vent facies deposits (for the Lava Flow Member and Dardanelles Member) are on the western margin (Figs. 6–10).

The faults on the west side of the graben were mapped by Slemmons (1953), although they were not identified as synvolcanic faults. Cenozoic strata to the northeast of the Kennedy Creek fault zone contain Stanislaus Group lava flow sections as much as 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 paleochannel existed there prior to eruption of TML (Roelofs, 2004; Busby, Andres, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). This shows that the lavas were entirely ponded within the Sierra Crest graben along this segment of it. However, 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 (Figs. 5 and 8) as paleochannel fill, and erosional remnants of the lava-filled paleochannel extend all the way to the Sierra Nevada foothills (Fig. 1; Gorny et al., 2009). This indicates that some lava flows were not confined in the Sierra Crest graben across the Seven Pines fault and flowed down the paleochannel. The Seven Pines fault extends directly northward into the newly recognized

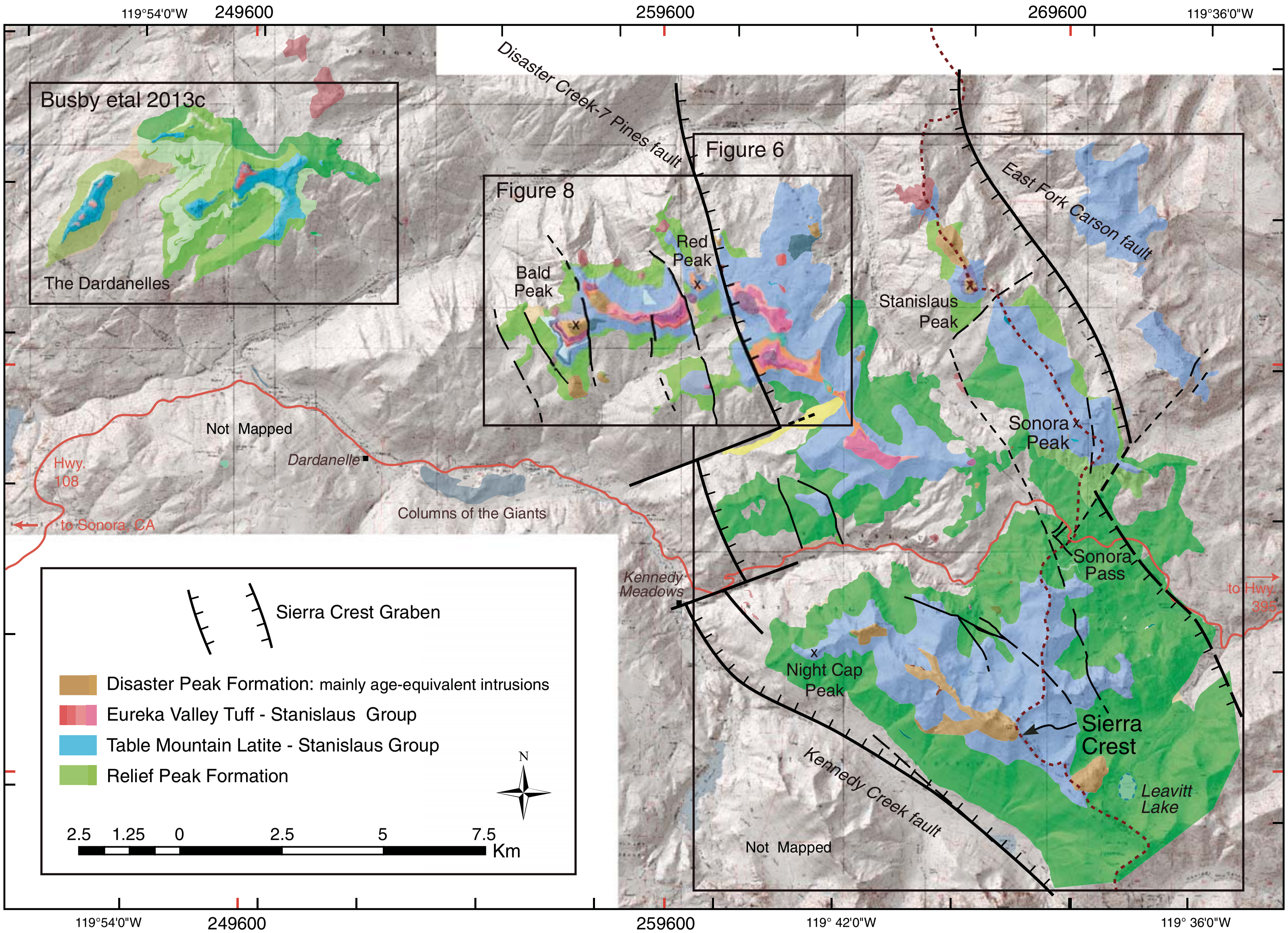

Figure 5. Generalized map of Cenozoic rocks and faults in the Sonora Pass area (location in Fig. 1), from the modern range crest westward to The Dardanelles (a prominent ridge), showing the spatial distribution of geologic maps presented in Figures 6 and 7; intervening regions that lack Cenozoic strata are not shown on those maps. Unfaulted paleochannel fill at The Dardanelles will be described elsewhere (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.).

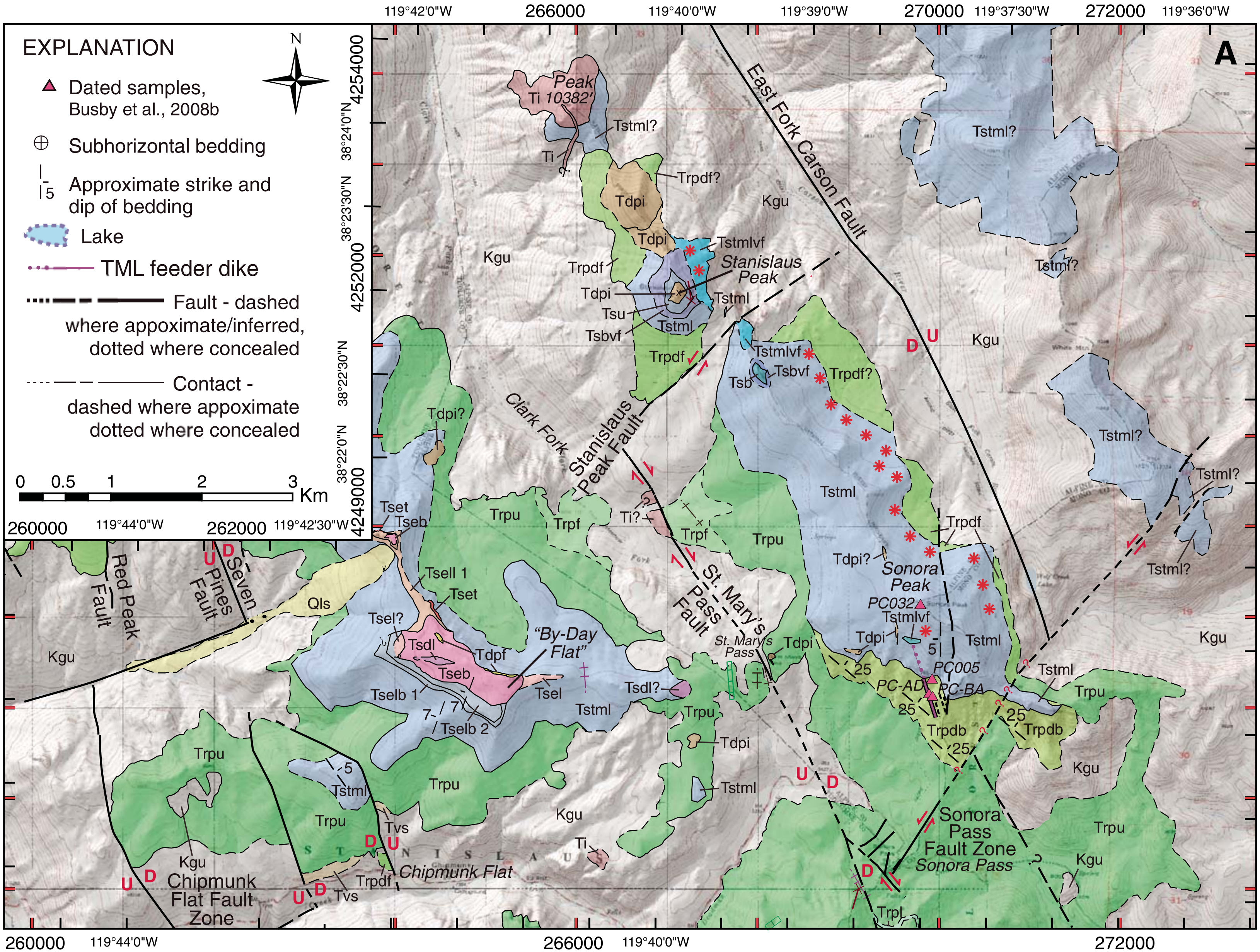

Figure 6 (*Continued on following page*). Geologic map of the Stanislaus Peak–Leavitt Lake–Night Cap Peak area, northern Emigrant Wilderness, central Sierra Nevada, California. Prior published geologic maps are by Slemmons (1953) and Keith et al. (1982). The mapping presented here was done by Cathy Busby in 2003–2010, Graham Andrews in 2010, Alice Koerner in 2008 and 2009 (U.S. Geological Survey EDMAP), Jeanette Hagan in 2007, and Dylan Rood in 2003 (U.S. Geological Survey EDMAP). U—upthrown; D—downthrown. Location given in Figures 1 and 5; key to map units is given in Figure 2B. For previously published geochemical samples, see Busby et al., (2008b) and Koerner et al. (2009).

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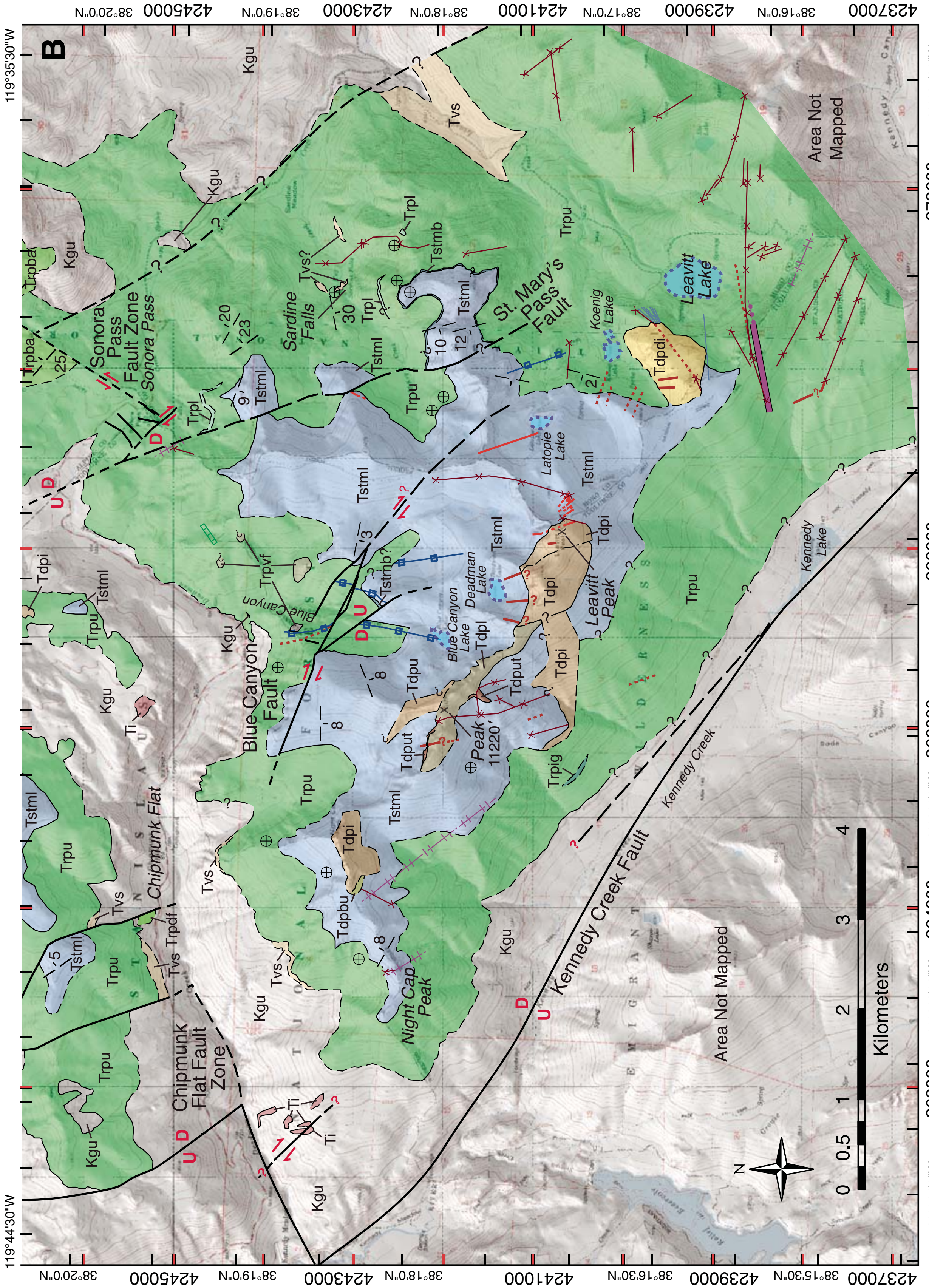

Figure 6 (*Continued*).

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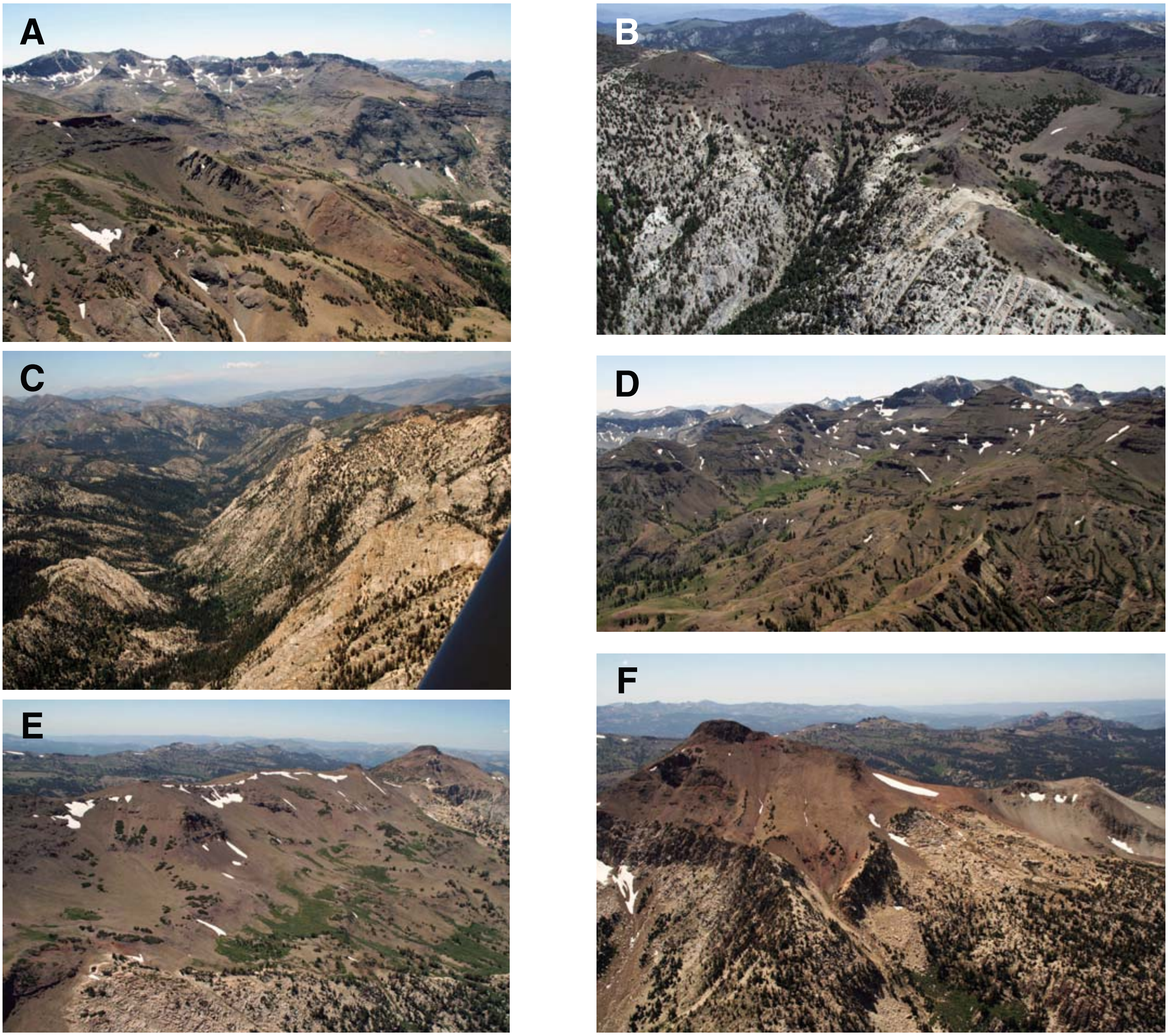

Figure 7 (*Continued on following page*). Deposits and faults in and around the eastern margin of the Sierra Crest graben (all locations referred to here are in Fig. 6). (A) Debris avalanche deposits in the basal fill of the Sierra Crest graben inside its eastern margin, seen as chaotic beds that dip in random directions, overlain by flat-lying lavas of the Table Mountain Latite (TML). View is to south-southwest, with Leavitt Peak on left and Night Cap Peak on far right skyline. A date on a rock within this debris avalanche deposit overlaps with the age of the basal TML here (within analytical uncertainty), indicating that the avalanching occurred immediately prior to eruption of the TML (Busby et al., 2008a). (B) The debris avalanche was derived at least in part from the eastern shoulder of the Sierra Crest graben, because TML directly overlies granitic basement on the east shoulder of the graben, with no intervening Relief Peak Formation (Figs. 5 and 6). View toward east, with the East Fork Carson River just out of view below bottom of photo. (C) View looking north along the headwaters of the East Fork Carson River, which follows the East Fork Carson fault; TML overlies granite on the uplifted footwall just barely visible on right skyline (see B). The East Fork Carson fault forms a prominent west-dipping cliff in the granitic basement on the right (east) side of the East Fork Carson River. Fissure deposits for the TML are out of the field of view to the left (west) on the hanging wall of the fault (E–I). (D) TML lava flows ponded in the Sierra Crest graben; view is toward the west-southwest of the Leavitt Peak area south of Sonora Pass (Fig. 6). Debris avalanche deposits of Relief Peak Formation derivation are below the well-layered lavas. Red fissure deposits are not evident along the eastern margin of the Sierra Crest graben south of Sonora Pass, but vertical TML feeder dikes are evident in the bottom right side of photo. (E) Red fissure deposits just inside the eastern margin of the Sierra Crest graben, north of Sonora Pass. These interfinger with basalts and high-K lava flows of the TML. View toward north-northwest, with Sonora Peak just out of view to left, and Stanislaus Peak at far end of ridge. (F) Close-ups of fissure deposits interstratified with TML lava flows on Stanislaus Peak (Fig. 6). These directly overlie granitic basement.

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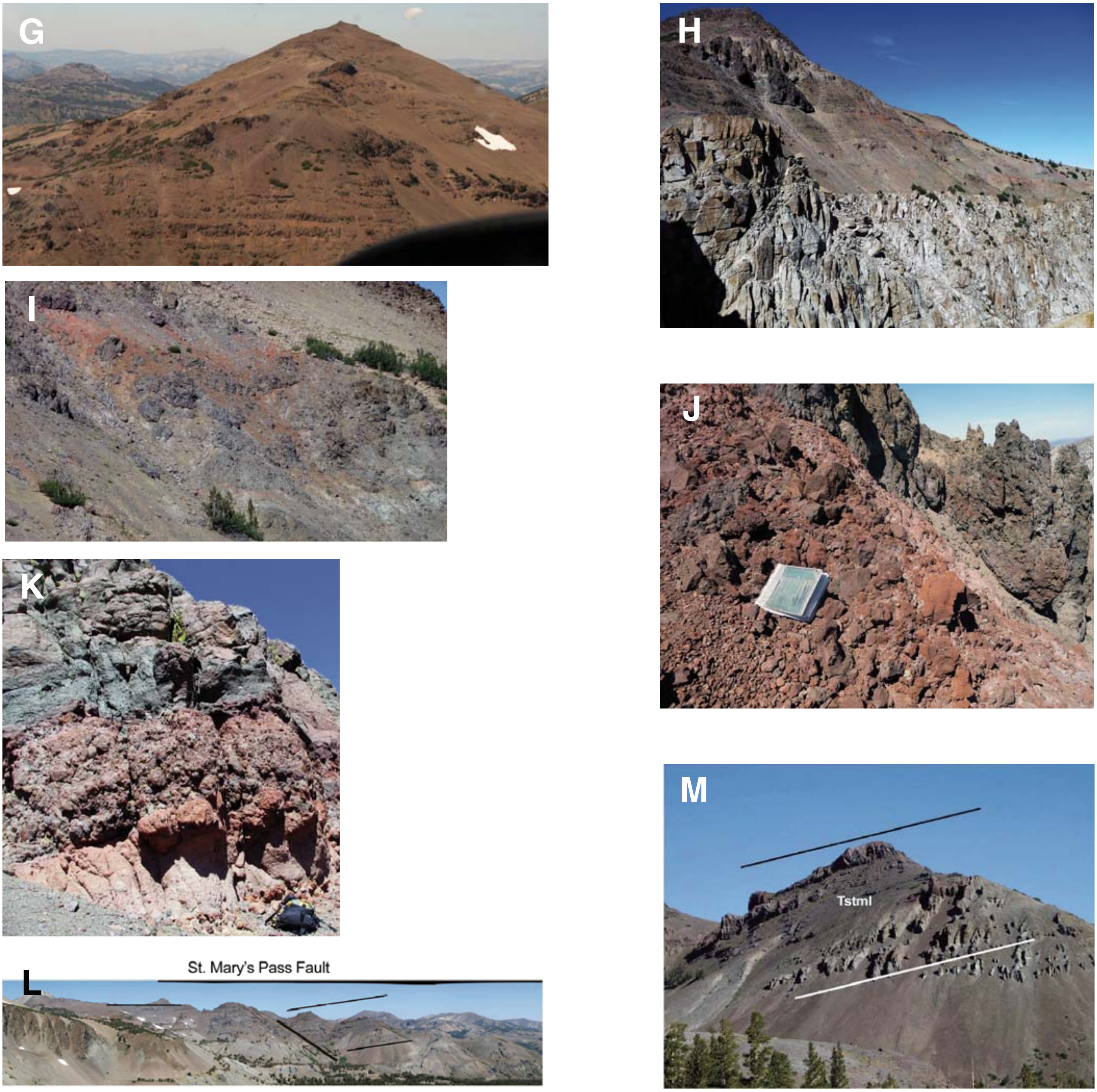

Figure 7 (*Continued*). (G) Close-ups of fissure deposits interstratified with TML lava flows on Stanislaus Peak (Fig. 6). These directly overlie granitic basement. (H) Steep contact between TML lava flows (to left above the highest ridgeline of granitic basement in the foreground), and red vent facies rocks (to right), suggesting that the earliest-erupted lavas were cut by ongoing fissure activity at this site. This steep contact is offset in a sinistral sense by the northeast-southwest Stanislaus Peak fault (Fig. 6A). (I) A close-up of the vent deposits, where the 200-m-thick section (no scale) contains Vulcanian blocks to 4 m in diameter dispersed in a deposit of red nonstratified scoria bombs and lapilli. (J) Red scoria blocks form relatively well sorted, clast-supported accumulations, suggesting that they are ballistic fall deposits (rather than scoria flow deposits). (K) Similar scoria block fall deposits occur all the way to Sonora Peak, where they are interstratified with TML lava flows. Thus, the north-northwest–south-southeast Sonora Peak to Stanislaus Peak ridge is a 6-km-long fissure that erupted trachyandesite and trachybasaltic andesite lava flows of the TML. (L) The Saint Mary's Pass fault is within the eastern part of the Sierra Crest graben, and was also active during eruption of the TML (view toward north from Leavitt Lake, of Sierra Crest 2 km northeast of Leavitt Peak). It dips opposite to the main graben-bounding fault to the east (East Fork Carson fault). (M) Close-up of L: L and M show that the fault tilts TML 25° westward on the hanging wall of the Saint Mary's Pass fault, and it is approximately flat-lying on the footwall of the fault. As shown in Figure 6A, this normal fault shows dextral offset of a Relief Peak Formation paleochannel axis at its north end.

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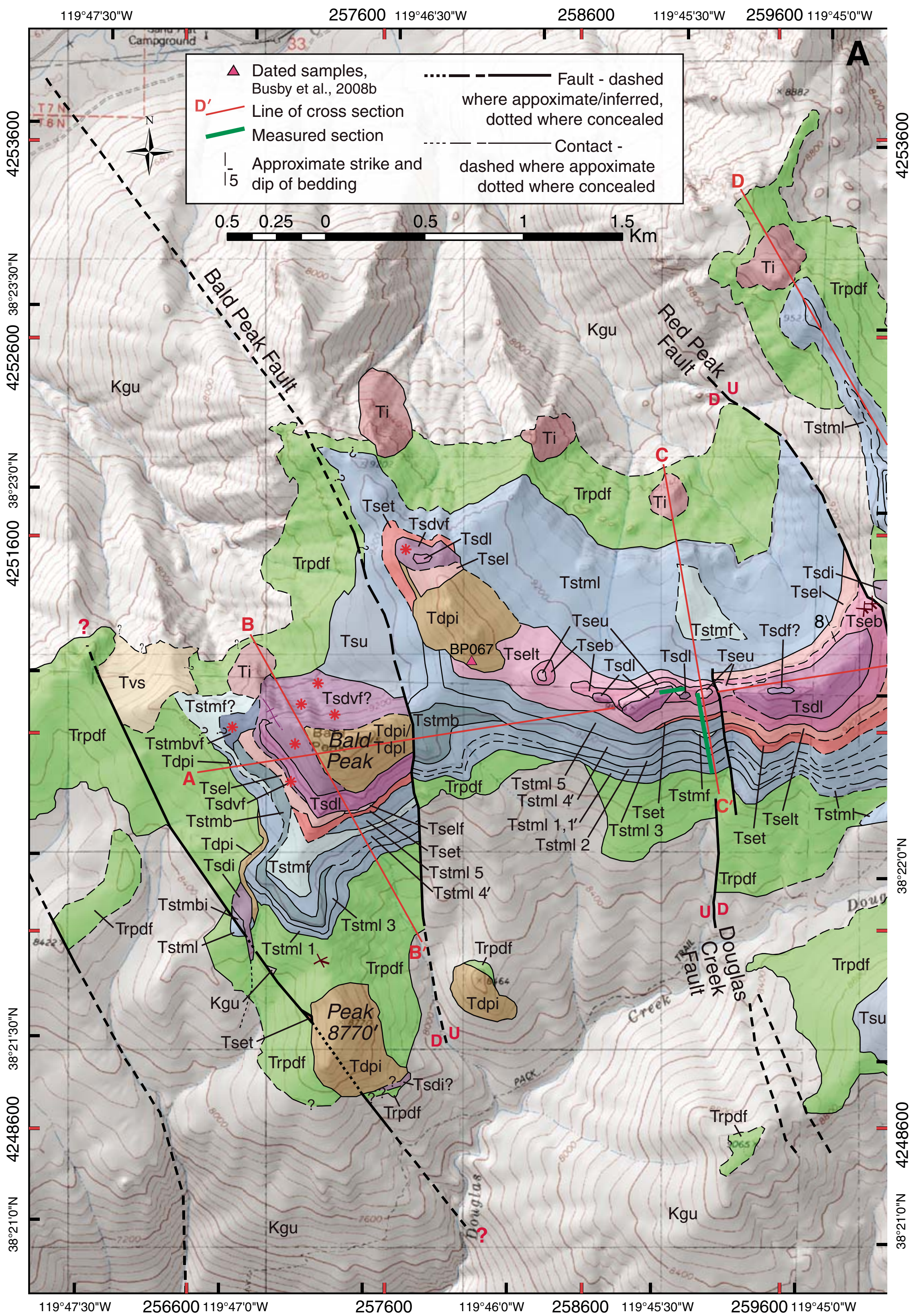
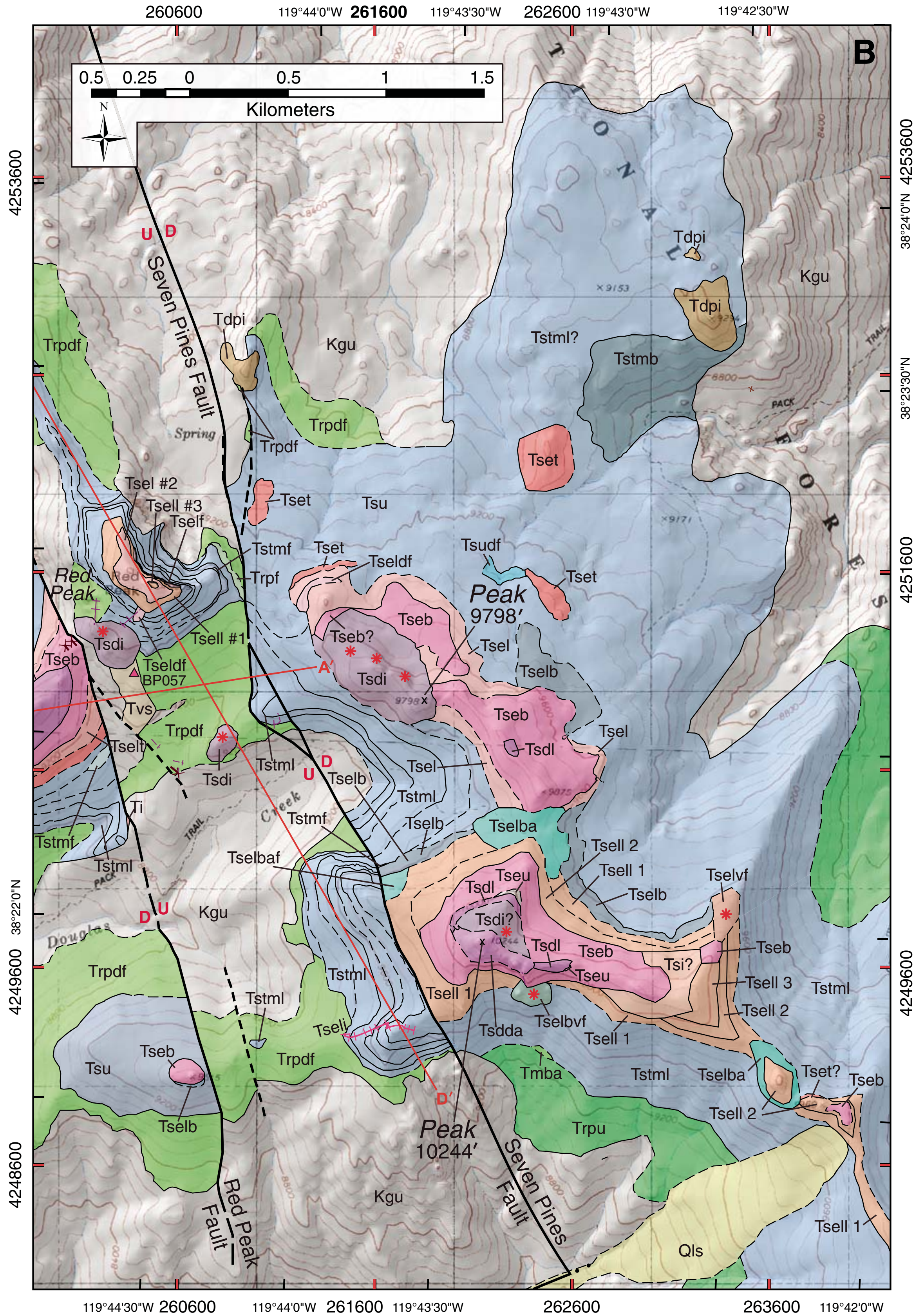


Figure 8 (*Continued on following page*). Geologic map of the Saint Mary's Pass–Red Peak–Bald Peak area, southern Carson-Iceberg Wilderness, central Sierra Nevada, California. Prior published geologic maps are by Slemmons (1953), Keith et al. (192), and Koerner et al. (2009). The mapping presented here was done by Busby in 2003–2010, by Koerner in 2008 and 2009 (U.S. Geological Survey EDMAP), and by Rood (2003, U.S. Geological Survey EDMAP). Location is given in Figures 1 and 4; key to map units is given in Figure 2B. Cross sections (A–A′, B–B′, C–C′, and D–D′) are shown in Figure 9. Position of measured section presented in Koerner et al. (2009) is shown as a green line. U—upthrown; D—downthrown. (For previously published geochemical samples, see Koerner et al., 2009.)



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Disaster Creek fault, which forms part of the west boundary of the Sierra Crest graben in the Disaster Peak–Arnot Peak areas (described in the following).

The stratigraphy of the Sierra Crest graben is complex, because it contains vent facies for lava flows of the Stanislaus Group, which are by nature lenticular, as well as intrusive equivalents, which interrupt 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 within the Sierra Crest graben is largely mapped as undifferentiated in Figures 6 and 8, because it is unclear how much of it represents in situ deposits, and how much can be mapped separately as debris avalanche deposits; however, we estimate the proportion of in situ deposits to be very low (~10%). It is important to describe the debris avalanche deposits in detail, because they are one of the key distinguishing features of the intra-arc Walker Lane pull-apart basins, in both the Miocene basins described in this paper, and in the Miocene–Pliocene pull-apart basin at Ebbetts Pass (Busby, 2011; Busby et al., 2013a). For reasons given here, we do not consider the debris avalanche deposits to represent volcano sector collapse deposits; instead we consider them to be avalanches triggered by faulting. It is also important to recognize in situ deposits, described herein, to try to reconstruct original vertical stratigraphic trends in the Relief Peak Formation, and to provide descriptions of Relief Peak Formation outcrops that have a stratigraphic context, and therefore may be useful for future geochemical or geochronological work.

Debris avalanche deposits in the Sierra Crest graben consist of a chaotic mixture of megablocks ~1 m–2 km in diameter, in accumulations as much as 500 m thick (Fig. 7A). The blocks include a wide variety of Relief Peak Formation rocks types, of widely varying colors, with unaltered rocks juxtaposed against highly altered rocks, locally mixed together with slabs of Valley Springs Formation (i.e., it sampled all older formations). Many megablocks have internal stratification, with dips that vary widely from megablock to megablock (Fig. 7A).

The largest megablock we have mapped as a separate unit in the Sierra Crest graben is that at the south foot of Sonora Peak, mapped as interstratified andesitic debris flow deposits and block-and-ash flow tuffs (Trpba; Fig. 6A). This ~2-km-long megablock was first described in Busby et al. (2008a); we consider it to be one slide block because the dips within it are relatively consistent (25°NE; Fig. 6A). The block-and-ash flow tuff dated as 10.39 ± 0.18 Ma (Fig. 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 of the Sierra Crest graben occurs as white tuff at the base of Sardine Falls (Fig. 6B), and is ~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. Many other smaller blocks of Valley Springs Formation are common in this area.

Four separate hornblende pyroxene intrusions that are within ~1.5 km of each other on the east and west side of Blue Canyon (Fig. 6B) are interpreted to be a once-contiguous body

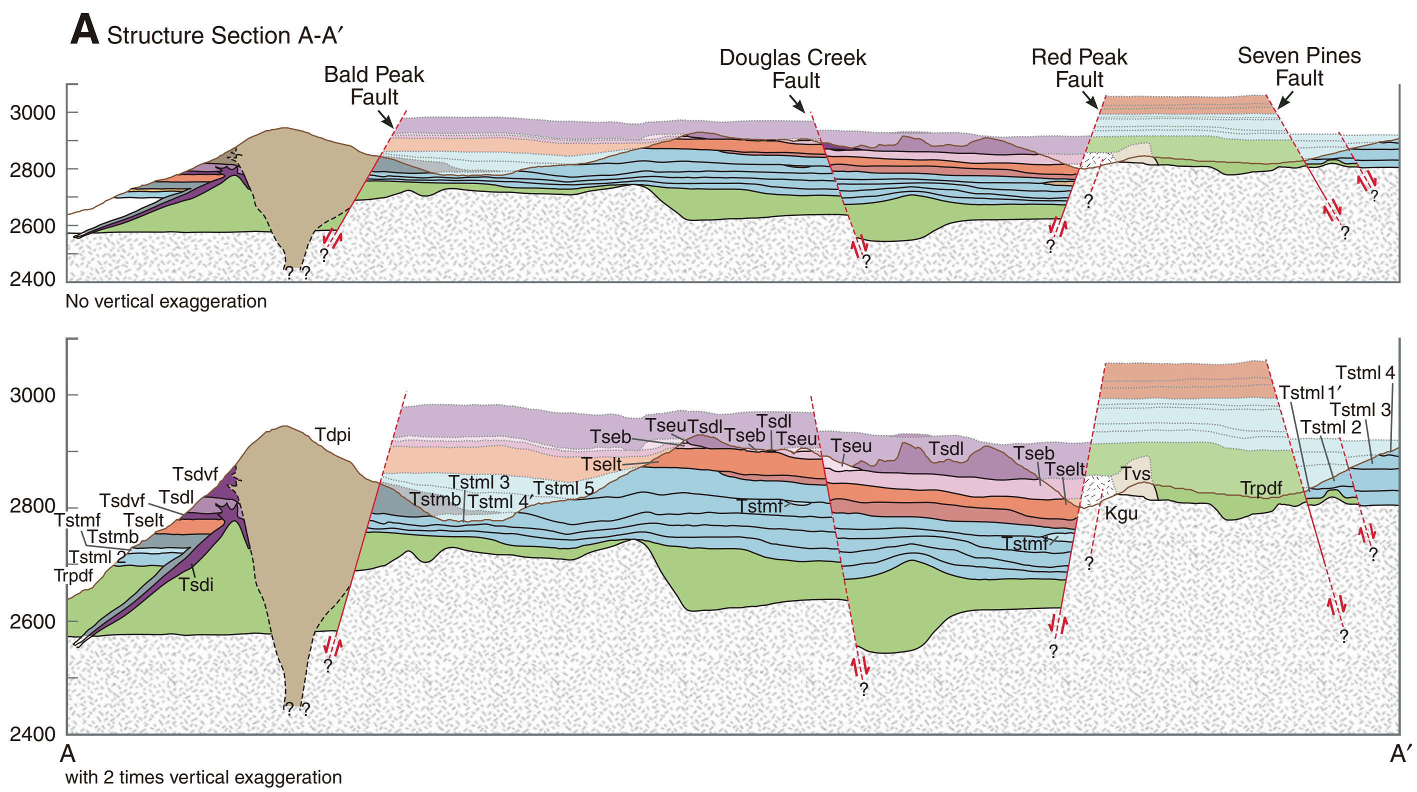

Figure 9 (*Continued on following page*). Structure sections through Miocene volcanic strata in the Bald Peak–Red Peak region (Koerner, 2010); locations are plotted in Figure 8. Shown at true scale and also with 2× vertical exaggeration. Key to map units is given in Figure 2B. (A) Cross-section A–A′ drawn longitudinal with respect to the paleochannel, and transverse to the faults, from Bald Peak to Red Peak.

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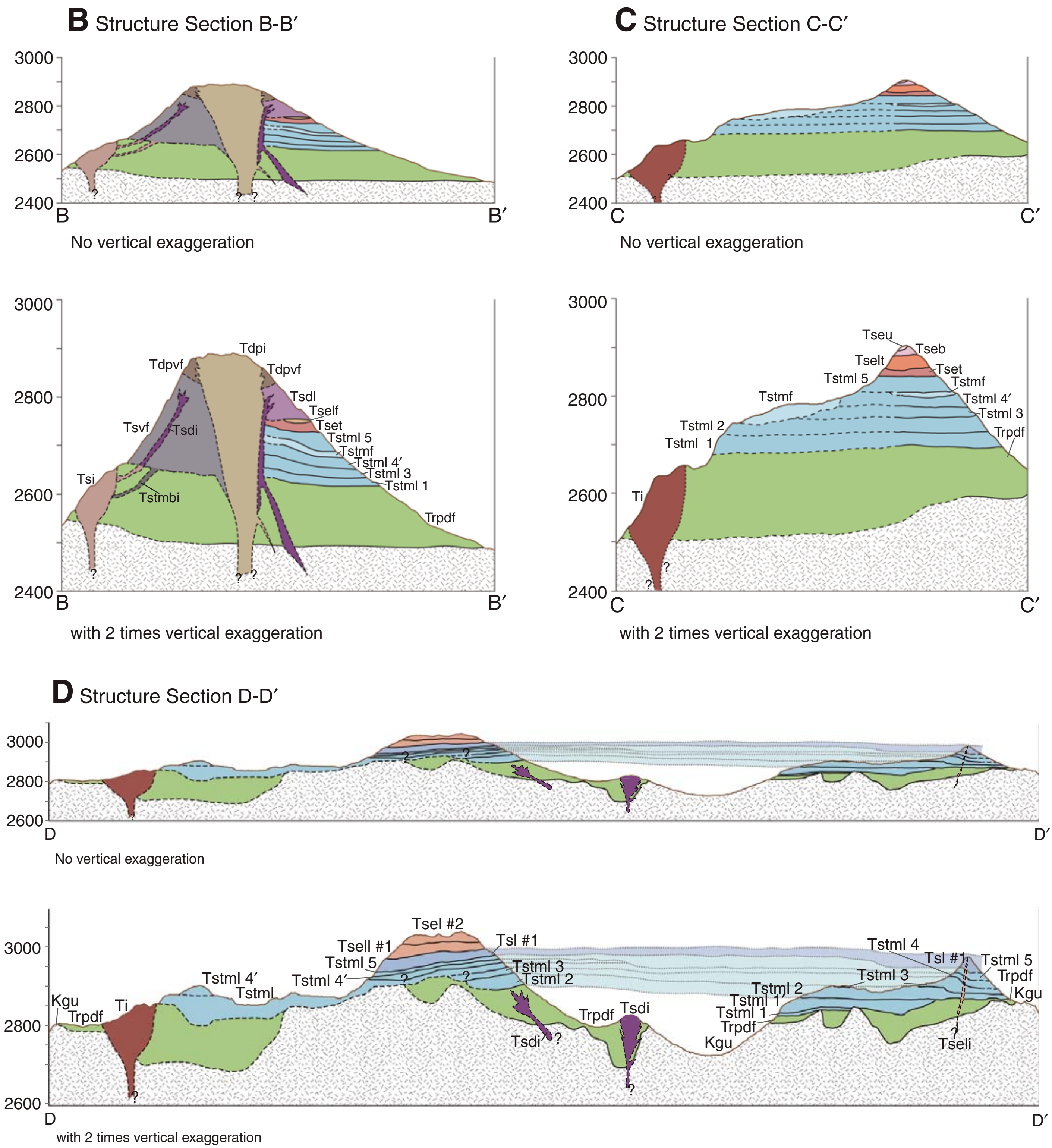

Figure 9 (*Continued*). (B) Cross-section B–B′ drawn transverse to the paleochannel, through Bald Peak. (C) Cross-section C–C′ drawn transverse to the paleochannel along the type locality for the Stanislaus Group, on the ridge between Bald Peak and Red Peak (east of A–A′). (D) Cross-section D–D′ drawn transverse to the paleochannel, through Red Peak (east of B–B′).

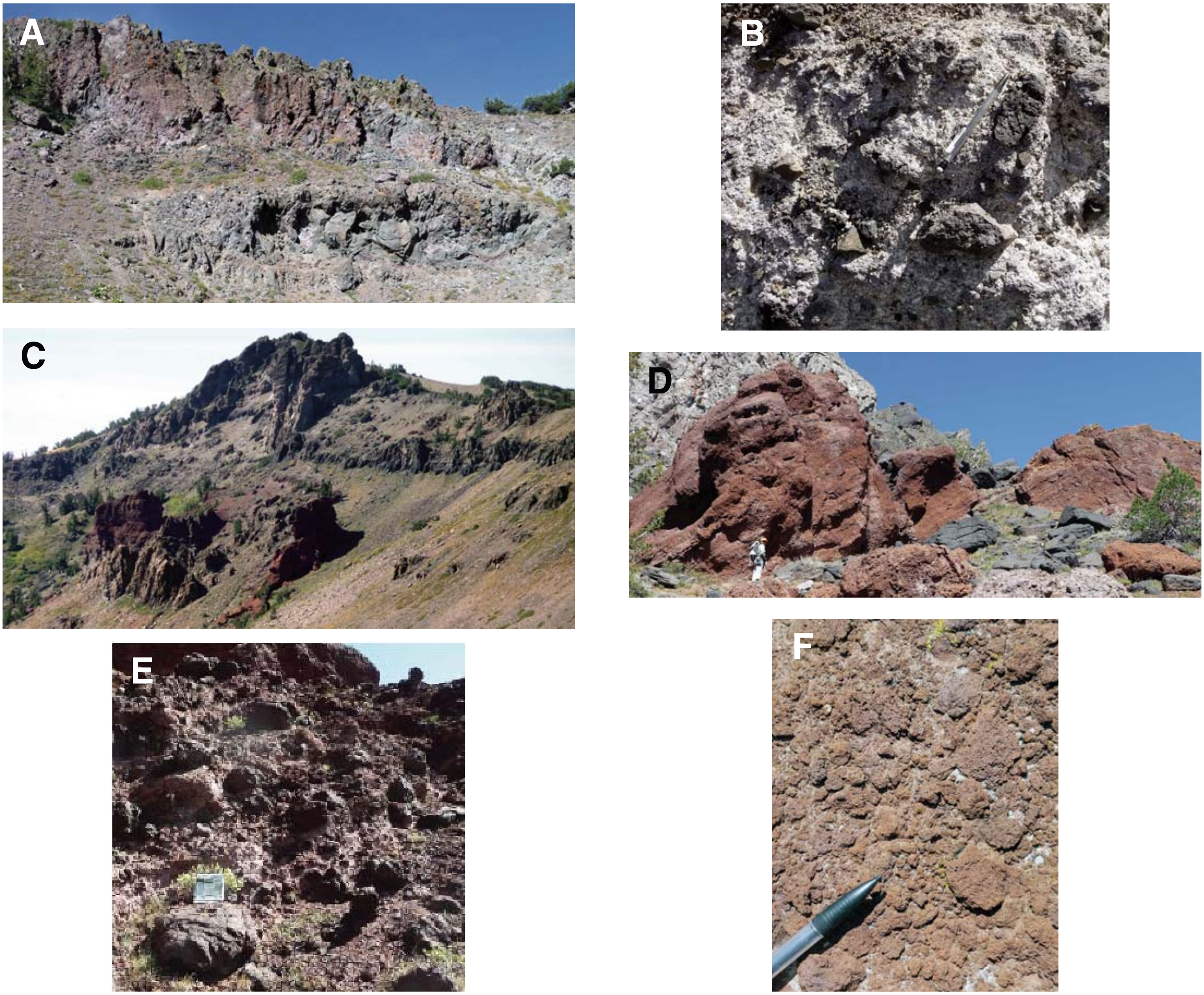

Figure 10 (*Continued on following page*). Vent facies deposits and proximal volcanic rocks erupted along the western margin of the Sierra Crest graben. High-K volcanics erupted along the western margin of the graben are younger than high-K units erupted along the eastern margin (Table Mountain Latite, TML, shown in Fig. 7), and include the Lava Flow Member of the Eureka Valley Tuff (EVT), as well as the overlying Dardanelles Formation. Debris avalanche deposits at the top of the high-K section indicate ongoing faulting along the graben margin, coeval with volcanism. (A) Two lava flows of the Lava Flow Member of the EVT, which is between the lower two ignimbrite members of the EVT (Tollhouse Flat and By-Day Members). The ignimbrites were erupted from the Little Walker caldera ~15 km to the east, but the lava flows were locally erupted, as shown by their lenticular nature. See discontinuous lenses of 1–3 latite lava flows (Tsell) just inside the graben (see peaks labeled at elevations of 10244′ and 9798′ on the topographic map, Fig. 8B) and just outside the graben (Red Peak; Fig. 8B; this photo was taken on the west side of peak 10244′). The upper flow is dominated by flow breccia while the lower one has a coherent interior. (B) Lens of block-and-ash flow tuff in the Lava Flow Member of the EVT (Tselba; Fig. 8B), likely formed by collapse of a small dome inside the western margin of the Sierra Crest graben. Black blocks of glass are dispersed in a matrix of black glass lapilli and white pumice. This is between flows 1 and 2 in a restricted area by peak 10244′, and is fluvially reworked (not photographed) immediately adjacent to the Seven Pines fault (Tselbaf; Fig. 8B). (C) Cliff-face cross section through a cinder cone (red), cut by an olivine basalt dike (black, less resistant rocks with red cinder cone rocks on either side), mapped as unit Tselbvf (vent facies olivine basalt feeder dike and cinder cone in Fig. 8B). This intrusion vented olivine basalt lava flows within the Lava Flow Member of the EVT (Tselb; Fig. 8B), not visible in photo. Depositionally above the red cinder cone rocks, forming a black horizontal band, is the vitrophyre of the By-Day Member of the EVT. That in turn is overlain by megabreccia debris avalanche deposits (Tsdda, on peak 10244′; Fig. 8B). (D) Cliff-face cross section through the upper part of the basalt cinder cone, showing steep dips form by construction of the cone (Tselbvf vent facies, olivine basalt feeder dike and cinder cone; Fig. 8B). Black fallen rocks in foreground are from the overlying By-Day Member of the EVT. (E) Lava bombs as much as 1.5 m long (map case for scale) in the cinder cone shown in B. (F) Scoria fall deposits on the cinder cone, showing excellent sorting.

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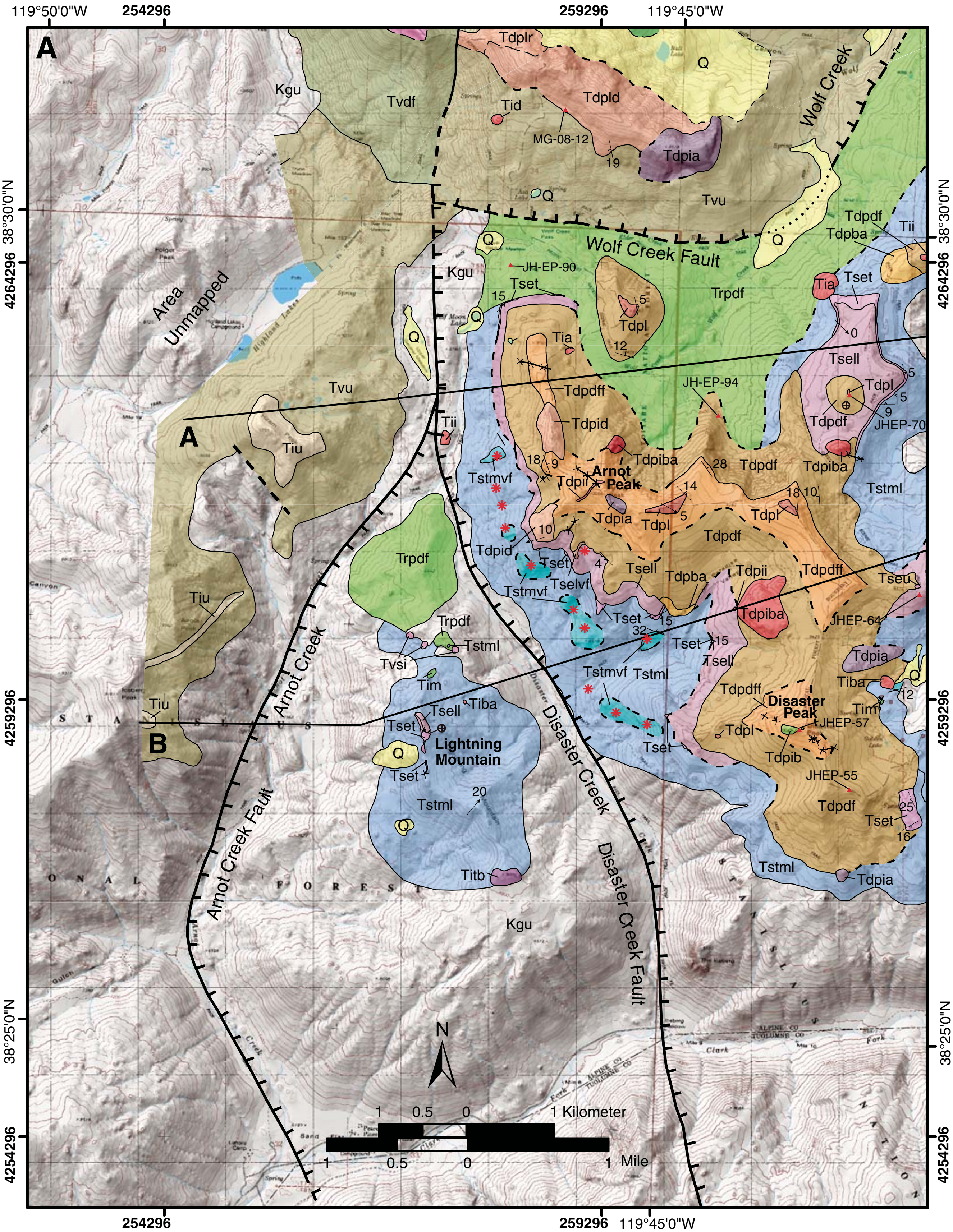
Figure 10 (*Continued*). (G) Close-up of olivine basalt intrusion cutting the scoria cone deposits shown in A. This is inferred to be the feeder to the olivine basalt lava flows that are at the same stratigraphic level as the cinder cone. (H) Debris avalanche deposits of the Dardanelles Formation (Tsdda, on peak 10244′; Fig. 8B), overlying By-Day Member of EVT (black outcrops of vitrophyre in lower left corner of photo). The debris avalanche deposit has megablocks of white nonwelded and black welded EVT. These debris avalanche deposits were shed onto the hanging wall of the Seven Pines fault into the western margin of the Sierra Crest graben, and are intruded by a probable Dardanelles Formation plug (not visible in photo; see Tsdi(?) in Fig. 8B). We infer that the Seven Pines fault controlled the position of the Lava Flow Member cinder cone and feeder dike, as well as the Dardanelles Formation(?) plug. (I) Dardanelles Formation lava flow filling a small channel, displaying columnar joints that radiate inward from the base and side of the channel.

that was disrupted by avalanching, along with its host sedimentary rock. All four bodies have peperitic margins wherever their contacts with the host sedimentary rock are preserved within a slide block, indicating they were intruded at very shallow levels into a wet sediment host. Landsliding must have occurred after consolidation of the host sediment, because it was transported intact with the intrusions (Trpvf; Fig. 6).

There are three main arguments for interpretation of the debris avalanche deposits of the Sierra Crest graben as fault related (rather than sector collapse related). (1) The debris avalanche deposits show a closer juxtaposition of a wider variety of Relief Peak Formation rock types (including a wide array of alteration types and degrees) than would be derived from collapse of a single volcano, including blocks containing very thick sections (as much as 200 m thick) of fluvial deposits, which are not normally found on the flanks of a volcano, as well as Oligocene paleochannel fill (the Valley Springs Formation). (2) The graben footwalls are nearly entirely stripped of pre–Stanislaus Group (Relief Peak Formation) strata (Figs 5, 6, and 7B), which we infer were remobilized onto graben hanging walls by land sliding. (3) As described in Busby et al. (2013a), our $^{40}Ar/^{39}Ar$ ages show that large slabs of rock ~1–5 m.y. older than the enclosing section were commonly recycled by landsliding in both Miocene and Miocene–Pliocene basins of the central Sierra Crest and range front; the landslides cover too broad an age range to be explained by collapse of the sector of a single volcano. In addition, the debris avalanche deposit beneath the TML is probably too voluminous to represent a stratovolcano sector collapse, although its original volume is difficult to estimate due to glacial dissection; however, a rough estimate of its minimum volume, that preserved in the area mapped in Figure 6, is at least 50 km^3, which is greater

Figure 11 (*Continued on following pages*). (A–C) Geologic map of the Lightning Mountain–Disaster Peak–Arnot Peak–Mineral Mountain area, northern Carson-Iceberg Wilderness, central Sierra Nevada, California. Prior published geologic mapping by Keith et al. (1982). The geologic mapping present here was done by Hagan in 2008 and 2009, by Melosh in 2010 (U.S. Geological Survey EDMAP), and by Busby in 2007–2012. Location given in Figure 1. Cross sections (A–A′ and B–B′) are shown in Figure 12. Sample numbers plotted on this map are $^{40}Ar/^{39}Ar$ age sample localities (age data presented in Busby et al., 2013a; complete age data will be available elsewhere). (D) Key. Red Stars are added to Stanislaus Group vent facies map units to make them easier to find on the geologic maps.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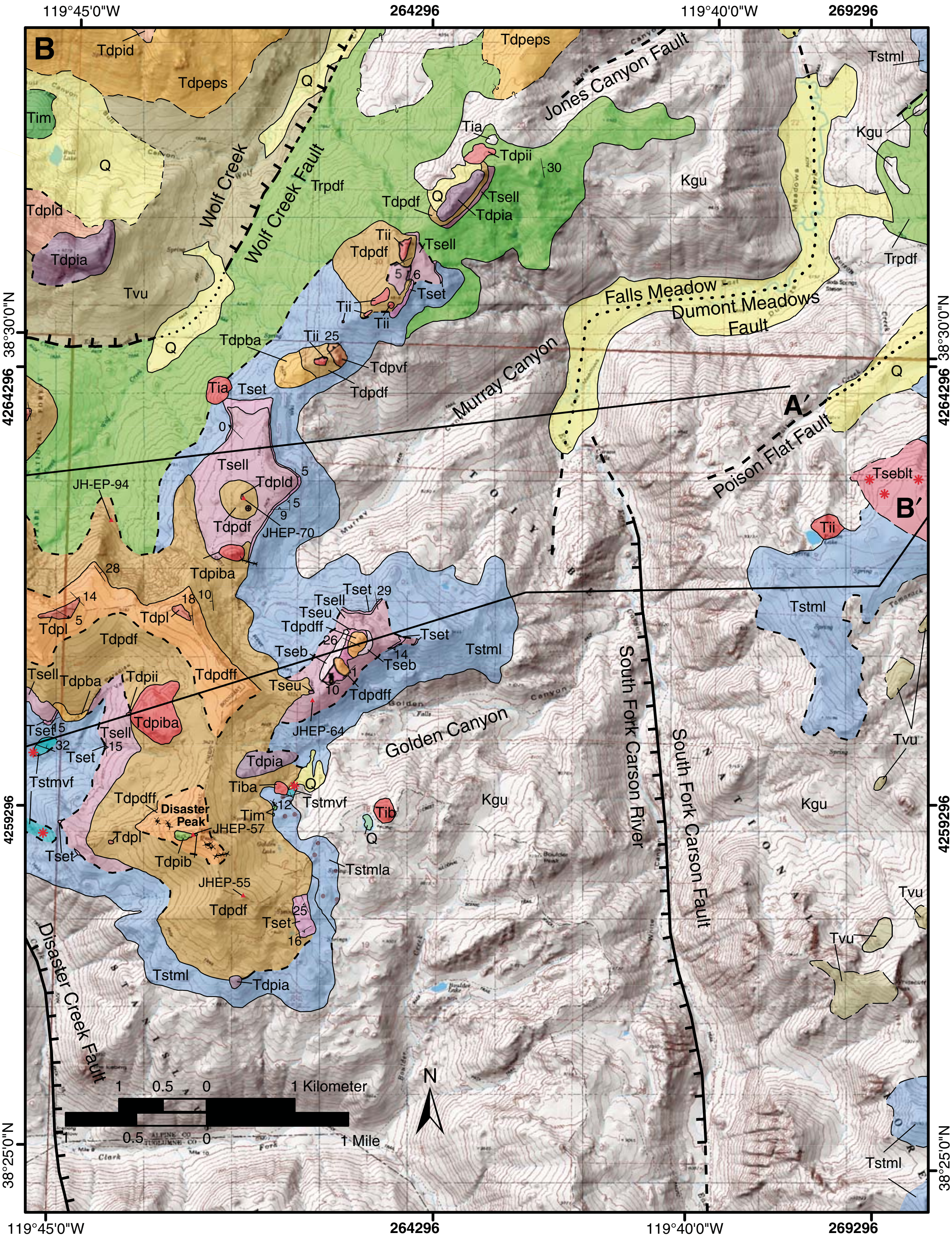

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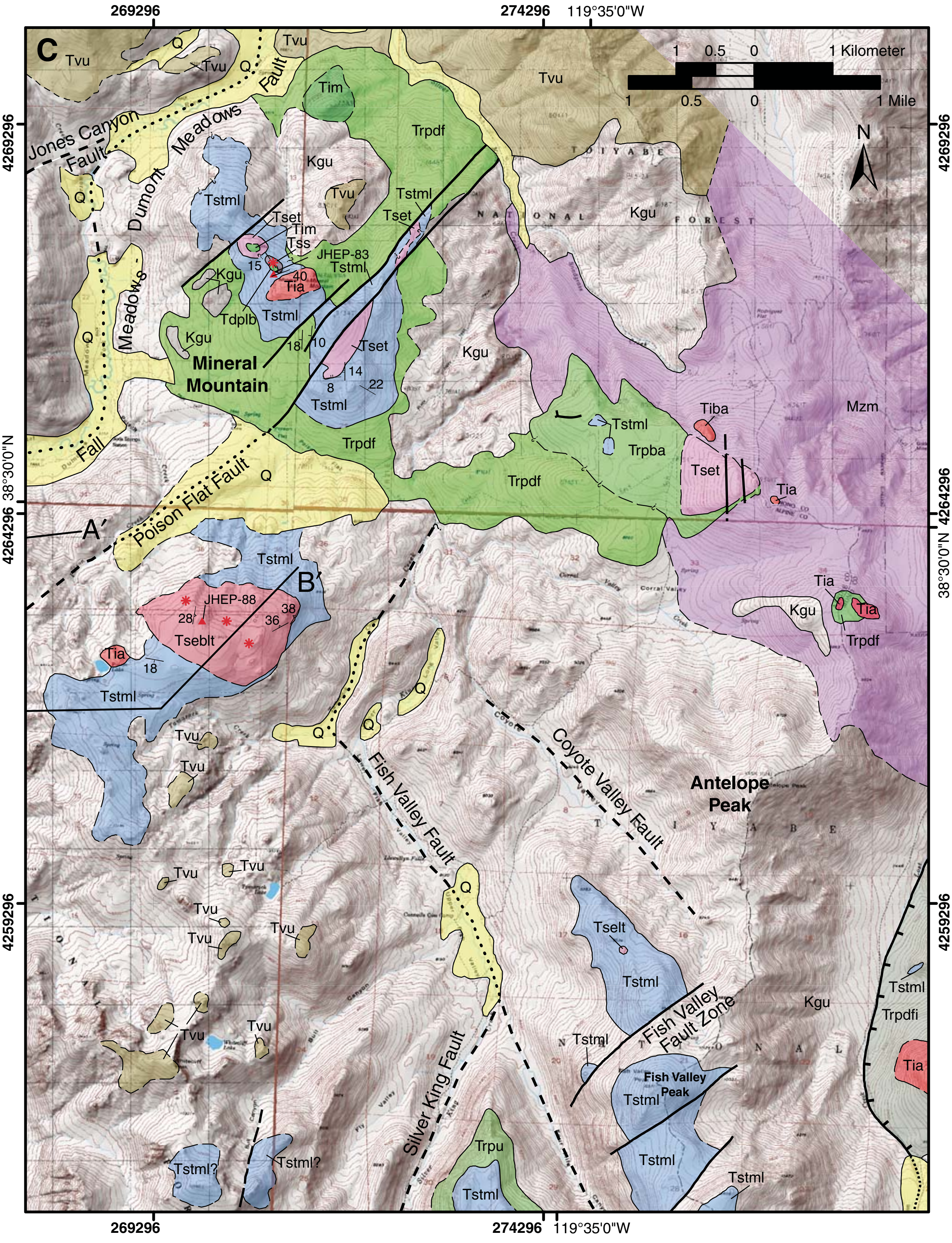
Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1



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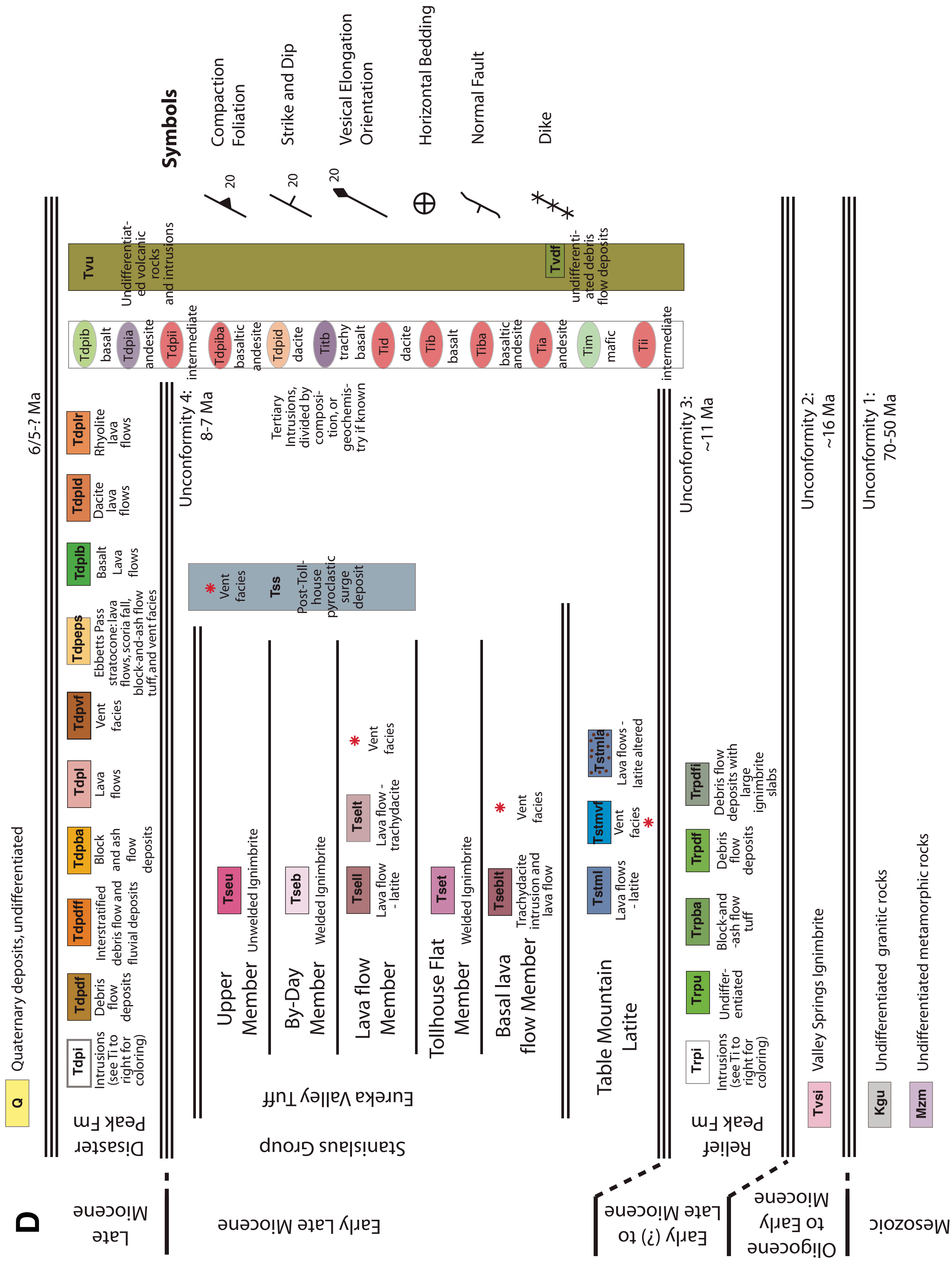

Figure 11 (*Continued*).

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

than the unusually large sector collapse deposit shed from ancestral Mount Shasta, estimated as ~35 km^3 (Crandall, 1989). It is ~25 times larger than the 1980 sector collapse at Mount St. Helens, described by Glicken (1996).

Strata that may represent in situ Relief Peak Formation in the Sierra Crest graben are identified by consistent flat dips or very low westward dips (concordant with regional dips). Possible in situ Relief Peak Formation includes the altered breccias that form the ridge east of Leavitt Lake (in the southeast corner of Fig. 6B); these breccias are heavily altered, but appear to have relict horizontal stratification, as does the Valley Springs Formation, in its correct stratigraphic position at the base of the section (Tvs; Fig. 6B) with horizontal welding compaction fabric. However, the possibility remains that this is a slide block of Valley Springs Formation, because at nearby Sardine Falls, slide blocks of Valley Springs Formation that are large enough to map individually are within chaotic deposits of Relief Peak Formation (Tvs and Trpu; Fig. 6B).

A relatively thin (less than tens of meters) section of in situ deposits is at the top of the Relief Peak Formation in the Sierra Crest graben, at one locality <1 km south of Sardine Falls and at another locality ~0.6 km south of Sonora Pass, because in both places, a 4-m-thick flat-lying mafic lava flow is present (Trpl; Fig. 6B). Another small in situ area of Relief Peak Formation in the Sierra Crest graben is in a narrow paleochannel cut into basement rocks west of Sonora Peak, at the north end of the Saint Mary's Pass fault (Fig. 6A). The paleochannel is filled with subhorizontal fluvial and debris flow deposits that are probably in situ (Trpf and Trpu; Fig. 6A), and forms a piercing point that we use to demonstrate a component of dextral slip on the Saint Mary's Pass normal fault (Fig. 6A), as described in the following.

The largest area of possible in situ Relief Peak Formation inside the Sierra Crest graben is along the western third of the ridge that extends west from Leavitt Peak (Trpu; Fig. 6B). There, stratification in the Relief Peak Formation consistently dips gently west. Exposures are very poor on the southwest side of the ridge (above Kennedy Creek; Fig. 6B) due to cover by talus, but a 20-m-thick ignimbrite (Trpig; Fig. 6B) shows flat compaction fabric, consistent with the interpretation that this section is in situ. 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 paleochannel deposits of the Relief Peak Formation on the opposite side of Kennedy Creek (Stanislaus paleochannel; Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). Along the northeast face of the same ridge, the Relief Peak consists of horizontally stratified fluvial and debris flow deposits that pass upward into massive debris flow deposits with interstratified block-and-ash flow tuffs near the top. A similar stratigraphy is present at the top of clearly in situ Relief Peak Formation west of the Sierra Crest graben, at The Dardanelles (mountain summit, Alpine, California; location shown in Fig. 5; Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.); perhaps they are correlative, but modal analysis, geochemistry, and dating are needed to determine this. At the base of the section on the northeast face of the ridge that extends west from Leavitt Peak, above Deadman Creek, discontinuous lenses of light colored rock are mapped as in situ Valley Springs Formation (Tvs; Fig. 6B). The in situ interpretation is supported by the fact that a lens 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 there is in situ. However, we have not succeeded in accessing the lenses on the south side of Deadman Creek (west of Blue Canyon), and it is not clear that previous workers did; those include Slemmons (1953), who mapped the unit as Valley Springs Formation, and Roelofs (2004), who mapped the unit as fluvial deposits within the Relief Peak Formation.

Primary volcanic rocks are abundant at a stratigraphically high position within the undifferentiated Relief Peak Formation in the Saint Mary's Pass region, similar to in situ primary deposits in this stratigraphic position at The Dardanelles, so it is possible that these are in situ. The rocks include a distinctive glassy plagioclase-biotite-hornblende dacitic (?) lava flow with flow breccia and a centimeter-scale glass hydration fracture pattern at Saint Mary's Pass, and a block-and-ash flow tuff with 20% hornblende crystals and glomerocrysts beneath the TML west of Saint 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 Saint Mary's Pass westward to Chipmunk Flat, probably representing the southeast side of an east-northeast–west-southwest–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 (intrusion or lava flows).

A coherent andesite makes up an ~1 km^2 area within the debris avalanche deposits south of the Sonora Pass highway in the southern end of the Sonora Pass fault zone (not mapped as a separate unit; Fig. 6). This body is important because it is indurated enough to display fault kinematic indicators, described in the following. It appears to have a chilled margin against the landslide megabreccias at one locality, so it may be an in situ intrusion into the debris avalanche deposit; alternatively, it may be within a larger slab.

To summarize, in situ Relief Peak Formation in the Sierra Crest graben may record an overall upward vertical trend from more distal (fluvial) to more proximal (debris flow) deposits, with more primary volcanic rocks toward the top (including block-and-ash flow tuffs, lava flows, and ignimbrite), similar to that recorded west of the graben in the paleochannel at The Dardanelles (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.).

TML Lava Flows

The thickest preserved sections of TML lava flows are within the Sierra Crest graben on Sonora Peak and Stanislaus Peak, on either side of Sonora Pass along the modern range crest (Fig. 6). The Sierra Crest graben also contains TML vent facies, described here from the Sonora Peak to Stanislaus Peak area; the Sierra Crest graben, and vent facies within it, continues north of the area described here, to the Disaster Peak–Arnot Peak area (Fig. 1). Here 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 (Fig. 6A) was measured and described in 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 more than 30 lava flows. A single ~7-m-thick olivine basalt lava flow is at the base of the TML ~600 m south of Sardine Falls (Tstmb; Fig. 6B). Similarly, a thin (3 m), discontinuous (30 m long) olivine basalt is at the base of the TML on the east wall of Blue Canyon (Tstmb?; Fig. 6B); this is overlain by ~24 latite lava flows of relatively uniform thickness (~15 m each).

West of Leavitt Peak, on the north face of Night Cap Peak, the TML may record tectonic disturbance during its emplacement. There the unconformity at the base of the TML (unconformity 3) on Relief Peak Formation is rugged, with >80 m of relief over a distance of <1 km, and the overlying TML lava flows show anomalous dips of 8° to the north-northeast (Fig. 6B). Further evidence for possible tectonic unrest is the presence of debris flow deposits interstratified with TML; these are dominated by large angular latite clasts, perhaps indicating disruption of the unit.

Farther west, along the north-facing cliffs east-northeast of Night Cap Peak (Fig. 6B), a prominent sharp boundary can be seen from a distance that separates the TML lava flows into two sections (unmapped within Tstml; Fig. 6B); this is a bedded latite tuff within the TML. Perhaps it was vented from the western margin of the graben, which is nearby; if so, this is the only vent facies deposit for TML on the west margin of the graben (all others are on the east margin, described in the following). Above that, the conical Night Cap Peak (Fig. 6B) forms a major landmark (see Fig. 7A). It is made of a single 30-m-thick TML lava flow with a 5-m-thick basal flow breccia. On the cliffs directly north of the Kennedy Lake pack trail (Fig. 6B), the TML consists of more than 24 subhorizontal latite lava flows.

To the west of Saint Mary's Pass fault (Fig. 6A), on the south and east side of By-Day flat, there are 5–9 latite lava flows preserved beneath EVT (Tstml, not mapped individually; Fig. 6A); however, on the west side of By-Day flat, the TML thickens rapidly into a low cut into Relief Peak Formation (unconformity 3; Fig. 2), and there are more than 10 lava flows.

On the west side of Stanislaus Peak (Fig. 6A), the TML consists of only 3 lava flows; it is thin here because the TML was deposited across substantial paleorelief on a paleocanyon wall, where the basal contact of the TML rises 100 m, and the TML directly overlies granitic basement. Paleorelief between the underlying Relief Peak Formation and the granitic basement is even more dramatic along this paleocanyon wall (~300 m; Fig. 6A). The TML lava flows interfinger with vent facies deposits on the east face of Stanislaus Peak (Fig. 6A).

TML Vent Facies Deposits and Feeder Dikes on the Eastern Margin of the Sierra Crest Graben

Previously unmapped vent deposits and feeder dikes for the TML occur along the eastern margin of the Sierra Crest graben, on the hanging wall of the East Fork Carson fault (Figs. 5–7). Slemmons (1966) outlined a 27 × 6 km^2 west-northwest–trending region that encompassed the entire Sierra Crest Sonora Peak–Stanislaus Peak area, westward to the Bald Peak area (geography shown in Fig. 5), and proposed that there were latite intrusives throughout this area; however, he did not describe any vents or give specific locations for them, and we have not found widespread latite intrusions in the area or elsewhere. Instead, we find vent facies eruptive products and lesser feeder dikes for the TML, and they are restricted to the eastern margin of the Sonora Pass segment of the Sierra Crest graben (Fig. 6). In contrast, TML vent deposits mainly lie along the western margin of the Disaster Peak–Arnot Peak segment of the Sierra Crest graben, described in the following (Fig. 11).

The Sonora Peak–Stanislaus Peak ridge preserves an ~6-km-long fissure deposit, which marks a major vent for TML lava flows along the east side of the Sierra Crest graben. Outcrops of TML vent facies deposits were individually mapped on the ground along the ridge top at Stanislaus Peak and Sonora Peak (map unit Tstmlvf; Fig. 6A); however, after that mapping was complete, one of us (Busby) was able to shoot low-angle oblique air photos of the inaccessible cliff face along the east side of the Sonora Peak–Stanislaus Peak ridge from a plane (Figs. 7 E, 7F, 7G). Those show continuous outcrops of thick red fragmental deposits interstratified with TML flows, inferred to be the same as the vent deposits shown in outcrops in Figures 7H–7K. Therefore, we infer that a TML fissure extends from Sonora Peak to Stanislaus Peak. The belt of vent facies deposits trends north-northwest, similar to the strike of a latite feeder dike that cuts underlying Relief Peak Formation on the south face of Sonora Peak (mapped in Fig. 6A and described in the following). The fissure deposits and the dike both strike parallel to the East Fork Carson fault (Figs. 5 and 6A). The linear map pattern of the vent deposits indicates that they are part of a cinder rampart, rather than individual cinder cone deposits. Fissures marked by cinder ramparts are common in flood basalt provinces, but not in andesite arc provinces (see Discussion). The same zone of weakness was later exploited by Disaster Peak Formation andesite plugs (Tdpi; Fig. 6A).

The sheer eastern face of Stanislaus Peak (Fig. 6A) provides excellent exposures of TML vent deposits, described in detail in Figure 7. These consist of very thick sections (as much as 200 m) of nonstratified red latite vesicular scoria lapilli, blocks, and bombs, with lesser larger (to 4 m) nonvesiculated angular blocks of latite. These deposits represent proximal, highly energetic ballistic fall accumulations. The fall accumulations interfinger with TML lava flows (Tstml; Fig. 6A) on the southeast 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 Sierra Crest.

A second accessible outcrop of TML vent facies deposits is ~1 km southeast of Stanislaus Peak (Tstmlvf) on another east-facing cliff, immediately south of the Stanislaus Peak fault (Fig. 6A). This vent facies deposit is also composed mainly of scoria and bombs with skeletal plagioclase typical of TML, but it lacks the dense Vulcanian megablocks of the Stanislaus Peak vent facies, and is crudely stratified rather than massive.

A third accessible outcrop of TML vent facies deposits is on the south face of Sonora Peak (400 m from the peak). These deposits resemble the Stanislaus Peak deposits, because they form a massive red deposit, as much as 50 m thick, with dense-clast TML megablocks to 3 m in size. These pass laterally into the thickest flow on Sonora Peak, 92-m-thick lava flow 19 (the other flows are <22 m thick; see fig. 10 of Busby et al., 2008a). These vent facies deposits also are 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; Fig. 6A). We interpret this to be a TML feeder dike.

Fissure vent deposits are not evident along the eastern margin of the Sierra Crest graben south of Sonora Pass (Fig. 6B), but TML feeder dikes are more common there (Fig. 7D). In addition, a map-scale TML dike cuts Relief Peak Formation along the Sierra Crest ~3 km southeast of Leavitt Peak, near the Pacific Crest Trail (080° striking purple line in Fig. 6B). This dike has the skeletal plagioclase typical of the TML.

Vent Deposits and Lava Flows of Undifferentiated Stanislaus Group on the Eastern Margin of the Sierra Crest Graben

Olivine basalt vent facies deposits and an associated lava flow overlie TML in the Stanislaus Peak area; these are mapped as undifferentiated Stanislaus Group (Tsbvf and Tsb; Fig. 4A) because we cannot prove that they form part of the TML, since we have recognized basalt vent facies and lava flows that overlie the Tollhouse Flat Member in the Sierra Crest graben (assigned to the Lava Flow Member of the EVT, described in the following). The Tollhouse Flat Member is regionally the most widespread Miocene volcanic unit (Fig. 1), but it is laterally discontinuous on map scale (Figs. 6, 8, and 11), and in the absence of dates, that unit must be present to distinguish TML lava flows from Lava Flow Member lava flows (Fig. 2). We prefer the interpretation that the basalts are within the TML, because many more TML flows are

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

preserved topographically higher on the ridge southward toward Sonora Peak (Fig. 4A). However, the other two TML olivine basalts (near Sardine Falls and in Blue Canyon) are at the base of the TML section (Tstmb; Fig. 4B), not above any latite flows, so the possibility remains that this is a Lava Flow Member unit, the topographically low position of which (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 the TML and which belong to the EVT, they are important for further 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 are 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 southeast 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; Fig. 4A), and is assigned to the Stanislaus Group because primary deposits in it (flow breccia and block-and-ash flow tuff) contain plagioclase and pyroxene, although debris flow deposits in it contain hornblende. Therefore, the primary breccias in the map unit (Tsu) could represent additional Stanislaus Group vent facies deposits.

EVT on the Western Margin of the Sierra Crest Graben (Including Lava Flows and Associated Vent Facies Deposits)

The EVT in the western part of the Sierra Crest graben (Figs. 6A and 8B) includes previously unrecognized lava flows (e.g., Fig. 10A) 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; Fig. 10B). As described in the following, vent deposits and plugs of the overlying Dardanelles Formation of the Stanislaus Group also hold up this resistant ridge. This north-northwest–trending ridge extends from By-Day flat (Fig. 6A) to the peaks labeled at elevations of 10244′ and 9798′ on the topographic map (Fig. 8B), and is in the hanging wall of the north-northwest–striking western graben-bounding fault to the west (Seven Pines fault), parallel to the fault. It is thus inferred that post-TML Stanislaus Group high-K volcanic units in this segment of the Sierra Crest graben were erupted from vents controlled by the Seven Pines fault, probably from splays of it that extended into the hanging wall, as described in the following.

The Tollhouse Flat Member of the EVT overlies, 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 (Fig. 6A), consists of a 13-m-thick, 275-m-long lens of biotite-phyric welded ignimbrite. The second locality, which is along the ridge about half-way between By-Day flat and peak 10244′ (Fig. 5), is a very small (~10 m × 4 m area) exposure of nonwelded biotite-phyric ignimbrite; lithologically, it could be confused with the Upper Member, but the By-Day Member is 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 (Fig. 8B). In all three localities, the presence of lenses of the Tollhouse Flat Member allows us to map EVT Lava Flow Member lava flows separately from TML lava flows that are lithologically identical, even though they differ in age by at least 780 k.y. (Fig. 2A).

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, which consists of the erosional remnant of an olivine basalt cinder cone cut by olivine basalt intrusions (Tselbvf; Figs. 6A and 8B). The olivine basalt cinder cone (Tselbvf) superficially appears in map view to crosscut the TML, but that is because it supports a pinnacled ridge that juts out over the top of the underlying TML (southeast face of peak 10244; Fig. 8B). 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 the EVT directly overlies it (Figs. 8 and 10). The cinder cone is bright red, with black and red stratified scoria fallout layers that dip ~30°–50° (Figs. 10C–10F). The cinders are locally agglutinated and contain large volcanic bombs (~2 m). A relatively thick (15–20 m) basalt lava flow crops out on the northwest and northeast sides of the same peak, and probably erupted from the cinder cone. Another erosional remnant of this lava flow is ~0.5 km to the north, also at the base of the Lava Flow Member. At that locality, it is topographically higher than the nearby Tollhouse Flat Member, although the contact is not preserved (Fig. 8B). In addition, 2 ~4-m-thick olivine basalt lava flows with flow-top breccias are at the base of Lava Flow Member on the southwestern face of By-Day flat (Fig. 6A).

The Lava Flow Member of the EVT has three latite lava flows along the ridge from By-Day flat to peak 10244′ (Tsel 1, Tsel 2, Tsel 3; Fig. 8B). The lowest flow (Tsel 1) is sparsely porphyritic, with small phenocrysts compared to the other two flows; it has spindle bombs on its flow-top breccia, presumably ballistic fall that was rafted away from the vent on the flow. The middle flow (Tsel 2) 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, Fig. 8B) exhibits platy parting on horizontal surfaces. A 75-m-thick erosional remnant of a latite cinder cone is within the Lava Flow Member along the ridge top ~1.2 km east of peak 10244′ (Tselvf; Fig. 8B). This red scoria-rich section contains abundant spindle bombs and blocks 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 lava flows separated by a debris flow deposit (Tseldf; Fig. 8B). A laterally discontinuous block-and-ash flow tuff is between lava flows 2 and 3 around peak 10244′ (Tselba; Fig. 8B; see photo in Fig. 10B). 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). This unit is fluvially reworked immediately adjacent to the Seven Pines fault (Tselbaf; Fig. 8B).

The By-Day Member of the EVT (Tseb; Fig. 8B) is thicker in the Sierra Crest graben than it is in other parts of the Sierra Nevada, and thus preserves more welding zonations than are typical for this unit elsewhere in the Sierra (for details, see Koerner, 2010).

The Upper Member of the EVT (Tseu; Fig. 8) is a bright white nonwelded ignimbrite, with white subrounded 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 (e.g., see Tseu, mapped 500 m northeast of peak 10244′, and also mapped <500 m east of peak 10244′; Fig. 8B). 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 is along the ridge that projects east from peak 10244′. It has 40%–50% skeletal plagioclase, and has irregular joints that are vertical in the

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

center and horizontal along the sides of the outcrop, suggestive of an intrusive origin (Tsi?; Fig. 5B); Slemmons (1953) also mapped an intrusion here. However, the By-Day Member of the EVT ramps up over it, and is not crosscut by it, which suggests that it was deposited on top of it. Furthermore, there are no post–By-Day Member latites of which we are aware, making it unlikely that it intrudes the By-Day Member. Therefore, it could be part of the Lava Flow Member, 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 overlies the Upper Member of the EVT, which in turn overlies the By-Day Member of the EVT (Fig. 8B). A small (~40 m wide and 400 m long) erosional remnant of the Dardanelles Formation lava flow overlies the By-Day Member of the EVT at By-Day flat, and an even smaller erosional remnant also overlies the By-Day Member on the ridge between peaks 10244′ and 9798′ (Fig. 6A). These exposures contain the typical very sparse plagioclase, pyroxene, olivine, and resorbed and/or oxidized hornblende phenocrysts. Another inferred erosional remnant of Dardanelles Formation is along the ridge crest, in a channel cut into TML lava flows and Relief Peak Formation debris flow deposits; the assignment to Dardanelles Formation is questioned (Tsdl?; Fig. 6A), because no EVT units intervene, and the flow is not as glassy as typical Dardanelles Formation, although it is otherwise identical. That lava flow has columnar joints that radiate inward from the base and side of this flow, due to cooling against the floor and wall of the small channel it fills (Fig. 10I).

Intrusions that are lithologically identical to the Dardanelles Formation lava flow, and crosscut units as young as the By-Day Member, are mapped here as Dardanelles intrusions; however, this interpretation must be tested by future dating and geochemical work. These intrusions are along the western boundary of the Sierra Crest graben, on either side of the Seven Pines fault (Tsdi; Fig. 8B). The largest plug is on peak 9798′, east of the fault; in addition, two smaller plugs and two dikes of identical lithology (shown as purple line with hachures; Fig. 8B) are west of the fault, on the south side of Red Peak on the Red Peak horst block (described in the following). Another lithologically identical north-northwest–striking dike is ~2 km west of Saint Mary's Pass, well within the Sierra Crest graben (Fig. 5A).

The southern part of the Sonora Pass segment of the Sierra Crest graben (Fig. 6B) 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-hachured line; Fig. 6B). Two of these dikes cut the TML near Night Cap Peak, and one cuts Relief Peak Formation along the range crest south of Leavitt Lake; these dikes strike northwest, parallel to the Kennedy Creek fault zone (Fig. 6B). A fourth northwest-trending dike is along the Saint Mary's Pass fault, ~500 m southwest of Sonora Pass (Fig. 6B). All of these dikes are black and nearly aphyric, with very sparse plagioclase, ± hornblende (commonly oxidized) and pyroxene phenocrysts, ± olivine microcrystals. Correlation of these dikes with the Dardanelles Formation lava flow must be tested by geochemical and geochronological work.

A Dardanelles Formation unit of uncertain origin is in the northern part of the Sierra Crest graben, just inside its west margin, on the north side of peak 10244′ (Tsdi?; Fig. 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 an erosional remnant on 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 in the following). 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; Fig. 8B).

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 irregularly shaped megablocks of nonwelded Upper Member EVT that are deformed between other block types (Fig. 10H). This indicates that the avalanche occurred before the tuff became lithified during burial. The debris avalanche deposit consists of megablocks (meters to tens of meters in size) of both Relief Peak Formation and Stanislaus Group rock types, including debris flow deposits, Upper Member EVT, latite 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 and Eastern Margins of the Sierra Crest Graben at Sonora Pass

Both the eastern and the western margins of the Sierra Crest graben at Sonora Pass are marked by ridges with intrusions, vent deposits, and vent-proximal deposits. These ridges presumably resisted erosion because they have a higher proportion of intrusions and primary volcanic rocks than the surrounding areas, which have a higher proportion of volcaniclastic rock.

Along the western margin of the Sierra Crest graben at Sonora Pass, the ridge formed of intrusions and vent deposits is on the hanging wall of the Seven Pines fault. The intrusions, vent deposits, and vent-proximal deposits are aligned roughly north-northwest, parallel to the Seven Pines fault on its hanging wall. The TML dramatically thickens on the east side of the ridge, relative to the west side of the ridge (Fig. 8B). This suggests that the Stanislaus Group vents were located along a north-northwest–striking, east-dipping normal fault strand of the Seven Pines normal fault that was east (in the hanging wall) of the mapped Seven Pines fault, which was active during emplacement of the TML, and was intruded by and buried under younger Stanislaus Group units and has not been reactivated since. In contrast, the Seven Pines fault (described in the following) 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. The western graben boundary fault acted as a conduit for units of the Stanislaus Group that are younger than the TML (EVT members and Dardanelles Formation).

Along the eastern margin of the graben, the vents for the voluminous TML are in the hanging wall of the East Fork Carson fault. The fault plane forms facets in the granitic basement, suggesting that it was reactivated after eruption of the TML. However, we infer that hanging-wall splays of the fault that controlled the positions of intrusions and vents were also healed by the magmatic activity, preventing their reactivation.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

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 rocks, and are assigned to Disaster Peak Formation (Figs. 6 and 8). One of these plugs, on Bald Peak (Fig. 8A), yielded the date of 7.28 ± 0.06 Ma (shown in Fig. 2A; reported in Busby et al., 2008a).

Only two very small patches of Disaster Peak Formation volcaniclastic fluvial deposits are above the Stanislaus Group in the Sonora Pass area, occupying a <20-m-wide channel cut into the By-Day Member of the EVT on By-Day flat (Tdpf; Fig. 6A). The channel fill consists of sandstone and conglomerate as well as reworked silicic white tuff. Clasts include a variety of andesitic rocks with hornblende, which is why we include it in the Disaster Peak Formation rather than the Stanislaus Group. Clasts also include a nonwelded white tuff with hornblende, feldspar, and quartz, similar to the reworked silicic white tuffs. The Disaster Peak Formation in the Sierra Crest graben in the Disaster Peak–Arnot Peak area (Figs. 1 and 11) has similar, abundant white tuffs, reworked tuffs, and tuff clasts.

Two primary volcanic rocks units that we assign to Disaster Peak Formation are along the ridge crest northwest of Leavitt Peak, inside the southwest boundary of the Sierra Crest graben near the Kennedy Creek fault. The lower of these units is a white-green ignimbrite that is within channels cut into the TML (Tdput, on the south and northwest sides of peak 11200′ [3413 m]; Fig. 6B; the latter locality was mapped by using binoculars because it is inaccessible). The white-green ignimbrite is nonwelded to incipiently welded, and contains pumice lapilli and pebble-sized lithic fragments of volcanic rock and sparse polycrystalline quartz. These are set in a matrix of glass shards and broken crystals, including (in order of abundance) sieve-textured plagioclase, bladed hornblende or 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 is a more extensively preserved >100-m-thick lava flow, which forms the tall cliff and jagged peaks that dominate the northwest-trending ridgeline northwest of Leavitt Peak (Tdpl; Fig. 6B). Previously workers assigned this unit to the Disaster Peak Formation (Slemmons, 1953) or the Dardanelles Formation (Giusso, 1981). The crystal-rich (~25%–30%) lava flow is distinctive because it contains two pyroxenes in addition to hornblende and plagioclase phenocrysts. 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 of the EVT because those flows contain only very sparse hornblende (<1%), whereas this unit contains ~10% hornblende. It is also 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 is on the same ridge as the ignimbrite and the lava flow (Tdpu; Fig. 6B) 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 (Fig. 8) than they are farther west in the range at The Dardanelles (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.) or to the east in the range front. The Disaster Peak intrusions are small plugs and dikes that vary little in character; for this reason, we provide a description of the Disaster Peak intrusions in Supplemental File 2[2], and do not describe them fault block by fault block as we do for strata, which record growth faulting.

PART IB: STRUCTURE OF THE SIERRA CREST GRABEN AT SONORA PASS

Here we describe and interpret faults of the Sierra Crest graben at Sonora Pass. We start with the north-northwest–striking East Fork Carson fault on the northeast graben boundary (Figs. 1 and 6A), then move westward to adjacent, smaller faults within the graben (Stanislaus Peak and Sonora Pass faults and the Saint Mary's Pass fault; Figs. 6A, 6B). This leads to a discussion of a fault within the southeast part of the graben (Blue Canyon fault; Fig. 6B), and parallel faults at the southwestern margin of the graben (Kennedy Creek fault; Fig. 6B). Faults of the western graben boundary are then tracked up through the Chipmunk Flat fault zone (Figs. 6A, 6B) into the Seven Pines fault (Fig. 8B).

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 (Fig. 3), with very obvious west-dipping facets cut into the granite on its eastern wall (Fig. 7C). The spectacular White Canyon segment of the Pacific Crest Trail follows the base of this fault scarp, on the floor of the East Fork of the Carson River. The segment of the East Fork Carson fault shown in Figure 6A forms only the southern third of the fault; its northern segment (Fig. 11B) also drops TML down to the west, as described in the following.

There is no Relief Peak Formation below TML on the footwall block of the East Fork Carson fault (Figs. 6A and 7B). 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, which forms part of the synvolcanic range-front fault system (Busby et al., 2013b). Only TML overlies the horst block to the northeast of the East Fork Carson fault (Figs. 6A and 7B). 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 became active before eruption of the TML.

Stanislaus Peak Fault

The northeast-striking Stanislaus Peak fault (see north part of Fig. 6A) is marked by a northeast-oriented, steeply dipping shear zone in the Cretaceous granite. A north-south steep contact between vent facies and lava flows of the TML (Tstmlvf and Tstml, Fig. 6A), well exposed on the south flank of Stanislaus Peak north of the fault (see Fig. 7H), is offset in ~300 m in a sinistral sense to the south of the fault (Fig. 6A). A small basalt cinder cone deposit that is upsection from these latite lava flows (Tsbvf, Fig. 6A) and feeds a basalt lava flow (Tsb, Fig. 6A) also appear to be offset in a sinistral sense, although these do not form as convincing a piercing point (i.e., they may have originally been more laterally extensive than evidenced by their map pattern). This fault is conjugate to the northwest–striking East Fork Carson fault and the Saint Mary's Pass fault, and its sinistral offset is like that of the northeast-striking Sonora Pass fault zone.

[2]Supplemental File 2. Disaster Peak Formation intrusions of the Sonora Pass region. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00670.S2 or the full-text article on www.gsapubs.org to view Supplemental File 2.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Sonora Pass Fault Zone

The eastern third of the northeast-striking Sonora Pass fault zone (Fig. 6A) was mapped by Slemmons (1953) where it clearly cuts the TML (see Busby et al., 2008a). A series of faults is also very well exposed at the southeast end of the fault zone (south of Highway 180, shown as solid lines; Fig. 6A), due to the presence of a competent coherent hornblende andesite intrusion or lava flow there (the intervening ground has rocks that are too soft to expose the fault well). There, northeast-striking fault surfaces dip >80°SE. 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 in Fig. 6A).

The central segment of the Sonora Pass fault zone is questionable (Fig. 6A) because it does not appear to offset the map trace of the TML, although it appears to cut an underlying large avalanche block of interstratified block and ash flow tuffs and debris flow deposits (Trpdb; Fig. 6A). However, the slide block may have been disrupted during the avalanche process, not by the fault. At that locality, the TML has lava flows on either side of the fault, and a flow breccia overlies 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 TML 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 (Fig. 6A). Approximately 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; Fig. 6A). The north end of this fault drops the base of the TML 30 m down to the west (Fig. 6A).

Saint Mary's Pass Fault

The Saint Mary's Pass fault is a north-northwest–striking normal fault that dips ~70°E; the trace passes through Saint Mary's Pass and Sonora Pass, displacing both the Relief Peak Formation and the TML (Figs. 6A, 6B). The southern end of the fault was mapped by Slemmons (1953, as Leavitt Peak fault) and Roelofs (2004), and the trace was extended to the north through Saint Mary's Pass (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 (Figs. 6B, 7L, and 7M). Hanging-wall TML lava flows are rotated ~8°–15° west, toward the fault (Figs. 7L, 7M); tilting increases southward from Sonora Pass toward Leavitt Lake (Fig. 6). Similarly, vertical separation of the contact between the Relief Peak Formation and the 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 more difficult to observe at its north and south ends, where there are no competent TML lava flows to expose fault planes or act as a strain marker.

There is some weak stratigraphic evidence for growth faulting on the Saint Mary's Pass fault during deposition of the Relief Peak Formation and the TML. The Relief Peak Formation abruptly doubles in thickness (by ~50 m) onto the hanging-wall block at Saint Mary's Pass. The TML also thickens from ~200 m on the footwall to >400 m on the hanging wall at Saint 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 (Fig. 6A). 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 hanging wall but not in the footwall (Busby et al., 2008a; Hagan, 2010). However, additional field work in 2010 convinced us that none of the Relief Peak Formation along the Saint Mary's Pass fault is in situ, except in the fluvial channel fill at the northern mapped end of the fault (Trpf; Fig. 6A). The chaotic nature of the Relief Peak Formation thus makes estimates of any pre-TML slip on the Saint Mary's Pass fault impossible.

In addition to normal offset along the Saint Mary's Pass fault, it also accommodated dextral strike-slip separation. Obliquely plunging lineations and Riedel shears are present in the Relief Peak Formation along the fault near Sardine Falls and Sonora Peak (Busby et al., 2008a). A 1-km-long, northwest-striking (320°) splay of the fault at Sonora Pass (shown by red dextral arrows; Fig. 6A) dips ~65°–70° west and has slickenlines that plunge obliquely (~25°) to the northwest; assuming normal displacement (rather than regionally unlikely reverse displacement), the slickenlines indicate right-oblique slip. In addition, at the north end of the mapped fault (which may continue further north), the paleochannel axis that 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; Fig. 6A).

Blue Canyon Fault

The Blue Canyon fault is a minor fault that parallels the much more important Kennedy Creek fault (Fig. 6B). It strikes west-northwest (~300°) and is subvertical. This fault shows 30 m of apparent dextral offset of a biotite dike 1 km north of Deadman Lake (blue line with boxes; Fig. 6B). Two splays off this fault are mapped in the area of Blue Canyon Lake (Fig. 6B). The southern of these two splays strikes northwest, and is marked by abundant northwest-striking surfaces; it clearly drops TML >80 m down to the southwest against the Relief Peak Formation (Fig. 6B). Along this northwest-striking normal fault, there are also north-striking, steeply west dipping undulatory surfaces (not mapped at the scale of Fig. 6) with slickenlines that plunge 35° to the north; this suggests that the normal fault also accommodated dextral slip. Where the southern splay meets the Blue Canyon fault, on the north side of the Blue Canyon fault, there is a 100-m-long fault (barely mappable at the scale of Fig. 6B) that strikes ~015°, dips steeply east, and contains slickenlines that plunge south ~75°–90°. If this is a normal fault, similar to other faults in the region, the slickenlines indicate a dextral component of slip. It thus appears that the more oblique, north-striking fault has a greater component of normal slip relative to the less oblique, northwest-striking splay, supporting the interpretation that the west-northwest–striking Blue Canyon fault accommodates dextral strike-slip offset.

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 (as much as 400 m thick), and none of the TML was deposited in the paleochannel to the west, defined by Valley Springs and Relief Peak Formation filling a paleocanyon carved into the basement there (Busby, Andres, Koerner, Melosh, and Hagan, 2—3–2013, personal observs.). The Kennedy Creek fault therefore 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 (Fig. 6B). It is subvertical and strikes ~320°, with ~30 m of apparent right-lateral separation. Slemmons (1953) connected the Kennedy

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Creek fault zone northward, to the westernmost fault of the Chipmunk Flat fault zone (Fig. 4B), across a northeast-striking transfer fault that he mapped in the dramatic steep, narrow gorge of Deadman Creek; we concur (Fig. 6B).

Chipmunk Flat Fault Zone

The Chipmunk Flat fault zone extends north-northwest from the transfer fault in Deadman Creek (Fig. 6). Slemmons (1953) mapped the eastern and western faults but not the central fault of the Chipmunk Flat fault zone, which is smaller (Fig. 6). 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 to 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 ~100 m, and the Relief Peak Formation thickens from ~160 m on the hanging wall to ~250 m on the footwall. These relations indicate growth faulting during deposition of the Relief Peak Formation.

The central fault of the Chipmunk Flat fault zone (Fig. 6) strikes 340° and dips east, and drops the base of the Relief Peak Formation down to the east ~60 m. The Valley Springs Formation is absent from its footwall, so it cannot be determined if growth faulting occurred during deposition of the Relief Peak Formation, but the absence of the Valley Springs Formation could indicate that the formation was shed or eroded from the hanging wall before the Relief Peak Formation was deposited. The central fault of the Chipmunk Flat fault zone may represent an antithetic fault to the eastern fault.

The western fault of the Chipmunk Flat fault zone (Fig. 4A) is subparallel to the other faults and dips east, bringing up granitic basement against the Relief Peak Formation. 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 (Fig. 5).

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 that follows a very narrow, straight creek with a northeast trend similar to many other transfer faults in the Sonora Pass area (Figs. 6, 8, and 11; Busby et al., 2013b), including the nearby transfer fault to the south in Deadman Creek. An unconsolidated landslide deposit, with abundant megablocks, is in this fault valley (Figs. 6A and 8B); the landslide is presumably postglacial.

Seven Pines Fault

The segment of the Seven Pines fault that crosses the ridge east of Red Peak (Fig. 8B) was also mapped by Slemmons (1953), as a down-to-the-east normal fault (referred to as the Iceberg fault). We trace it 4 km farther to the south (Fig. 8B), where we infer that it transfers to the westernmost Chipmunk Flat fault (Fig. 6A). We also trace the Seven Pines fault continuously northward, where it becomes the Disaster Creek fault (Figs. 5 and 11); similarly, Slemmons (1953, p. 149) stated that it may "have a northern extension up Disaster Creek." 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., 2013a).

The Seven Pines fault strikes 340°, dips east ~60°, and has a normal sense of displacement. The base of the TML is downdropped to the east ~50–80 m across the fault, both east of Red Peak (Fig. 9A) and west of peak 10244′ (Fig. 8B). Drainages generally follow the fault trace, 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 any of the slip predated deposition of the TML. The TML does not thicken dramatically onto the hanging wall of the Seven Pines fault, but it does thicken dramatically across the ridge that is intruded and buried by Stanislaus Group plugs, vent deposits, and flows of the EVT and the Dardanelles Formation. Therefore, we infer that a buried strand of the Seven Pines fault formed the main graben boundary east of the Seven Pines fault, 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.

PART II: SYNVOLCANIC HALF-GRABENS IN THE CATARACT PALEOCHANNEL ON THE WESTERN MARGIN OF THE SIERRA CREST GRABEN

Westward from the western edge of the Sierra Crest graben at Sonora Pass, Tertiary volcanic and volcaniclastic sedimentary rocks were deposited in a west-flowing paleochannel. The deposits in the paleochannel are thin relative to the graben fill to the east, but the paleochannel was progressively disrupted into half-grabens before and during deposition of the Stanislaus Group. The deposits of the syndepositionally faulted paleochannel form the resistant ridge from Red Peak to Bald Peak (Fig. 8). The faults here also controlled the sites of vents and intrusions that represent satellites to the Sierra Crest graben-vent system.

We follow Lindgren (1911) by referring to this as part of the Cataract paleochannel, which continues westward through The Dardanelles (Fig. 5), and Whittaker's Dardanelles to Knight's Ferry (Fig. 1). This narrow, relatively shallow paleochannel and its fill (Fig. 9) contrast markedly with the Sierra Crest graben to the east, where accommodation was provided by rapid tectonic subsidence over a very large area. However, as shown here, some accommodation was provided by faulting in this reach of the paleochannel.

Herein we present evidence for growth faulting along the Red Peak, Douglas Creek, and Bald Peak faults, before and during deposition of the Stanislaus Group, by describing the stratigraphy of each fault block, from east to west. We also show that the grabens produced by the faults filled as quickly as they formed, because the paleochannel continued to function throughout the eruption of the Stanislaus Group, even though Stanislaus Group volcanic rocks were locally vented along faults into the paleochannel.

Red Peak Horst Block

The Red Peak horst block is in the footwall of the Seven Pines fault to the east and the Red Peak fault to the west (Figs. 8B and 9A). Granitic basement is brought up in the Red Peak horst block, and ~500 m south of Red Peak, the Valley Springs Formation (Tvs) is preserved as a 100-m-thick and 300-m-long erosional remnant on a paleoledge on the side of a paleochannel in the granitic basement (unconformity 1; Kgu; Fig. 8B). The base of the Relief Peak Formation is locally topographically lower than the base of the Valley Springs Formation here (Fig. 8B), due to a reincision event in the paleocanyon that produced unconformity 2 (Fig. 2).

In contrast with the debris avalanche deposits that dominate the Sierra Crest graben, Relief Peak Formation strata are in situ in the Cataract paleochannel fill of the Red Peak horst block. Debris flow deposits dominate (Trpdf), but fluvial deposits are also present (Trpf; Fig. 6B). These have "huddled" clasts (where clasts pile up behind each other), clast imbrication, and well-developed trough cross-beds that indicate a paleotransport direction of 238° to 283°, consistent with transport in the Cataract paleochannel.

The TML consists of six lava flows on Red Peak and seven lava flows on the ridge west of 10244′ peak (mapped individually in Figs. 8B, 9A, and 9D). Fluvial sandstone and

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

conglomerate with pebble- to boulder-sized, well-rounded clasts of latite are between flows 2 and 3 on Red Peak (Tstmf; Fig. 8B). Other fluvial conglomerates, with rounded cobbles and sparse boulders of latite and minor hornblende andesite, occur between the TML lava flows and the EVT Lava Member lava flows on the northeast face of Red Peak. These fluvial deposits indicate that water continued to flow down the Cataract paleochannel between eruptions.

Although in situ Tollhouse Flat Member is not present on the Red Peak horst block, the boundary between TML and EVT Lava Flow Member latites is marked by a deep (25 m), narrow (25 m) channel cut into TML that is filled with a debris flow deposit containing megablocks (to 3 m in size) of the Tollhouse Flat Member of the EVT (Tseldf; Fig. 8B). The debris flow deposit has cobble- to pebble-sized clasts of diverse compositions, including hornblende andesite as well as latite, and boulders of olivine basalt.

Three Lava Flow Member lava flows are preserved on Red Peak (Tsell 1, Tsell 2, Tsell 3; Fig. 8B). Flows 1 and 2 are typical latites, but flow 3 (only preserved as tiny erosional remnant, ~8 m long and <1 m thick) is unusual for its extremely finely layered and highly contorted flow banding, and highly scoriaceous and glassy character (shown in Fig. 4F). Nonetheless, it has skeletal plagioclase, like the typical latites. Perhaps it is a trachydacite, similar to the Lava Flow Member flow analyzed in the next fault block to the west (described in the following).

In the Red Peak horst block there is a latite dike that cuts up through TML latite flows, on the ridge that extends west from peak 10244′ (west of the Seven Pines fault, shown as a pink line with cross-hachures; Fig. 8B). The dike has skeletal plagioclase laths, clinopyroxene, and small unaltered olivine phenocrysts set in a black groundmass. We map this latite dike as a Lava Flow Member feeder dike, rather than a TML dike, because it intrudes TML, and because there are other Lava Flow vent facies deposits nearby to the east (Tselvf, Tselbvf; Fig. 8B), and we have not found any TML feeders or vent facies along the western boundary of the Sierra Crest graben at Sonora Pass.

Red Peak Fault

The Red Peak fault strikes 165° and dips 70° westward (Figs. 8 and 9A). The base of the TML lava flow is separated vertically ~235 m (down to the west), and the EVT Lava Flow Member dips 8° east toward the Red Peak fault, opposite the regional shallow westward dip. A northwest-striking fault forms a splay off the Red Peak fault south of Red Peak, where dikes and granitic basement are sheared and brecciated, and the Valley Springs paleoledge deposit is truncated.

The Red Peak fault was probably active during volcanism. The thickness of the Relief Peak Formation is variable, due to paleotopographic effects, but it appears to thicken abruptly onto the downthrown block, particularly on the north side of the Red Peak–Bald Peak ridge (Figs. 8A and 9A). The Tollhouse Flat and By-Day Members of the EVT are absent from the section in the upthrown fault block, but they form a relatively continuous deposit on the downthrown block (Fig. 8). The By-Day Member doubles in thickness toward the footwall of the Red Peak fault, in the short distance between the Douglas Creek fault (30 m) and the Red Peak fault (60 m). Dikes are parallel to the fault, and some are along it (Ti; Fig. 8B), suggesting that it is synmagmatic.

Douglas Creek Fault: Antithetic Fault to the Red Peak Fault

The Douglas Creek fault consists of two minor, en echelon faults that strike north-south and dip >70° east (Fig. 8A), and are thus antithetic to the Red Peak fault (Figs. 8 and 9A). The fault downdrops Relief Peak Formation against granitic basement (Fig. 8A), where the base of the Relief Peak has an apparent offset of 80 m, and the granitic basement is sheared. The base of the TML, as well as the trachydacite Lava Flow Member (Tselt) and By-Day Member (Tseb), are separated vertically ~35 m (Fig. 9A). The Relief Peak Formation appears to thicken onto the downdropped block (Fig. 9A), although this could be a paleotopographic effect. However, the Tollhouse Flat Member thickens abruptly from 7 m on the upthrown block to 25 m on the downthrown block, where it maintains a uniform thickness east to the Red Peak fault (Fig. 8). The By-Day Member thickens abruptly from 20 m to 30 m across the fault onto the downthrown block (Figs. 8 and 9A). Thus, the fault was active before and during eruption of the Stanislaus Group, as well as after it.

Bald Peak Fault

The Bald Peak fault strikes 340°, dips 60° west, and cuts all Miocene volcanic units, including the Relief Peak Formation, TML, EVT, and Dardanelles Formation, and probably the Disaster Peak Formation plug (Figs. 8 and 9A). The base of the TML is separated vertically ~130 m. The Relief Peak Formation (Trpdf) thickens significantly, from 45 m to 110 m, on the downthrown block, where it contains megablocks of pink and white block-and-ash flow tuff. These have highly irregular margins, indented by more rigid, dense blocks around them, indicating that they were incorporated before they were fully lithified (i.e., they were remobilized along the fault scarp soon after deposition). Also on the downthrown block, the Stanislaus Group has the thickest fluvial deposits in the Bald Peak–Red Peak area, suggesting that they were trapped in a basin.

Stratigraphy in the Hanging Walls of the Red Peak and Bald Peak Faults

A detailed description of a stratigraphic section measured along the green line shown in Figure 8A was given in Koerner et al. (2009). A 220-m-thick remnant of Valley Springs Formation on the north side of Bald Peak (Fig. 8A) is consistent with the interpretation that the section here is within the Cataract paleochannel. West of the Red Peak fault, the Relief Peak Formation consists entirely of crudely stratified to massive debris flow deposits (Trpdf). Noncharred petrified wood fragments and trunks are common.

The TML contains five latite flows totaling 100–150 m in thickness between the Red Peak and Bald Peak faults, and thins westward to 30–110 m, with only 3 or 4 latite flows, west of the Bald Peak fault. Measurements of stretched vesicles in this area (225°; see Fig. 11 of Koerner et al., 2009) indicate transport parallel to the trend of the Cataract paleochannel. Discontinuous, black, olivine-plagioclase-phyric basalt lava flows are between TML flows 3 and 4 on either side of the Bald Peak fault (Tstmb; Fig. 8). The olivine basalt lava flow that is west of the fault strikes into olivine basalt vent facies deposits on the northwest side of Bald Peak (Tstmbvf; Fig. 8A). The vent facies consists of black to orange stratified deposits, in beds that in part dip steeply, formed of scoria and spindle bombs and tuff, with bomb sags. Beds of gray tuff and lapilli tuff with angular juvenile clasts are more abundant in this deposit than is usual for a cinder cone, suggesting that it is at least in part phreatomagmatic; this interpretation is supported by the presence of angular accidental fragments of TML, andesite, and rare granite. Thus, these magmas probably erupted through water-saturated paleochannel fill deposits. A possible feeder to this basalt within the TML is ~1 km southwest of Bald Peak, on the east side of an unnamed fault, where the Relief Peak Formation and TML are intruded by a olivine basaltic dike that strikes approximately parallel to the fault (Tstmbi; Fig. 8A).

Fluvial deposits within the TML on the hanging wall of the Bald Peak fault (Tstmf; Fig. 8) are as much as ~30 m thick, and have a mixture of andesite and latite clasts, with rounded boulders to 2 m in size, suggesting high axial gradients

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

in the paleochannel. TML lava flow 5 tapers out within a small channel cut into one of these fluvial deposits (Fig. 8A). Fluvial deposits are also interstratified with TML on the north side of the Red Peak–Bald Peak Ridge (Tstmf; Figs. 8 and 9C), where they form an ~40-m-thick section of white sandstone and conglomerate that fines upward (Tstmf; Fig. 8).

The Lava Flow Member of the EVT was mapped and measured for the first time in the Sierra Nevada at this locality (Koerner et al., 2009). This was also the first place that a silicic lava flow (trachydacite, Tselt) was mapped within the Stanislaus Group. The chemistry of the trachydacite is quite distinct from that of all the other previously recognized lava flows in the Stanislaus Group, which are trachyandesite-latite or basaltic trachyandesite-shoshonite, but it is similar to the EVT ignimbrites (Koerner et al., 2009). A trachydacite lava flow and associated feeder also intrude and overlie the TML near Poison Lake (Figs. 1 and 11C), and in the range front at Sonora Pass (Busby et al., 2013b). Trachydacite lava also occurs in the EVT Lava Flow Member in a downchannel stretch of the Cataract paleochannel, at The Dardanelles (Koerner, 2010). The trachydacite lava (Tselt) at Bald Peak–Red Peak differs from TML by having oxidized amphibole phenocrysts, but like TML, it has phenocrysts of skeletal plagioclase and clinopyroxene. In the line of the measured section, it is a single lava flow with a distinctive purple-gray or orange-brown very highly vesiculated top that passes laterally into a thick flow-top breccia (Tselt; Fig. 8). The trachydacite lava flow is continuous along the ridge between the Red Peak and Bald Peak faults, where it is underlain by the Tollhouse Flat Member and overlain by the By-Day Member. A relatively complete section through the By-Day ignimbrite is preserved here; it includes a basal ~5-m-thick white and tan nonwelded to incipiently welded tuff, passing upward through welded tuff, and a locally preserved orange vapor phase altered top. This in turn is overlain by erosional remnants of Upper Member of the EVT (Tseu; Fig. 8), with a basal, ~20-cm-thick, fine-grained white ash-fall tuff, overlain by a white nonwelded ignimbrite, in turn overlain by a lithic-rich tan nonwelded ignimbrite, and capped by stratified fluvially reworked tuff with polylithic volcanic pebbles. The vitrophyres in the Tollhouse Flat and By-Day Members have unusually well developed perlitic fractures, perhaps suggesting quenching by running water within the paleochannel.

The single black, nearly aphyric lava flow of the Dardanelles Formation is preserved as erosional remnants as much as 60 m thick on the ridge between the Red Peak and Bald Peak faults; it is 40 m thick where it is intruded by the Bald Peak plug, and where its flow-top breccia is mostly obliterated or eroded. The thick (>10 m) pink-red flow-top breccia is injected by coherent lava from the flow's interior, indicative of its low viscosity. In thin section, the Dardanelles Formation lava flow contains microcrystalline olivine (~5%), pyroxene (~3%), and plagioclase laths, and it has a basaltic-trachyandesite composition (Koerner et al., 2009). On the ridge crest within several meters of the line of the measured section (green line; Fig. 8A), in an erosional remnant only 8 m × 8 m, the Dardanelles lava flow locally has a peperite base, indicating it was emplaced onto wet sediment in the Cataract paleochannel. Approximately 5 m of flow-bottom breccia at the top of the outcrop passes downward into ~4 m of very irregular shaped or pillow-like or angular fragments encased in a host of massive sandstone. This indicates that the flow locally burrowed into and interacted with wet sediment in the paleochannel. The Dardanelles lava flow fills channels cut into the Upper Member and locally down into the top of the By-Day Member of the EVT, and is overlain by a single small erosional remnant of fluvial sandstone and conglomerate, with angular to rounded clasts of andesite and latite, tentatively assigned to the Dardanelles Formation (Tsdf?; Fig. 8).

The Dardanelles Formation lava flow (Tsdl) on the west side of Bald Peak overlies a thin (~2 m) section of vent deposits and strikes into a 200-m-thick section of vent deposits on the north side of the peak; the lava flow is also overlain by a thick (~50 m) section of vent deposits on the west side of the peak (Tsdvf?; Fig. 8A). Thus, it is possible that the lava flows issued from part of a cone that formed in the same eruption. The vent deposits consist of scoria fall and phreatomagmatic deposits. The scoria fall deposits are black to red, nearly aphyric bombs and scoria with <5% dense rigid angular blocks, also aphyric, suggesting that Vulcanian blasts accompanied Strombolian activity. The possible phreatomagmatic deposits are better stratified and thinner bedded, and are not red; they consist of black or gray angular pebble- to sand-sized clasts. In addition to vent facies deposits, we tentatively assign to Dardanelles Formation a dike on the northwest side of Bald Peak (purple line with cross-hachures; Fig. 8), and an elongate, pod-shaped intrusion that crosscuts a fault 1.1 km south-southwest of Bald Peak. The presence of Dardanelles vent facies deposits and intrusions in this area is consistent with the presence of Dardanelles Formation plugs on the western margin of the Sierra Crest graben, and their absence on the eastern margin.

Unnamed Faults West of Bald Peak

A fault ~1 km west of Bald Peak strikes ~320° and the base of the TML is separated vertically ~50 m with an apparent down-to-the-west slip, and it may drop the Relief Peak Formation down to the west against the Valley Springs Formation, although this is less clear because the Valley Springs Formation does not crop out west of the fault (Fig. 8A). However, this fault juxtaposes granitic basement with Relief Peak Formation with an apparent opposite sense of vertical slip, although the basement contact has a great deal of paleorelief (Fig. 8A). The fault does not offset the hornblende-bearing Disaster Peak Formation intrusion at peak 8770′ (peak elevation 2673 m), or the Dardanelles Formation intrusion (Tsdi) north of that (Fig. 8A), providing further evidence of previously unrecognized synvolcanic faulting in the region.

A fault ~2 km west of Bald Peak strikes 330°–340° and downdrops Miocene volcanic units to the east (Figs. 5 and 8A; Slemmons, 1953), where the Relief Peak Formation is juxtaposed against the granitic basement. The Cretaceous granite is highly fractured in this region, with subvertical joints.

PART III: SIERRA CREST GRABEN AT DISASTER PEAK–ARNOT PEAK, AND ASSOCIATED TRANSFER ZONE BASINS

We describe here the Disaster Peak–Arnot Peak segment of the north-south Sierra Crest full graben, as well as a northeast-southwest graben-vent system that emanates from its eastern edge and extends down the modern range front, referred to here as transfer zone basins (Figs. 1 and 11–14). The transfer zone basins are important for showing that the Sierra Crest graben-vent system has a structural style similar to that of the transtensional Walker Lane belt, not the extensional Basin and Range. The Stanislaus Group was not previously mapped in the part of the range front described in this section (Fig. 11C), except at its southernmost end at Fish Valley Peak (Slemmons, 1953).

The displacement histories of faults in the Disaster Peak–Arnot Peak sector of the Sierra Crest graben and the associated transfer zone basins are not reconstructed in as great detail as the Sonora Pass sector or the Sonora Pass range front (Busby et al., 2013b). This is largely because paleochannel deposits pass through the Sonora Pass area, giving us greater opportunity for demonstrating displacements before, during, and after formation of the Stanislaus Group, while paleochannel deposits are absent between Sonora Pass and Ebbetts Pass

(Fig. 15). In addition, the Sonora Pass crest and range front are more accessible by four-wheel-drive vehicles, day hikes, and backpack trips, while the remoteness of the region between Ebbetts and Sonora Pass presents more challenges. However, the mapping described here clearly shows for the first time that a system of north-south and northeast-southwest faults ponded Stanislaus Group volcanic rocks to great thicknesses, and controlled the siting of fissure vents and point source vents.

We name this segment of the Sierra Crest graben the Disaster Peak–Arnot Peak segment, for two major peaks along the modern Sierra Nevada crest (Fig. 11). The strata of this segment of the Sierra Crest graben are separated from the Sonora Pass segment by the South Fork Clark River glacial valley, which erodes the Mesozoic basement below the graben. However, some of the full graben-bounding faults are continuous between the two areas (East Fork Carson fault on the east, and Disaster Creek–Seven Pines fault on the west), and the graben fill has a similar thicknesses, so it seems likely that the graben was originally continuous between the two areas (making it 28 km long and 8–10 km wide). The Disaster Peak–Arnot Peak segment of the Sierra Crest graben (including Lightning Mountain; Fig. 11) has a preserved length of 7.6 km and width of 8 km, and its fill has a maximum stratigraphic thickness of 1.3 km.

Similar to the Sonora Pass segment of the Sierra Crest full graben, the western edge of Disaster Peak–Arnot Peak sector of the Sierra Crest graben does not consist of a single fault. It has two approximately north-south faults that break the surface, which we identify for the first time, the Disaster Creek fault and the Arnot Creek fault (Figs. 11 and 12). The Disaster Creek fault is relatively straight and appears to be a high-angle planar fault. The Arnot Peak fault is curved (Fig. 11A), and the TML on its hanging wall appears to dip toward the fault at a moderate angle (~30°); thus this

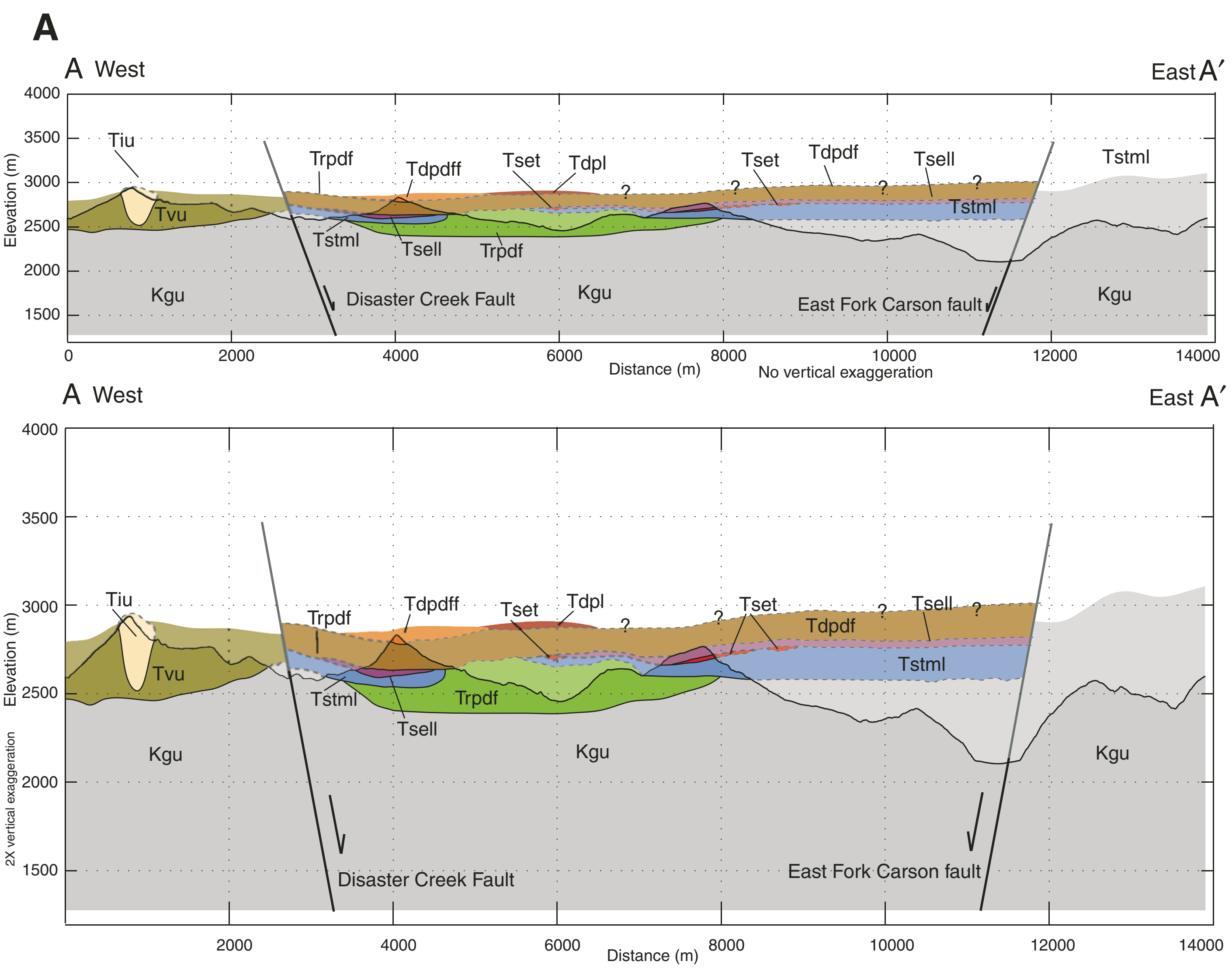

Figure 12 (*Continued on following page*). Structure sections through Miocene volcanic strata in the Disaster Peak–Arnot Peak area; locations are plotted in Figure 11. Shown at true scale and with 2× vertical exaggeration. Key to map units is given in Figure 11D. (A) Cross-section A–A′ is drawn across the northern part of the Disaster–Arnot Peak sector of the north-south Sierra Crest full graben, including a northeast transfer zone basin on the east. Disaster Creek fault is down to the east, and East Fork Carson fault is down to the west. Strata in the graben are flat-lying.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

fault is interpreted to be concave upward at depth (Fig. 12B).

The eastern edge of the Sierra Crest graben is more complicated in the Disaster Peak–Arnot Peak segment than it is in the Sonora Pass segment, because it passes eastward into an ~24-km-wide zone of northeast-southwest faults, connected by shorter approximately north-south faults, which extend ~24 km down the modern range front (Fig. 11). We show here that these faults formed basins that accommodated Stanislaus Group deposits, and controlled the siting of Stanislaus Group vents (as well as younger vents in the arc). For this reason, the range-front fault zone shown in Figure 11C is included in the Sierra Crest graben-vent system, and the northeast basins are referred to as transfer zone basins.

Faults of the transfer zone are east of the modern range crest, and include, from north to south (Fig. 11), the east-west to northeast-southwest Wolf Creek fault, the northeast Jones Canyon fault, the northeast and north-south Falls Meadows–Dumont Meadows faults, the northeast Poison Flat fault zone, and a northeast fault at the north end of the north-northwest Fish Valley and Coyote faults; those in turn bound a northeast fault zone at Fish Valley Peak. Most of the faults in the transfer zone form valleys in the granitic basement, commonly covered with sediment (Fig. 11); this means that the fault planes are rarely exposed, similar to most of the faults in the central Sierra Nevada range front (Busby et al., 2008a, 2008b; Hagan et al., 2009; Busby and Putirka, 2009). None of these faults were mapped previously, except for the Fish Valley fault and the Fish Valley Peak fault zone of Slemmons (1953).

At the north end of the transfer zone, the Wolf Creek fault drops ca. 6–4 Ma volcanic and volcaniclastic rocks down to the north against the ca. 12–9 Ma Relief Peak Formation–Stanislaus Group section to the south, forming the southern boundary of a younger (Miocene–Pliocene) pull-apart basin centered over Ebbetts Pass (Busby, 2011, 2013; Busby et al., 2013a). However, we infer that the Wolf Creek fault had an earlier movement history, of the opposite (down to the south) sense, because ponded Stanislaus Group rocks form a prominent northeast ridge south of the Wolf Creek fault, formed by topographic inversion of the resistant basin fill, which projects to the northeast out of the north end of the north-south Sierra Crest graben. We infer that the other side of this northeast transfer zone basin was controlled by the northeast and north fault system that runs from the Murray Canyon–Falls Meadow valleys to the Dumont Meadows valley (and northward to the Silver King Valley, not shown in Fig. 11; see Busby et al., 2013a).

The Relief Peak Formation is restricted to the north margin of the Sierra Crest graben and the transfer zone basins that emanate

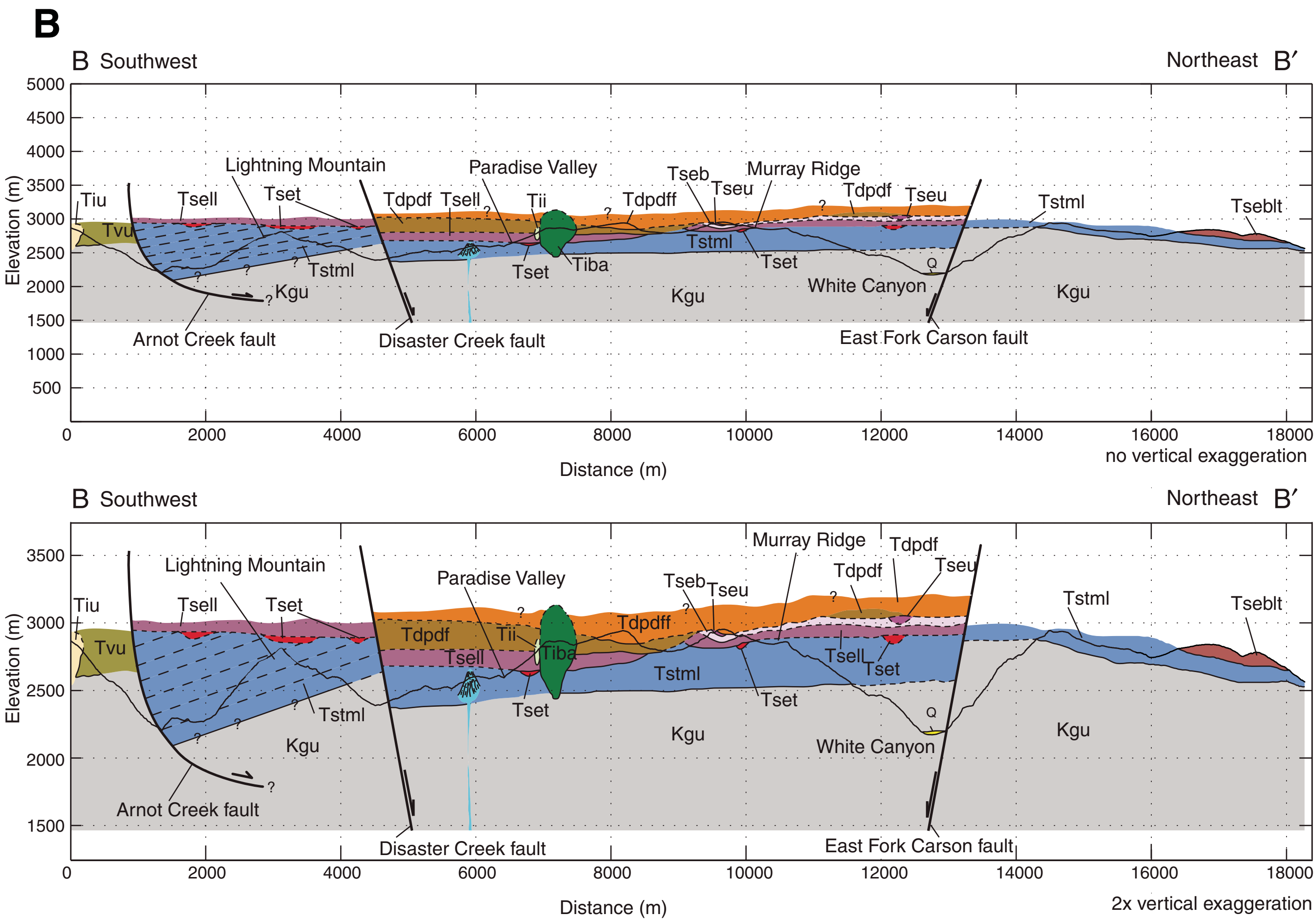

Figure 12 (*Continued*). (B) Cross-section B–B′ is drawn across the southern part of the Disaster–Arnot Peak sector of the Sierra Crest graben. The Arnot and Disaster Creek faults bound the west side of the graben and the East Fork Carson fault bounds the east side. Strata between Disaster Creek fault and Arnot Creek fault dip toward the west, because the Arnot Creek fault is curved.

northeast from it (Fig. 11), perhaps indicating that this is the only part of the Disaster Peak–Arnot Peak segment of the Sierra Crest graben-vent system that had a pre-TML subsidence history. It consists largely of massive volcanic debris flow deposits (Trpdf; Fig. 11), but it also contains lenses of block-and-ash flow tuff (not mapped separately). One of these (at the northernmost end of the full graben) has a hornblende $^{40}Ar/^{39}Ar$ age of 11.33 ± 0.03 (sample JHEP-90; Busby et al., 2013a). The Relief Peak Formation also has block-and-ash flow tuffs in the northeast transfer zone basins along the Poison Flat fault zone, some mapped separately (Trpba; Fig. 11C), but those are undated. The Relief Peak Formation of the transfer zone basins lacks any fluvial deposits, and there is no Valley Springs Formation beneath it, so we do not interpret it as paleochannel fill; instead, we infer that the Relief Peak Formation was preserved in fault-bounded basins that trapped lava dome collapse deposits and their reworked equivalents, prior to the eruption of the TML. The northeast Jones Canyon fault may have partitioned the northernmost transfer basin into two subbasins during deposition of The Relief Peak Formation (see map pattern in Fig. 11B), but it became buried by the Stanislaus Group; however, the fault probably acted as a conduit for the line of andesite plugs that cut the Stanislaus Group on that ridge (Tii, Tia, Tiba; Fig. 11B).

Northeast transfer zone faults of the broad Poison Flat fault zone are exposed on Mineral Mountain, where they were clearly reactivated after deposition of the Stanislaus Group (Fig. 11C). However, Miocene deposits are concentrated along this fault zone (Relief Peak Formation and Stanislaus Group), and were vented from it at two localities (described in the following), so this fault zone had a synvolcanic slip history. The TML is not as thick here as it is in the Sierra Crest graben (<150 m), and it thins to zero at the eastern mapped extent of the Poison Flat fault zone; there, the EVT Tollhouse Flat Member directly overlies the Relief Peak Formation and dips 35° to the west (Fig. 11C), suggesting tilting about a north-south, down-to-the-east fault like those that dominate the range front immediately to the south (Busby et al., 2013b). However, no north-south fault is mapped there (Fig. 11C); this is the least-known area described herein. East of that, the Poison Flat fault zone strikes northeastward into undifferentiated Tertiary volcanic rocks, which we have not mapped; however, this section appears to consists of massive, monotonous debris flow deposits, and the Stanislaus Group strikes into it, suggesting that the valley in between has a north-northwest fault.

Northeast transfer zone faults of Fish Valley Peak form the southern boundary of the range-front transfer zone (Fig. 11C), but because we have not found any Stanislaus Group vents along those faults, we do not include them in the Sierra Crest graben-vent system. For that reason, they are described in detail with synvolcanic faults of the range front at Sonora Pass (Busby et al., 2013b). However, an undated trachydacite lava flow is above the TML in the Fish Valley Peak fault zone (Fig. 11C), in a position similar to the dated trachydacite intrusion and lava flow in the Poison Flat fault zone, so it is possible that future exploration will find a vent or feeder intrusion there. The northeast Fish Valley Peak faults are interpreted to be down-to-the-northwest sinistral oblique normal faults that were rotated ~35° toward the northwest after the TML was deposited, by down-to-the-east slip on the Fish Canyon normal fault (Busby et al., 2013b).

The Disaster Peak–Arnot Peak sector of the Sierra Crest graben differs from the Sonora Pass sector in that it lacks Relief Peak Formation–derived debris avalanche deposits below the TML. We infer that is because there was no Relief Peak Formation on the graben footwalls, because (1) no paleochannel crossed the Sierra Nevada at this latitude, and (2) any Relief Peak Formation that existed in the area was trapped in low-lying transfer zone basins, and therefore could not be shed into the full graben. The only candidate for paleochannel deposits, or pre-TML landslide megablocks, is in the southwest corner of the area mapped in Figure 11, at Lightning Mountain, on the hanging wall of the Arnot Creek fault in the Sierra Crest graben. There, three very small (~100 × 100 m each) outcrops of Valley Springs Formation ignimbrite are below the TML (TVsi; Fig. 11A). The welded ignimbrite is white, with 5%–7% phenocrysts of quartz, sanidine, and biotite, typical of Valley Springs Formation; in contrast, Miocene ignimbrites lack quartz and sanidine, although a Pliocene welded ignimbrite to the north at Ebbetts Pass has these minerals (Busby et al., 2013a). Therefore it seems likely that this ignimbrite is the Valley Springs Formation. The presence of the Valley Springs Formation here is puzzling, because it is far from any paleochannels, which are defined by semicontinuous belts formed of erosional remnants of the Valley Springs Formation. The closest Valley Springs Formation is within the Cataract paleochannel 8 km south (in the Red Peak–Bald Peak area; Fig. 5), and within the paleochannel that passed through Ebbetts Pass (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.) 8 km north of here (see Tvs mapped on Lookout Peak by Keith et al., 1982). A small (~200 × 200 m) outcrop of andesitic debris flow deposits is among the small Valley Springs Formation outcrops, and a much more extensive andesitic debris flow unit is to the north of that at peak 8642′ (Fig. 11A). The basal contact of the TML rises toward these debris flow deposits, from 2438 m on the east side of the TML to 2682 m on the north side of the TML; therefore the TML may have onlapped them, which is why we assign them to the Relief Peak Formation (Trpdf; Fig. 11A). Even if it is the Relief Peak Formation, however, it may not be in situ. Due to their anomalous occurrence, we tentatively suggest that the pre-TML strata on the hanging wall of the Arnot Creek fault are within slide blocks, similar to those well exposed beneath TML at Sonora Pass. We do not know whether any of these rocks match strata on the footwall to the west, because we have not studied those rocks (mapped as undifferentiated volcanic rocks, Tvu; Fig. 11).

All formations and members of the Stanislaus Group are present in the Disaster Peak–Arnot Peak sector of the Sierra Crest graben, except for the Dardanelles Formation, which so far has only been found as a single lava flow and associated intrusions inside and outside the western edge of the graben at Sonora Pass. An intrusion on the south side of Lightning Mountain is a trachybasalt (Busby, Putirka, and Melosh, personal observs.), like the Dardanelles Formation, so it could be related, but it has not been dated to test this correlation. The TML in the Disaster Peak-Arnot Peak segment of the Sierra Crest graben consists of mafic to intermediate lava flows, but compositions here differ by including more andesites and/or basaltic andesite and less trachyandesite and/or trachybasaltic andesite than is typical of lavas at Sonora Pass (Hagan, 2010; Busby, Putirka, and Melosh, personal observs.). As at Sonora Pass, the TML also contains olivine basalt lava flows (Hagan, 2010). The TML contains vent facies deposits on the hanging wall of the Disaster Creek fault (Fig. 11A); these do not outcrop as well as the lava flows, and are interpreted to form a more continuous deposit than the mapped series of outcrops (Tstmlvf, Fig. 11A), shown by a more continuous pattern of red stars (Fig. 11A). We infer that these deposits mark the site of an ~6-km-long fissure controlled by the Disaster Creek fault on the western graben margin, similar to the fissure deposits that are better exposed in the east-facing cliff between Sonora Peak and Stanislaus Peak, controlled by the East Fork Carson fault in the eastern graben margin (described herein). The vent deposits are identical in character, and are not described further here. A small area of TML vent facies is also identified on the east side of the graben, at the head of Murray

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Canyon (Tstmvf; Fig. 11B). The TML is also heavily altered in this area (Tstmla; Fig. 11B), consistent with its position around a vent with probable feeders below.

All members of the EVT are very well represented in the Disaster Peak–Arnot Peak sector of the Sierra Crest graben, in terms of thickness. The Tollhouse Flat Member welded ignimbrite is also preserved as a more continuous sheet than is typical, especially in the eastern part of the graben (see Figs. 11A, 11B, and 12). The Tollhouse Flat Member is also preserved in the transfer zone basin at Mineral Mountain (Fig. 11C). Unusually thick By-Day Member and Upper Member ignimbrites are preserved in the eastern part of the Sierra Crest graben; these are described in detail in Figure 13.

The EVT Lava Flow Member in the Disaster Peak–Arnot Peak segment of the Sierra Crest graben includes basaltic trachyandesite, trachyandesite, and trachydacite lavas, and also has a trachydacite vent facies deposit on the west side of graben (Tselvf; Fig. 11A; geochemistry and modal analyses in Hagan, 2010). The EVT Lava Flow Member appears chaotic where the Pacific Crest Trail crosses it on the ridge between Golden Canyon and Murray Canyon, and a $^{40}Ar/^{39}Ar$ plagioclase age of 11.33 ± 0.07 (sample JHEP-64; Busby et al., 2013a; age data will be available elsewhere) on a latite from that section is clearly too old for Lava Flow Member, because it overlies the 9.54 ± 0.04 Ma Tollhouse Flat Member (Fig. 2A). We infer that the latite sample was taken from a slide block derived from the eastern shoulder of the graben; the alternative is that the plagioclase we dated is xenocrystic; we prefer the former interpretation, because slide blocks of resistant lava flow lithology are common in the Miocene and Pliocene pull-apart basins of the Sierra Crest. For example, another slide block composed of lava flow has been dated nearby, also in eastern part of this graben (to the north), but higher in the section (sample JHEP-70, on the ridge northeast of the head of Murray Canyon; Fig. 11B; Busby et al., 2013a; age data will be available elsewhere). This slide block forms a small (~100 × 100 m) outcrop on the top of a hill, and we mapped it as a lava flow because it has an ~2-m-thick basal breccia that seems continuous all the way around the base of the ~6–8-m-thick outcrop (top eroded). We included it in the Disaster Peak Formation (Tdpl; Fig. 11B) because it overlies debris flow deposits that are on intact (laterally very extensive) Stanislaus Group strata (from base to top, Tollhouse Flat Member of TML, Lava Flow Member of EVT; Fig. 11B); the debris flow deposits and the lava flow must therefore be the Disaster Peak Formation. However, a hornblende $^{40}Ar/^{39}Ar$ age of 11.05 ± 0.33 Ma on the lava flow (Busby et al., 2013a; age data will be available elsewhere) shows that it is too old to be upsection from the Tollhouse Flat Member ignimbrite, which is dated as 9.54 ± 0.04 Ma (Fig. 2A). This lava flow in Disaster Peak Formation must therefore represent a slide block. A similar situation is described for (1) a Relief Peak–aged andesite slide block that is with the Stanislaus Group in the range front at Sonora Pass (Busby et al., 2013b), and (2) an andesite slide block that is ~2 m.y. older than enclosing strata of the Ebbetts Pass volcanic center (described in Busby et al., 2013a; age data will be available elsewhere). Tectonically controlled stratigraphic recycling of resistant lava flow slabs is more common than we first recognized in the field within the Walker Lane pull aparts of the Sonora Pass–Ebbetts Pass region (Busby et al., 2013a; age data will be available elsewhere). The age of the 11.33 ± 0.07 latite landslide block within the EVT Lava Flow Member is the oldest age, by ~1 m.y., that has been obtained on latite in the region (see dates on TML in Fig. 2A). We suspect that future dating in the region may show that, like its chemistry, the age of the TML is more variable than shown in Figure 2A; this is not surprising, now that we know that it vented from multiple localities.

We previously mapped a hornblende biotite two-pyroxene trachydacite in the transfer zone basin at Poison Lake as the Lava Flow Member of the EVT (Hagan, 2010), but herein we define a new member of the EVT, Basal Lava Flow Member, and assign the trachydacite to it (Tseblt, Basal Lava Flow Member trachydacite; Fig. 11C, 11D). This trachydacite intrudes upward through the TML, with vertical flow banding, and also overlies it (Fig. 11C), so the inclusion in the Lava Flow Member seemed reasonable to Hagan (2010) because high-K silicic lavas were previously recognized in that member (Koerner et al., 2009), but there are no silicic lavas in the TML. However, at the locality shown in Figure 11C, the Tollhouse Flat Member does not intervene between the TML and the trachydacite (Fig. 11C), so its assignment to the Lava Flow Member of the EVT (which is above the Tollhouse Flat Member) was tenuous. We now have a hornblende $^{40}Ar/^{39}Ar$ age of 9.94 ± 0.03 Ma on this unit (Busby et al., 2013a; complete age data will be available elsewhere), which shows that it is intermediate in age between the Tollhouse Flat Member (9.54 ± 0.04 Ma) and the youngest age obtained so far on the TML (10.36 ± 0.06 Ma). A similar silicic high-K lava flow has been recognized between the TML and Tollhouse Flat Member at the type section of the Stanislaus Group, and is referred to as the Basal Lava Flow Member of the EVT (Chris Pluhar, 2013, written commun.). We therefore define a new member of the EVT (Fig. 11D), the Basal Lava Flow Member, which overlies the TML, but is distinguished from it by chemistry. We suspect that more Basal Lava Flow Member trachydacites will be discovered through future geochemical and geochronological work. The trachydacite intrusion and lava flow dated here are important for showing that Stanislaus Group magmas vented into a range-front transfer zone basin in this location, and that the TML here was largely ponded within the Sierra Crest graben prior to the onset of high-K explosive volcanism at the Little Walker caldera (shown in Figs. 1 and 15).

A second Stanislaus Group transfer zone basin vent deposit is mapped ~400 m north of Mineral Mountain peak (Tss; Fig. 11C). This is a 10-m-thick pyroclastic surge deposit (Fig. 14), with the distinctive sieve-textured plagioclase laths of the Stanislaus Group. It overlies the TML, and the Tollhouse Flat Member of the EVT is adjacent to it (Tset; Fig. 11C), but not in contact with it, so its age relative to the Tollhouse Flat Member is not known. However, it has lithic clasts that look like the Tollhouse Flat Member (with obvious biotite), so it could be part of the Lava Flow Member of the EVT. A pyroclastic (not sedimentary) origin is indicated by the fact that it is formed of 95% vesicular glass lapilli of uniform composition, and some layers are predominantly accretionary lapilli. Deposition from pyroclastic surge is indicated by cross-bedding, lenticular bedding, wavy bedding, minor scour and fill structures, and good sorting. The proximal nature of the deposit is clear from the presence of 8–10-cm-diameter ballistic fall blocks (Fig. 14D); the cohesive nature of strata deformed by the fall blocks suggests deposition from wet surges, as does the abundance of accretionary lapilli (Fig. 14A). Accidental clasts form ~5% of the pyroclastic surge deposit overall, but are concentrated in layers (Fig. 14D) suggestive of throat-clearing events. The accidental clasts are granitic basement rock, which rarely occurs in Miocene volcanic debris flow and fluvial deposits of the region, supporting the interpretation that the ballistic blocks record throat-clearing episodes in the conduit. The pyroclastic surge section is capped by 2–3 m of material reworked by debris flow. The pyroclastic surge and ballistic fall deposit (Tss; Fig. 11C) is important for showing that the range-front transfer zone basins contain vent deposits for the Stanislaus Group.

In contrast with the Sonora Pass sector of the Sierra Crest graben, where very little of the Disaster Peak Formation is preserved, the Disaster Peak Formation forms a major component of the preserved graben fill in the Disaster

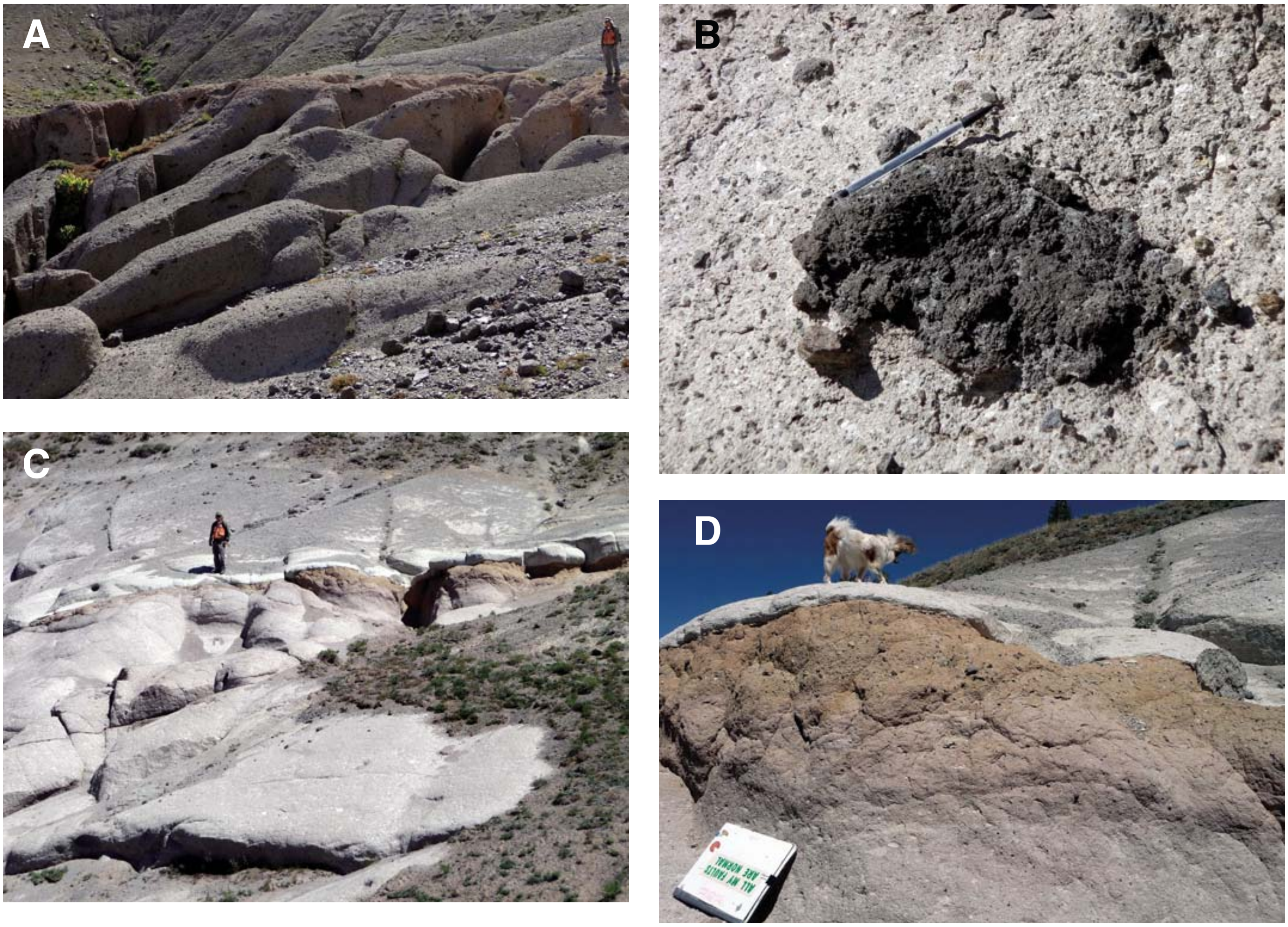

Figure 13. Unusually thick sections of By-Day Member and Upper Member of the Eureka Valley Tuff (EVT), preserved within the northern part of the Sierra Crest graben (Disaster Peak–Arnot Peak segment), on the ridge between Golden Valley and Murray Canyon (Fig. 11B). This section is ~20 km from the inferred source to the south-southeast at the Little Walker caldera. (A) Unusually thick section of the EVT By-Day Member, which commonly only has the basal vitrophyre preserved; in this view, the nonwelded upper part of the ignimbrite is preserved, with vapor phase alteration (pinkish-orange) visible high in the section. Glassy blocks, shown in B, are big enough to be seen from a distance. (B) Close-up of a nonflattened block of glass in the EVT By-Day Member. Delicate surface textures are preserved on the surface of this block. (C) The EVT Upper Member is nonwelded and thus has low preservation potential in the paleochannels, but here in the Sierra Crest graben it forms a thick composite deposit, composed of multiple pyroclastic flow units, with intervening fluvially reworked beds and fall deposits. (D) Close-up of the orange layer (below and to the right of the person in C), which is an incipient paleosol, indicating that some time elapsed between emplacement of the underlying and overlying pyroclastic flow units. The orange layer is overlain by a very white Plinian fall deposit (made entirely of pumice lapilli). The gray rocks above the Plinian fall deposits are pyroclastic flow deposits (nonwelded ignimbrite) and fluvially reworked pyroclastic flow deposits. (E) Crudely cross-bedded interval in EVT Upper Member, overlying the Plinian fall deposits shown in D. The cross-beds appear to be too crude and poorly sorted to represent surge cross-beds; instead they probably record fluvial reworking.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Peak–Arnot Peak sector (as much as 540 m of the preserved 1300 m). The Disaster Peak Formation here consists of andesitic volcanic debris flow and stream-flow deposits, with minor block-and-ash flow tuffs, similar to the Relief Peak Formation but with a very important difference: instead of filling east-west paleochannels, these sediments were transported from south to north along the axis of the Sierra Crest graben (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). Meanwhile, the paleochannels downstream from the Sonora Pass sector of the graben were abandoned; that is, they contain no Disaster Peak Formation (Busby, Andrews, Koerner, Melosh, and Hagan, 2003–2013, personal observs.). We thus infer that the Cataract paleochannel system was beheaded during development of the Sierra Crest graben, and that the drainage system became deranged into the north-south, structurally controlled pattern that persists to this day.

It is relevant that the Sierra Crest graben-vent system remained magmatically active during deposition of the Disaster Peak Formation. Series of small lava flows were emplaced in the Disaster Peak–Arnot Peak sector of the Sierra Crest graben (Tdpl; Fig. 11A, 11B), ranging from andesite to basalt in composition (Busby et al., 2013a). A coarse-grained block-and-ash flow tuff, representing a proximal volcanic deposit, occurs with Disaster Peak Formation debris flow deposits on the south flank of Disaster Peak; this hornblende orthopyroxene andesite yielded an $^{40}Ar/^{39}Ar$ hornblende age of 4.96 ± 0.05 Ma (sample JHEP-55; Busby et al., 2013a; complete age data will be available elsewhere).

Disaster Peak–aged plugs are much more common in the Sierra Crest graben and associated transfer zone basins than they are in unfaulted granitic rock away from these basins (Fig. 11). Intrusions with no geochemical analyses are mapped as mafic or intermediate (Tim, Tii), and where we have geochemical analyses, they are mapped as basalt (Tib), basaltic andesite (Tiba), andesite (Tia), and lesser dacite (Tid) intrusions (geochemistry and modal analyses will be available elsewhere). During this time, a line of plugs was emplaced above the buried Jones Canyon transfer fault (Fig. 11B). The two-pyroxene olivine basalt plug on the top of Disaster Peak (Tib; Fig. 11A, 11B) is partly surrounded by its own basalt ejecta, including red scoria and bombs, so it does not appear to have been greatly eroded since it was emplaced.

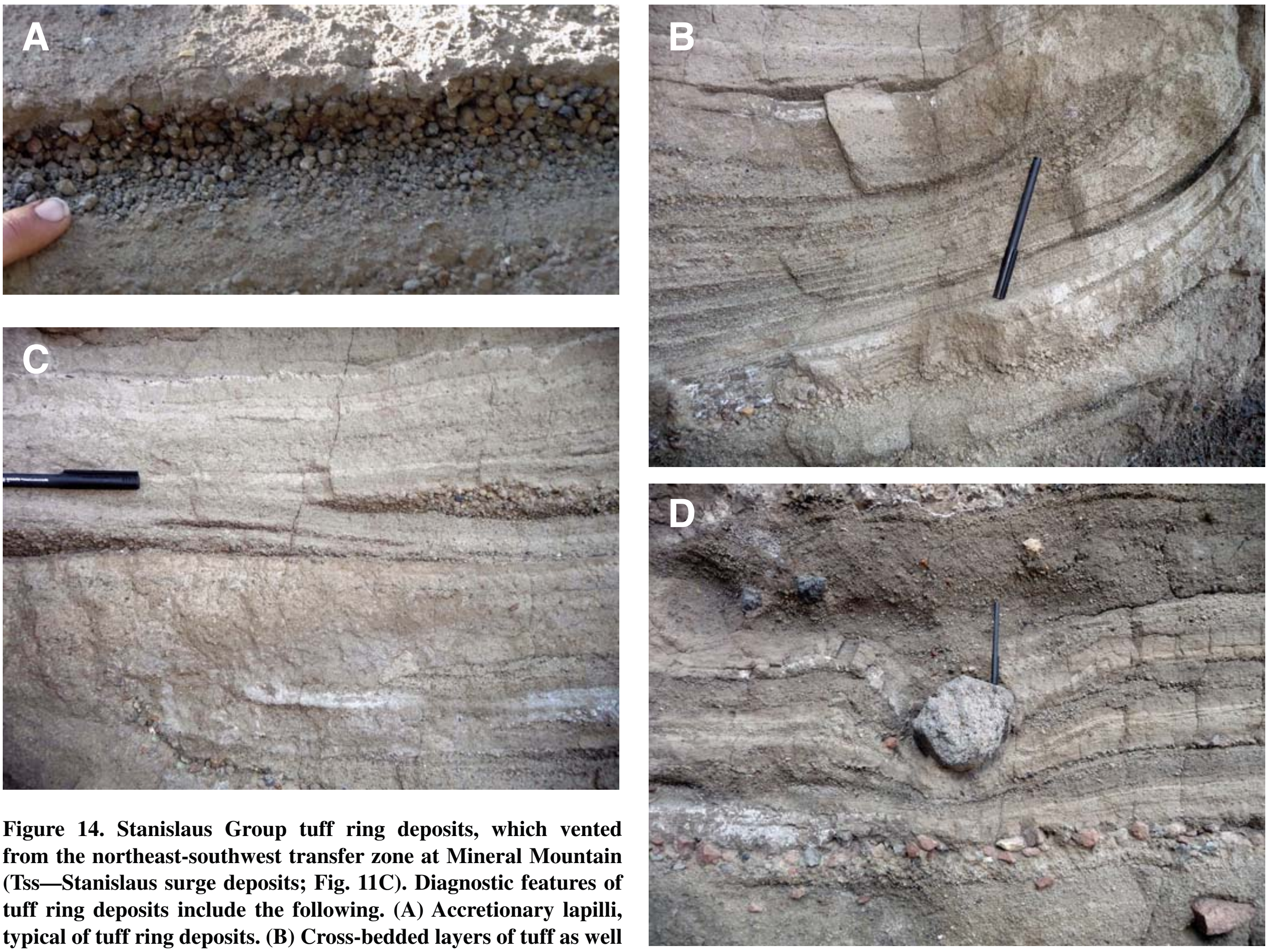

Figure 14. Stanislaus Group tuff ring deposits, which vented from the northeast-southwest transfer zone at Mineral Mountain (Tss—Stanislaus surge deposits; Fig. 11C). Diagnostic features of tuff ring deposits include the following. (A) Accretionary lapilli, typical of tuff ring deposits. (B) Cross-bedded layers of tuff as well as lapilli tuff formed of accretionary lapilli, typical of pyroclastic surge deposits. (C) Lenticular bedding in tuff and accretionary lapilli tuff, typical of pyroclastic surge deposits. (D) Bomb sag formed by ballistic fall, typical of proximal ejecta; the cohesive nature of the deformed beds is typical of tuff ring deposits, which are commonly emplaced in a wet state. This suggests that water was present in the vent, which formed in a graben along the transfer zone.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

It yielded a $^{40}Ar/^{39}Ar$ plagioclase age of 3.69 ± 0.03 Ma (Busby et al., 2013a; complete age data will be available elsewhere), and is thus too young to represent an arc basalt, since the Mendocino triple junction likely was at the latitude of Lake Tahoe at that time (e.g., Cousens et al., 2008); rather, it records exploitation of the Sierra Crest graben by rift magma.

Evidence for ponding of the Stanislaus Group within the Disaster Peak–Arnot Peak sector of the Sierra Crest graben includes the following.

1. The TML does not occur anywhere west of the western boundary of the graben (this work; see also Keith et al., 1982). That is, it does not occur on the footwall of the Disaster Creek fault north of the Arnot Creek fault (section A–A′; Fig. 12), and south of that, it does not occur on the footwall of the Arnot Creek fault (Figs. 11 and 12).

2. The TML is ponded to a thickness of as much as 480 m in the Sierra Crest full graben, similar to its thickness in the Sonora Pass segment of the graben (Figs. 11 and 12).

3. The TML is absent from the footwall of the East Fork Carson fault along the line of cross-section A–A′ (Figs. 11 and 12). It is present on the footwall of the East Fork Carson fault along the line of cross-section B–B′, where its thickness is well constrained by the granite below and the trachydacite that overlies it; it is 150 m thick there, which means that it thins a total of 330 m across the East Fork Carson fault (Fig. 12B).

4. The Tollhouse Flat Member and Lava Flow Member of the EVT occur across the width of the Sierra Crest graben, on the hanging walls of both the Arnot Creek fault and the Disaster Creek fault (Fig. 12), but they do not occur anywhere west of that at this latitude (this work; also see Keith et al., 1982).

5. The maximum thickness of the Lava Flow Member in the north-south Sierra Crest graben (cross-section B–B′) is similar to its thickness in the northeast-southwest transfer zone graben shown in cross-section A–A′, at ~100 m, and it does not occur on the hanging walls of these grabens.

The Disaster Creek fault was clearly reactivated after deposition of the Stanislaus Group, because the Tollhouse Flat Member is offset down to the east on the Disaster Creek fault (Figs. 11A and 12B). This is consistent with the fact that its northern extension, the Nobel Canyon fault, dropped down to the west to accommodate Miocene–Pliocene strata of the Ebbetts Pass volcanic center (Busby et al., 2013a), and was further reactivated to cut the strata of that center (Hagan, 2010), dated by $^{40}Ar/^{39}Ar$ plagioclase as 4.90 ± 0.02 Ma (Busby et al., 2013a; complete age data will be available elsewhere). The range-front faults were also reactivated, because they cut the volcanic rocks.

SUMMARY OF RESULTS FROM MAP DATA ON THE SIERRA CREST INTRA-ARC TRANSTENSIONAL GRABEN-VENT SYSTEM

We use the term Sierra Crest graben-vent system to refer to synvolcanic grabens with fault-controlled vents that erupted ca. 11.5–9 Ma high-K volcanic rocks of the Stanislaus Group. 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 Nevada; 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-to-the-east normal faults on the eastern range front. However, offset before or synchronous with emplacement of the TML is much more difficult to recognize than later offset, and no one has recognized it anywhere. This is because the effects of paleorelief 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. Our detailed findings are summarized in the following.

1. The previously unrecognized Sierra Crest graben-vent complex is formed mainly of an ~28-km-long, ~8–10-km-wide, north-northwest–south-southeast graben along the Sierra Crest (from the Sonora Pass area to the Disaster Peak–Arnot Peak area). The graben-vent complex also includes smaller half-grabens that are along the western edge of the Sonora Pass sector of the Sierra Crest graben (in the Red Peak–Bald Peak area), as well as smaller transfer zone basins that are on the northwest margin of the graben (in the modern range front south of Ebbetts Pass).

2. The large full graben has flat-lying strata; in contrast, the previously recognized down-to-the-east half-grabens on the southeastern range front (not described here, because they do not contain vents) are narrower (~2–4 km), with strata westward tilted as much as 45° (Hagan, 2010; Busby et al., 2013b).

3. The east-dipping Kennedy Creek fault on the southwest margin of the Sierra Crest graben at Sonora Pass must have slipped >400 m before ca. 10 Ma, in order to pond the TML on what is now the Leavitt Peak–Night Cap Peak ridge. Similarly, the newly recognized west-dipping East Fork Carson fault on the northeast margin of the Sierra Crest graben at Sonora Pass contains as much as 730 m of debris avalanche deposits older than the TML on its footwall, while the TML overlies granite on its hanging wall. The original difference in thickness of footwall TML versus ponded TML across the East Fork Carson fault cannot be calculated, because the top is eroded in both places. However, the offset to accommodate the Relief Peak Formation landslide deposits is of a magnitude just as great as that of faulting synchronous with or later than emplacement of the TML on the modern Sierran range front (Busby et al., 2013b).

4. The Sierra Crest graben at Sonora Pass has earlier (TML) high-K lava flow vents, feeder dikes, and vent-proximal deposits inside its eastern margin, and later (Lava Flow Member and Dardanelles Formation) high-K lava flow vents, feeder dikes, and vent-proximal deposits along its western side. Olivine basalt lava flows and vent deposits are interstratified with both TML and Lava Flow Member high-K lava flows.

5. We infer that a buried strand of the Seven Pines fault formed an important northwest boundary to the segment of the Sierra Crest graben described herein, but it is not exposed because it was not reactivated postvolcanically, due to stitching by Lava Flow Member and Dardanelles Formation intrusions and lavas.

6. Fault-controlled vents for the TML and Dardanelles Formation extend 3 km westward from the edge of the Sierra Crest graben, within the Cataract paleochannel, where some eruptive products record explosive interaction with water or groundwater. The Relief Peak Formation thickens abruptly onto western, downthrown blocks of faults west of the Sierra Crest graben, with estimated pre-TML vertical slip of 65 m on the Bald Peak fault, and an uncertain amount on the Red Peak fault. In addition, the eastern Chipmunk Flat fault, mapped just inside the western boundary of the Sierra Crest graben, shows 90 m of vertical down-to-the-west offset predating the TML. These offsets are trivial compared to the offset required to emplace as much as 730 m of Relief Peak Formation–derived debris avalanche in the Sierra Crest graben before eruption of TML, which is ponded to an additional thickness of as much as 400 m. However, they are significant for demonstrating faulting predating emplacement of the TML.

7. The Saint Mary’s Pass fault, which is 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 increases southward, from ~70 m near Sonora Pass to ~130 m near Sardine Falls. The Saint Mary's Pass fault is important because it has a piercing point that crosses it (the axis of a narrow paleochannel filled with Relief Peak Formation, described in the following), and piercing points are rare, making it difficult to demonstrate a strike-slip component on faults.

8. Kinematic indicators and apparent offsets indicate a right-slip component on the north-northwest normal faults. These include Riedel shears and obliquely plunging lineations on the Saint 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 Saint 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.

9. Kinematic indicators and apparent offsets indicate a sinistral component on the northeast normal faults; these include apparent sinistral offset of a vertical contact between TML vent facies and lavas on Stanislaus Peak fault, and kinematic indicators along the Sonora Pass fault zone. This is consistent with a sinistral oblique normal faulting on northeast faults on the range front at Sonora Pass (Fish Valley Peak fault zone, discussed briefly in the preceding; Busby et al., 2013b).

10. The map-scale pattern of the interaction between north-northwest and northeast faults is indicative of dextral transtension, because the northeast faults appear to accommodate right steps along in the north-northwest faults. So, although we have no kinematic indicators on the two northeast-trending faults on the western margin of the Sierra Crest graben (in Deadman Creek and the next creek to the north; Fig. 3), the fault pattern strongly suggests that they have a sinistral component. A similar right step on the eastern margin of the Sierra Crest graben (Fig. 5), accommodated by the Sonora Pass fault zone (Fig. 6), has kinematic indicators consistent with the interpretation of sinistral motion. Similar patterns exist on the range front at Sonora Pass (Busby et al., 2013b). The regional-scale pattern of Walker Lane belt transtensional faults was discussed in Busby et al. (2010).

11. Further dating and paleomagnetic work are required to determine how much time is covered by the TML, now that we know it vented in several places, and that a slide block of latite is ~1 m.y. older than in situ latite.

12. The vent system for the TML is extremely unusual, compared to other intermediate-composition volcanic centers. It includes 6–8-km-long scoria ramparts that form the surficial expression of fissures. This is generally considered typical of basalt eruptions, in particular flood basalt eruptions, not andesite eruptions. Although basalts are present in the TML, they form a small proportion of it (less than a few percent). The volume of the TML is also unusual for intermediate-composition lavas. The total minimum volume is estimated as 199 km^3 (Supplemental File 1 [see footnote 1]), but the original volume may have been twice that.

COMPARISON WITH OTHER INTERMEDIATE-COMPOSITION INTRA-ARC GRABEN-VENT SYSTEMS

We are aware of only one close analog for the Sierra Crest graben-vent system, and that is the Late Miocene to middle Pleistocene Hiatsu volcanic field of southern Kyushu, Japan (Nago et al., 1995, 1999; Miyoshi et al., 2010). There, so-called flood andesite lavas are ponded to an average thickness of 400 m in the Hiatsu volcano-tectonic depression (the same as the thickness of graben-ponded TML in the Sierra Nevada). Like the Sierra Crest graben-vent complex, topographic inversion has now made the Hiatsu graben fill into plateaus. Like the Sierra Crest graben-vent system, the lavas include high-K as well as low-K andesite, and minor basalt; like it, these were erupted from fissure vents or lines of vents (not individual centers), which moved around the volcano-tectonic depression over time. The Hiatsu volcano-tectonic depression covers about twice as much area as the exposed parts of the Sierra Crest graben-vent complex, with more than twice the estimated volume (~560 km^3); however, if the Sierra Crest graben continues under the modern Bridgeport basin, as we suspect it must (for reasons given above), the size and volume would be the same.

Another possible analog for the Sierra Crest graben-vent complex is the younger than 780 ka Indian Heaven volcanic field, described by Hildreth (2007). The analogy is not as close as that of the Hiatsu volcanic field, because (1) it is more mafic: 80% of the field is true basalt, and the rest is basaltic andesite, with sparse andesite erupted from several vents along the crest; and (2) its volume is about one-third our minimum estimate for the TML alone. However, its surface features (only part exposed) may form a close analogy to the Sierra Crest graben-vent system. Approximately one-half of the vents (including the most productive ones) are aligned more or less parallel to the arc, forming a 30-km-long constructional highland composed of coalescing mafic shields and a scattering of cinder cones. Presumably, if deeper structural levels were exposed, one would see fault-controlled dikes and fissure vent deposits similar to those exposed in the Sierra Crest graben-vent system.

Neither the Hiatsu volcanic field nor the Indian Heaven volcanic field are strictly analogous with the Sierra Crest graben-vent system in terms of tectonic setting; both are within in an arc, but neither show evidence for transtensional rifting, which is a key factor in generation of the high-K melt pulse of the Sierra Crest graben-vent complex. It has previously been inferred that low-degree partial melts of mantle lithosphere were trapped beneath a thick lithospheric column, and were tapped by the inception of trantensional stresses, recording the birth of the Walker Lane plate boundary (Putirka and Busby, 2007).

The geologic aspect of continental arcs has been neglected relative to geochemical and geophysical aspects (Hildreth, 2007). The perception still exists that a magmatic arc consists of "one or two single-file chains of evenly spaced stratovolcanoes" (Hildreth, 2007, p. 1), when in fact the best studied continental arc in the world, the Quaternary Cascades, includes more than 2300 volcanoes, with fewer than 30 stratovolcanoes (Hildreth, 2007). Although we can find only one very close analog to the Sierra Crest graben-vent system, we hope that our study alerts others to the necessity of making extremely detailed volcanic lithofacies maps in order to understand the true geologic complexity of arc systems.

REGIONAL IMPLICATIONS

The structure of the Miocene Sierra Crest intra-arc transtensional graben-vent system is very similar to that of the transtensional rift volcanic field in the Long Valley region (Bursik, 2009; Riley et al., 2012); there are further similarities in that both fields developed calderas of similar and size and shape, in similar structural settings (Fig. 15). We infer that the Sierra Crest graben-vent system formed at the leading tip of Walker Lane transtension, which followed the northward migration of the Mendocino Triple junction; further northward propagation resulted in the shut-down of arc magmatism at Sonora Pass, and development of a slightly younger arc pull-apart basin and large volcanic center to the north at Ebbetts Pass (Fig. 15; also see Busby et al., 2010, 2013). Ancient east-west Nevadaplano paleochannels were beheaded, and the drainage system became deranged by the Walker Lane faults (Fig. 15).

The importance of Walker Lane transtension has only recently become recognized in the eastern Sierra Nevada. Previous models called for progressive westward encroachment of Basin and Range extension into the eastern

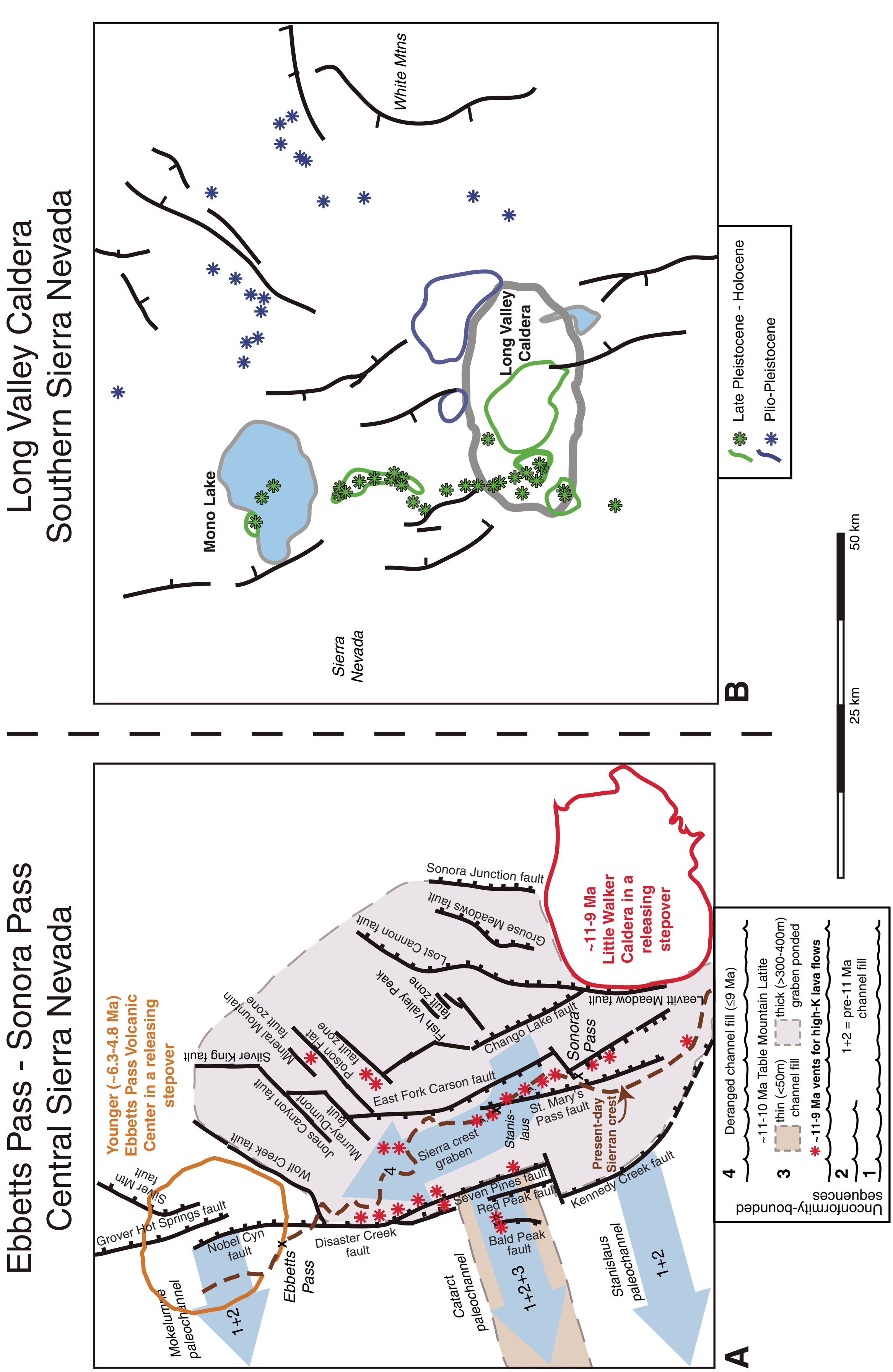
Ebbetts Pass - Sonora Pass
Central Sierra Nevada
A
Younger (~6.3-4.8 Ma) Ebbetts Pass Volcanic Center in a releasing stepover
~11-9 Ma Little Walker Caldera in a releasing stepover
Sonora Junction fault
Grouse Meadows fault
Lost Cannon fault
Fish Valley Peak fault zone
Chango Lake fault
Leavitt Meadow fault
Sonora Pass
Silver King fault
Mineral Mountain fault zone
Poison Flat fault zone
East Fork Carson fault
Jones Canyon fault
Murray-Dumont fault
Wolf Creek fault
Silver Mtn fault
Grover Hot Springs fault
Nobel Cyn fault
Sierra crest graben
Stanislaus
St. Mary's Pass fault
Present-day Sierran crest
Seven Pines fault
Red Peak fault
Kennedy Creek fault
Disaster Creek fault
Bald Peak fault
Ebbetts Pass
Mokelumne paleochannel
Cataract paleochannel
Stanislaus paleochannel
1+2
1+2+3
4
Unconformity-bounded sequences
4 Deranged channel fill (≤9 Ma)
3 ~11-10 Ma Table Mountain Latite
thin (<50m) channel fill
thick (>300-400m) graben ponded
~11-9 Ma vents for high-K lava flows
2
1
1+2 = pre-11 Ma channel fill
Long Valley Caldera
Southern Sierra Nevada
B
White Mtns
Mono Lake
Long Valley Caldera
Sierra Nevada
Late Pleistocene - Holocene
Plio-Pleistocene
25 km
50 km

Figure 15.

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

Figure 15. (A) The Sierra Crest graben-vent system (ca. 11.5–9 Ma), ancestral Cascades arc (this study), and (B) the Long Valley rift volcanic field shown at same scale for comparison (modified from Bursik, 2009; also see Riley et al., 2012). Synvolcanic faults for the Stanislaus Group (see stratigraphy in Fig. 2A) are shown in A. The lavender area shows the region of ponded trachyandesite and trachybasaltic andesite flood lavas of the Table Mountain Latite. The Lava Flow Member of the Eureka Valley Tuff (EVT) (which includes trachydacite as well as trachyandesite lava) is also ponded in some of these grabens. Vents (red stars) occur mainly as fault-controlled fissures, with minor point sources. These vents are in the approximately north-south Sierra Crest full graben, in approximately north-south half-grabens that affected the Cataract paleochannel on the west (Bald Peak–Red Peak area), and in northeast-southwest transfer zone faults and basins along the northeast boundary of the graben (Poison Flat–Mineral Mountain area). Note the position of the modern Sierra Nevada crest; most fault reactivation since 9 Ma has occurred to the east of the crest, on the modern range front, except for Miocene–Pliocene reactivation of the Disaster Creek fault during development of the Ebbetts Pass volcanic center. We have found no high-K vents associated with range-front faults along the southeast side of the Sierra Crest vent-graben system (e.g., Chango Lake, Leavitt Meadows, Lost Cannon), but half of the slip on these faults occurred before or during deposition of the Table Mountain Latite (Busby et al., 2013b). This system of faults steps right in a releasing stepover, like that which controls the position of the Long Valley caldera (B); we infer that the culminating silicic explosive eruptions at the Little Walker caldera (EVT) formed under a similar transtensional strain regime, but in the upper plate of a subduction zone. Arc magmatism at Sonora Pass was shut off as the leading edge Walker Lane transtension migrated northward, to the Ebbetts Pass region, where a previously unrecognized Late Miocene–Pliocene volcanic center formed within a pull-apart basin (Busby, 2011; Busby et al., 2013a). This northward migration is a direct response to northward migration of the Mendocino triple junction, which has caused the progressive northward shut-off of the Cascades arc, to its present-day southernmost position at Lassen (Busby, 2011; Busby et al., 2013a). Also shown are approximately east-west paleochannels (blue arrows) of the Nevadaplano (see text). Sequences 1 and 2 (Valley Springs Formation and Relief Peak Formation; Fig. 2A) define these paleochannels. A small volume of the sequence 3 (Stanislaus Group) lavas and pyroclastic flows escaped the Sierra Crest graben and flowed into the Cataract paleochannel, but the other paleochannels were beheaded. Sequence 4 (Disaster Peak Formation) volcaniclastics and lavas were entirely diverted into the new north-northwest–south-southeast structural grain, which controls the river valleys of the Walker Lane belt east of the modern Sierra Nevada crest to the present day.

Sierra Nevada, arriving ca. 3–4 Ma, preceded by a thermal pulse associated with arc magmatism (Surpless et al., 2002). Furthermore, Faulds and Henry (2008) did not consider the Long Valley–Mono Basin–Tahoe graben region to be part of the Walker Lane belt. However, discovery of the active strike-slip Polaris fault near Truckee, California, places the Tahoe graben within the Walker Lane belt (Hunter et al., 2011). Similarly (see Fig. 15), the Long Valley volcanic field is now widely considered to be trantensional. The transtensional setting of the Sierra Crest graben-vent system, and its relationship to the Little Walker caldera, will be discussed in more detail elsewhere (Busby et al., 2013b). A plate-margin scale model for siting of large arc and rift volcanic centers at major stepovers in the Walker Lane belt from ca. 12 Ma to present will be presented elsewhere.

CONCLUSIONS

Preservation of the vast majority of the Miocene arc volcanic-volcaniclastic rocks along the central Sierra Nevada crest and its range front was accommodated by syndepositional faulting, not by one or more paleochannels, as assumed previously. North-northwest normal faults (with a dextral component of slip) and northeast normal faults (with a sinistral component of slip) record dextral transtension, beginning by 10.6 Ma (the age of oldest dated in situ TML) or by 11.5 Ma (the date on a landslide block of latite).

We have shown that previously unrecognized faults in the Sierra Crest graben and associated range-front transfer zone controlled the positions of vents for effusive rocks of the Stanislaus Group. These, together with faults of the range front at Sonora Pass that ponded the volcanic rocks but were not involved in their eruption (Busby et al., 2013b), formed a major magmatic-tectonic structure within the axis of the ancestral Cascades arc, under a Walker Lane transtensional strain regime. Vents in the volcano-tectonic depression consist dominantly of fissures, unusual for an intermediate-composition volcanism; furthermore, the volumes are unusually high for effusive eruptions of that composition. We therefore refer to the rocks as flood andesites. The Sierra Crest graben-vent complex is a magmatic-tectonic structure that is similar in scale to Quaternary volcanic fields in the Cascades arc and the Long Valley rift volcanic field, but it is exposed at a structural level that has allowed us to herein demonstrate the relations between faults, conduits, and basin fill. Growth of this magmatic-tectonic structure culminated in the development of the Little Walker caldera, in a structural setting very similar to the Long Valley caldera in the Long Valley volcanic field, as discussed further by Busby et al (2013b).

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants EAR-01252 (to Busby, Gans, and Skilling), EAR-0711276 (to Putirka and Busby), and EAR-0711181 (to Busby), U.S. Geological Survey EDMAP program awards 06HQA061 and 09HQPA0004 (to Busby), and by the University of California Santa Barbara (UCSB) Academic Senate (Busby).

Field assistance was particularly important, due to the ruggedness and remoteness of the area; we thank UCSB undergraduates Maia Davis, Megan Gambs, Carolyn Gorny, Eiko Kitao, and Philip Linder; UCSB graduate students Adrienne Kentner and Jessica Thompson; and University of California Santa Cruz graduate Greg Martin. We also thank Chip Hagan and Senator Kay Hagan for field assistance and the UCSB summer field class of 2006 for their input into this mapping.

We are also grateful to Matt Bloom, owner of the Kennedy Meadows Pack Station, for his generous support of our work. Many times he picked up a sack of rocks for us *gratis* on his way out from a commercial trip, and he cut us many financial breaks on hauling our supplies into remote areas. We also thank his cowboys for their patience in helping us locate suitable campsites in remote off-trail areas. Busby thanks Charles Rogers at Rogue City College for the ride in his private plane so that she could take the oblique air photos presented here.

We also thank David Wagner (California Geological Survey) for encouraging Busby to begin work in Cenozoic rocks of the Sierra, and for his many discussions with us at all stages of the work; Art Sylvester for serving on the thesis committees of Koerner and Hagan; and Keith Putirka, Chris Pluhar, David John, Jason Saleeby, Chris Henry, George Bergantz, Burt Slemmons, Garniss Curtis, John Wakabayashi, Jim Faulds, Ed DuBray, John Platte, Ellen Platzman, 2010 GSA Penrose conference participants, and 2003 Volcanological Society of Sacramento field trip participants for discussions in the office and in the field.

We thank formal reviewer David John for his thorough analysis of the paper, which helped Busby substantially improve its presentation and interpretations, and we thank Elizabeth Miller for her formal review,

Geosphere, published online on 26 June 2013 as doi:10.1130/GES00670.1

which prompted Busby to better place the results in a regional framework.

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

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