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New evidence for alternating effusive and explosive eruptions from the type section of the Stanislaus Group in the 'Cataract' palaeocanyon, central Sierra Nevada

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High-K volcanic rocks of the Stanislaus Group record magmatic events that occurred when the Sierra Nevada microplate began to calve off from the western edge of the Nevadaplano at 10–9 Ma. Despite the fact that these rocks have been studied in the Sierra Nevada for 120 years, their stratigraphy is not well known, because they were largely deposited in a complicated palaeocanyon network that drained the Nevadaplano and are preserved on high peaks in roadless areas. We present new 1:6000 scale mapping and a detailed measured section in the Bald Peak–Red Peak area of the Sonora Pass, in the upper reach of the 'Cataract' palaeocanyon, or palaeo-Stanislaus river. The Bald Peak–Red Peak area was proposed as the type section for the Stanislaus Group in 1953 but had not been mapped or measured in sufficient detail to demonstrate stratigraphic relations. Our work demonstrates the following stratigraphy (from base to top): (1) Table Mountain Latite (TML) trachyandesite (latite) and basaltic trachyandesite (shoshonite) lava flows, with phenocrystic clinopyroxene and skeletal plagioclase and groundmass olivine, and minor olivine basalt and basaltic andesite lava flows; (2) Tollhouse Flat Member of the Eureka Valley Tuff (EVT) welded ignimbrite, with abundant phenocrystic biotite; (3) a single trachydacite lava flow with phenocrystic amphibole, referred to here as the Lava Flow Member of the EVT; (4) By-Day Member of the EVT welded ignimbrite, which lacks phenocrystic biotite; (5) Upper Member of the EVT, consisting of unwelded ignimbrite; and (6) a single, very thick (60 m) aphyric basaltic trachyandesite (shoshonite) lava flow that we assign to the Dardanelles Formation. Our work confirms for the first time that the Dardanelles Formation exists as a unit that overlies all members of the EVT, and that its geochemistry is the same as that of the TML in the type section. Our documentation of a trachydacite lava flow within the EVT in the central Sierra Nevada shows that widespread effusive volcanism alternated with the explosive volcanism, rather than merely preceding and following it, and that magmas of trachydacitic composition were erupted as lavas as well as pyroclastic flows. The preservation of all formations and members of the Stanislaus Group in the 'Cataract' channel suggests that it was an important palaeogeomorphic feature.

Keywords: Sierra Nevada; high-K magmatism; Walker Lane

Introduction

The Stanislaus Group of the central Sierra Nevada consists of voluminous, widespread high-K volcanic rocks interpreted to record the birth of the Sierra Nevada microplate through transtensional faulting at about 11–9 Ma (Busby and Putirka 2009). The Stanislaus Group consists of high-K lava flows and pyroclastic flows that were likely erupted from

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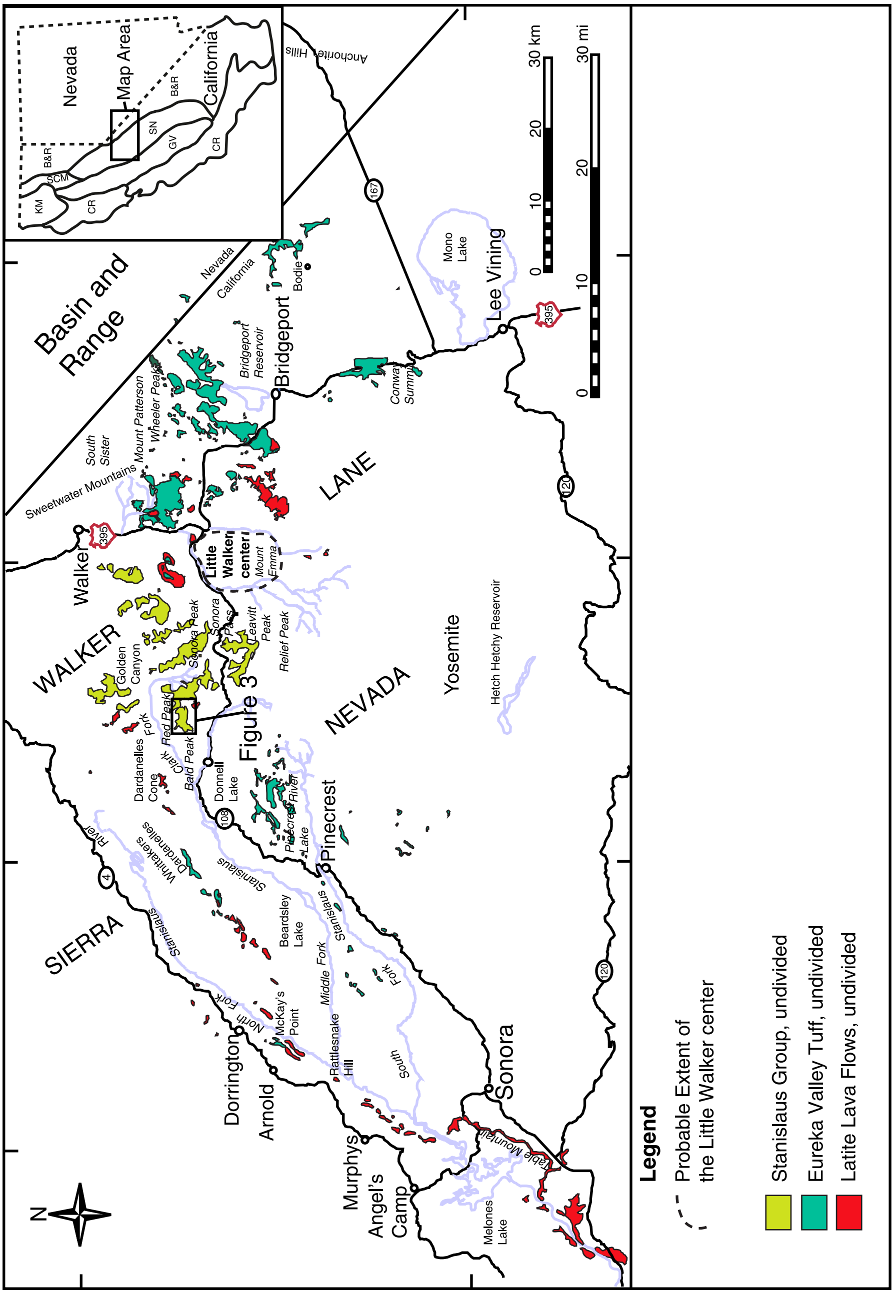
the Little Walker Center, 8 km east of the present-day Sierran crest, and flowed mainly westwards down a palaeochannel/palaeocanyon system cut into Mesozoic granitic and metamorphic basement, towards the Central Valley (Figure 1; Ransome 1898; Lindgren 1911; Slemmons 1953; Curtis 1954; Garside *et al.* 2005; King *et al.* 2007; Busby *et al.* 2008a; Busby and Putirka 2009; Gorny *et al.* 2009). Despite the fact that these high-K volcanic rocks have been studied for 120 years, their stratigraphy remains poorly understood, partly due to the difficulty of access in roadless wilderness areas. For example, Slemmons (1966) named the Bald Peak–Red Peak area of the Sierra Nevada high country as the type section for the Stanislaus Group, but due to its 'relative inaccessibility', Noble *et al.* (1974) proposed a reference section in the Sweetwater Mountains along Highway 395 (Figure 1). The stratigraphy of these rocks is also poorly understood because they were deposited in a palaeoriver canyon system where erosion took place between eruptions. It is also likely that different lava flows or pyroclastic flows followed different parts of the palaeocanyon system.

This paper focuses on the stratigraphy along a segment of the 'Cataract palaeochannel' of Ransome (1898) and Lindgren (1911). The 'Cataract palaeochannel' is a palaeoriver canyon that roughly coincides with the modern Stanislaus River along much of its length (Figure 1), so it was referred to as the palaeo-Stanislaus River by King *et al.* (2007). Our new geologic mapping of a segment in the upper reach of this palaeoriver canyon (Figures 2 and 3) contributes to an understanding of the palaeomorphology of the western edge of the Nevadaplano, by showing that all formations and members of the Stanislaus Group are preserved within it (Figure 4). The study area thus preserves the most complete stratigraphic section through the Stanislaus Group that has been recognized within the Sierra Nevada (Figure 5). This complete section records alternating effusive and explosive volcanism, including (from base to top): basaltic to trachyandesitic effusive volcanism (including shoshonite and latite lava flows; Table Mountain Latite (TML)); trachydacitic explosive and effusive volcanism (ignimbrite and Lava Flow Member of the Eureka Valley Tuff (EVT)); and basaltic trachyandesite effusive volcanism (i.e. shoshonitic; Dardanelles Formation). This section therefore provides a relatively complete and complex record of magmatic and eruptive processes that operated at the Little Walker Center, over a period of at least a million years, when the Sierra Nevada microplate began to calve off from the western edge of the Nevadaplano.

Previous stratigraphic work

High-K volcanic rocks of the central Sierra Nevada were first recognized in 1898 by Ransome, who described latite lava flows (TML) overlain by 'biotite augite latite', in turn overlain by the Dardanelles Flow (Figure 5(a)). The 'biotite augite latite' was later recognized as welded and unwelded ash-flow tuffs (ignimbrites) by Slemmons (1966), who referred to it as the Eureka Valley Member of the Stanislaus Formation (Figure 5(a)). Slemmons (1966) grouped all the high-K volcanic rocks (TML, EVT, and Dardanelles Flow) into the Stanislaus Formation, and designated the Bald Peak–Red Peak area as the type section, although a measured section was not made of the type section. Even though Slemmons (1966) reported latite lava flows within the Eureka Valley Member in the type section, their exact location was not identified, and later reports were not made of them in the central Sierra. Noble *et al.* (1974) identified three distinct ignimbrites within the Eureka Valley Member and they raised it to formational status, the EVT, subdivided into the Tollhouse Flat, By-Day, and Upper members (Figure 5(a)). This subdivision required elevation of the Stanislaus Formation to group status (Figure 5(a); Noble *et al.* 1974).


Basin and Range
Nevada
California
Map Area
B&R
SCM
KM
CR
SN
GV
Anchorite Hills
Bodie
Bridgeport
Bridgeport Reservoir
Conway Summit
Mono Lake
Lee Vining
30 km
30 mi
0
10
20
Sweetwater Mountains
South Sister
Mount Patterson
Wheeler Peak
LANE
Little Walker center
Mount Emma
Walker
WALKER
Golden Canyon
Sonora Peak
Sonora Pass
Leavitt Peak
Relief Peak
Yosemite
Hetch Hetchy Reservoir
NEVADA
Figure 3
Red Peak
Bald Peak
Clark Fork
Dardanelles Cone
Donnell Lake
Pinecrest Lake
Pinecrest
Whittakers Dardanelles
Stanislaus
River
SIERRA
Beardsley Lake
Middle Fork
North Fork
South
McKay's Point
Rattlesnake Hill
Dorrington
Arnold
Murphys
Angel's Camp
Sonora
Table Mountain
Melones Lake
119°
119.5°
120°
120.5°W
38.5°
38°N
N
Legend
Probable Extent of the Little Walker center
Stanislaus Group, undivided
Eureka Valley Tuff, undivided
Latite Lava Flows, undivided

Because of the difficulty of access to the type section, a reference section was proposed to the east (~20 km) of the Sierra Nevada in the Sweetwater Mountains, 6 km east of highway 395 and north of the Little Walker Center (Figure 1; Noble *et al.* 1974).

For the past 35 years, the stratigraphy of the Stanislaus Group in the central Sierra has been portrayed as a section of quartz latite ignimbrite (EVT members) sandwiched between latite lava flows below and above (the TML and the Dardanelles Formation), as shown in Figure 5(a) (Noble *et al.* 1974). The reference section does not include the Dardanelles Formation (King *et al.* 2007), nor had the Dardanelles Formation been found to rest upon any strata younger than the basal member of the EVT (the Tollhouse Flat Member; Figure 5(b)). Thus, before our study, it had not been proven that the Dardanelles Formation is younger than all of the units of the EVT Formation. When Hagan *et al.* (2008) discovered a latite lava flow sandwiched between the Tollhouse Flat and Upper members of the EVT, they questioned the existence of the Dardanelles Formation, and suggested it was actually a member of the EVT. In their interpretation, pyroclastic flow eruptions alternated with, but outlasted, the lava flow eruptions. Our study demonstrates that the high-K pulse of magmatism ended with the eruption of an aphyric basaltic trachyandesite lava flow.

As is common in all volcanic terranes, the volcanic stratigraphy is more complicated in and around the Little Walker eruptive centre, due to the emplacement of intrusions and aerially restricted eruptive units. According to Priest (1979), the Little Walker Center has latite lava flows that lie between the Tollhouse Flat and By-Day members of the EVT, and Brem (1977) reported a latite lava flow in the same stratigraphic position in another locality (the Sweetwater Mountains), calling it the 'Latite Flow Member' of the EVT. The new magnetostratigraphic work of Pluhar *et al.* (2009) shows that this member consists of at least two lava flows, because it has normal polarity at one stratigraphic section, and reversed polarity at another stratigraphic section. Moreover, as discussed below, the lava flow we recognized within the EVT is more silicic than the latite lava flows Pluhar *et al.* (2009) describe. Therefore, we cannot follow Brem's (1977) nomenclature for the lava flow between the Tollhouse Flat and By-Day members (Figure 5(b)). In an effort to alter the nomenclature established by previous literature as little as possible, we refer to this unit as the Lava Flow Member of the EVT, dropping the word 'Latite' from its name. Our newly-defined Lava Flow Member of the EVT thus consists of one trachydacite lava flow at the type locality (described here; Figure 7) and at least two trachyandesite (i.e. latite) lava flows outside the study area (Pluhar *et al.* 2009). We introduce this revised nomenclature with the caveat that it will have to be abandoned if more lava flows are found higher in the section (i.e. between the By-Day and Upper members). For example, in the Little Walker Center, Priest (1979) reported 150 m (500 ft) of biotite–quartz–latite lava flows below the Upper Member at Fales Hot Springs. Priest (1979) suggested that the By-Day Member may underlie the biotite–quartz–latite lava flows, but this was based on the presence of float there. Furthermore, it is unclear from the description whether the biotite quartz latites are lava flows or intrusion(s). In any event, the Fales Hot Springs unit appears to be restricted to the Little Walker Center and is therefore not important to the

Figure 1. Distribution of high-K volcanic rocks of the central Sierra Nevada (Stanislaus Group), modified from King *et al.* (2007). Inset shows physiographic setting: B&R, Basin and Range; CR, Coast Ranges; GV, Great Valley; KM, Klamath Mountains; SCM, Southern Cascade Mountains; SN, Sierra Nevada.

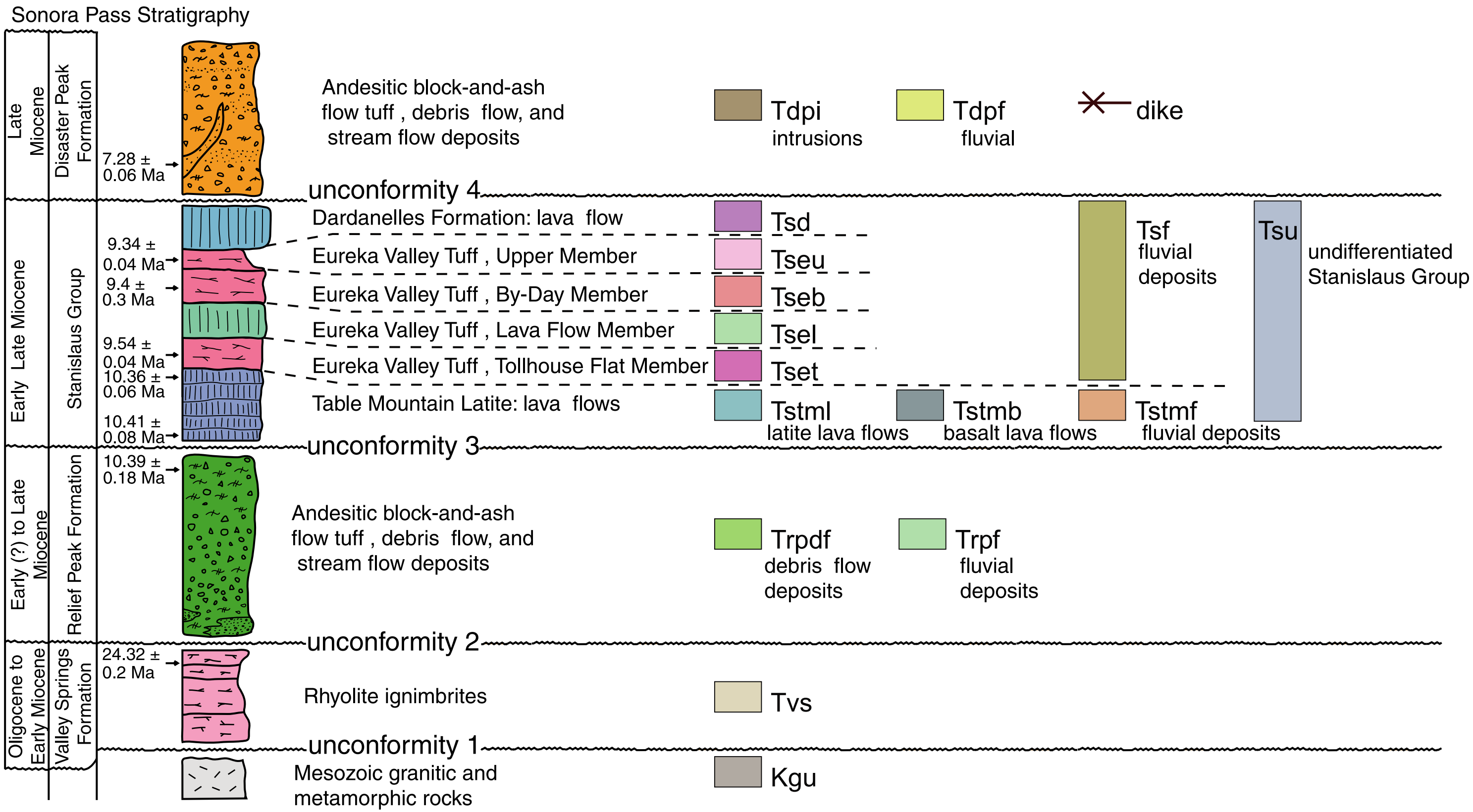
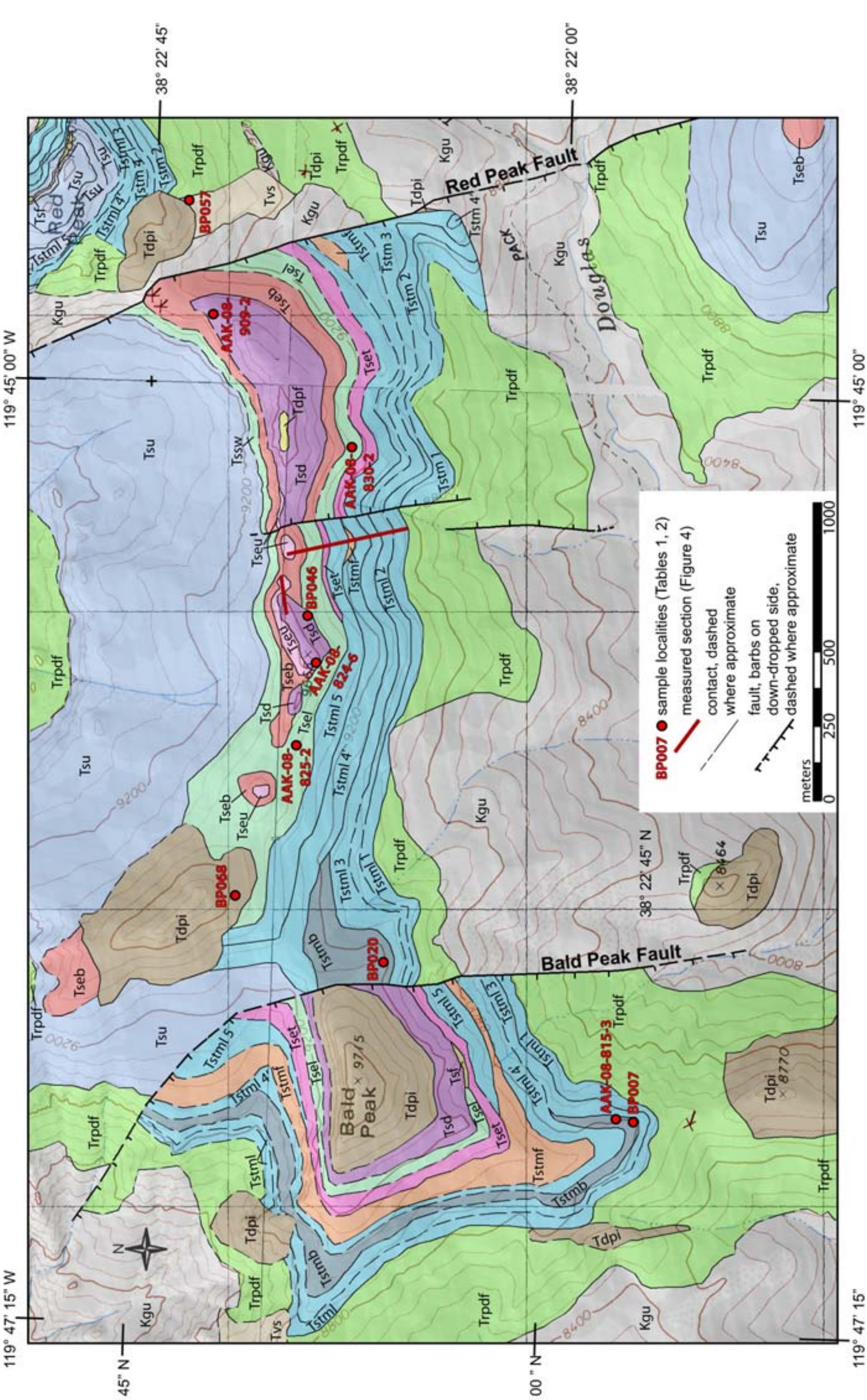


Figure 2. Stratigraphy of volcanic and volcaniclastic rocks in the Sonora Pass region of the central Sierra Nevada, modified from Busby *et al.* (2008b). Relative thicknesses of units are extremely variable and are not shown to scale. Age data (recalculated from Busby *et al.* 2008b) are summarized in Table 1. Figure 3 map units are depicted on the right side of the diagram. Formations are divided by lithofacies wherever possible.


Red Peak Fault
Bald Peak Fault
Bald Peak
BP007 sample localities (Tables 1, 2)
measured section (Figure 4)
contact, dashed where approximate
fault, barbs on down-dropped side, dashed where approximate
meters
0 250 500 1000
119° 45' 00" W
119° 47' 15" W
38° 22' 45" N
38° 22' 00" N
38° 22' 45"
38° 22' 00"
119° 45' 00"
119° 47' 15"
BP057
BP068
BP046
BP020
AAK-08-909-2
AAK-08-830-2
AAK-08-824-6
AAK-08-825-2
AAK-08-815-3

regional stratigraphy. A complete summary of previous stratigraphic work and new results from the region in and around the Little Walker Center are given in Pluhar *et al.* (2009).

We find that the central Sierran palaeocanyon fill contains a trachydacite lava flow within the EVT, between the lower two members (i.e. the Tollhouse Flat and By-Day members), and a basaltic trachyandesite lava flow on top of the Upper Member of the EVT (Figure 5(b)); we describe both units so that they can be recognized elsewhere. The high-K pulse of volcanism initiated with effusive volcanism (i.e. TML), then alternated between effusive and explosive (i.e. EVT) eruptions, and finally ceased with an effusive eruption (i.e. Dardanelles Fm.). We also present new geochemical data on these units, which show that the units are all similar in being high in K_2O, but show a large range of silica content.

Structural and stratigraphic setting

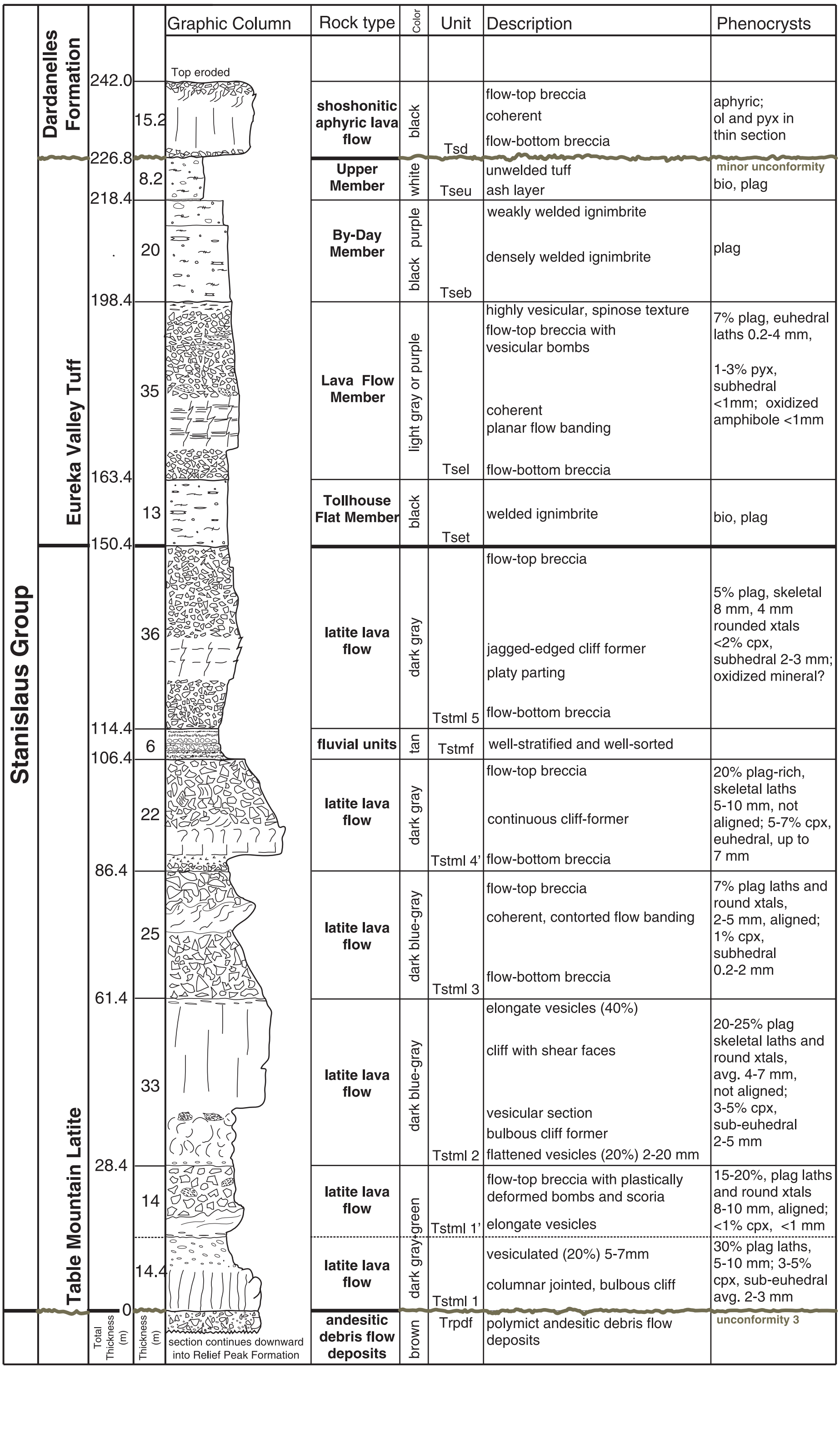
Tertiary volcanic and volcaniclastic rocks of the Bald Peak–Red Peak area lie 7 km west of the Sierra Nevada crest at the Sonora Pass (Figure 1). They consist of Oligocene ignimbrites and Miocene andesitic and trachytic volcanic and volcaniclastic rocks that dip less than a few degrees and are cut by plugs and a series of NNW-striking faults (Figure 3; Slemmons 1953).

We mapped two west-dipping normal faults, as well as two intervening, east-dipping normal faults that show only minor offset (Figure 3). We call the eastern fault the Red Peak fault (Figure 3); it dips about 70° westwards and has 235 m of vertical separation. Two minor fault splays, located <1 km to the west of the Red Peak fault, dip 70° eastward and display only 35 m of vertical separation; we interpret them as antithetic faults related to the Red Peak fault. The western fault, herein called the Bald Peak fault, dips $\sim 60°$ westwards and has 130 m of vertical separation. Faults are not common west of the range crest in the central Sierra Nevada, although many faults lie west of the crest in the southern Sierra (Saleeby *et al.* 2009).

Stanislaus Group strata are largely absent from the footwall block of the Red Peak fault due to erosion of the upthrown side. We speculate that the Bald Peak fault displacement began during the accumulation of the Miocene section, because a fluvial unit within the TML (Tstmf) is confined to the downthrown block (Figure 3), and because landslide megablocks several metres in length lie within the debris-flow deposits of the Relief Peak Formation (Trpdf) adjacent to the fault. Similarly, abrupt thickening of the Tollhouse Flat Member of the EVT onto the downthrown block of the antithetic faults may indicate that it (and, if related, the Red Peak fault) began to move during emplacement of the Stanislaus Group. However, map units clearly thicken and thin in places where we see no evidence for faulting (Figure 3), so these thickness changes may simply record evolving palaeotopographic effects within the palaeocanyon.

The Oligocene and Miocene strata in Figure 3 lie within a much broader palaeochannel/palaeocanyon, cut into Mesozoic granitic and metamorphic basement (unconformity 1; Figure 2), whose axis was probably centred at Sonora Peak (Figure 1).

Figure 3. Geologic map of the Bald Peak–Red Peak area, southern Carson–Iceberg Wilderness, central Sierra Nevada, California: mapping by Alice Koerner in 2008 at a scale of 1:6000. Map location is outlined in Figure 1. Key to map units is displayed in Figure 2. In the TML, individual lava flows are mapped and numbered; these and other units of the Stanislaus Group are described in detail in the measured section shown in Figure 4.


Graphic Column
Rock type
Color
Unit
Description
Phenocrysts
Stanislaus Group
Dardanelles Formation
Eureka Valley Tuff
Table Mountain Latite
Total Thickness (m)
Thickness (m)
Top eroded
242.0
15.2
shoshonitic aphyric lava flow
black
Tsd
flow-top breccia
coherent
flow-bottom breccia
aphyric; ol and pyx in thin section
226.8
minor unconformity
8.2
Upper Member
white
Tseu
unwelded tuff
ash layer
bio, plag
218.4
20
By-Day Member
black purple
Tseb
weakly welded ignimbrite
densely welded ignimbrite
plag
198.4
35
Lava Flow Member
light gray or purple
Tsel
highly vesicular, spinose texture
flow-top breccia with vesicular bombs
coherent
planar flow banding
flow-bottom breccia
7% plag, euhedral laths 0.2-4 mm,
1-3% pyx, subhedral <1mm; oxidized amphibole <1mm
163.4
13
Tollhouse Flat Member
black
Tset
welded ignimbrite
bio, plag
150.4
36
latite lava flow
dark gray
Tstml 5
flow-top breccia
jagged-edged cliff former
platy parting
flow-bottom breccia
5% plag, skeletal 8 mm, 4 mm rounded xtals <2% cpx, subhedral 2-3 mm; oxidized mineral?
114.4
6
fluvial units
tan
Tstmf
well-stratified and well-sorted
106.4
22
latite lava flow
dark gray
Tstml 4'
flow-top breccia
continuous cliff-former
flow-bottom breccia
20% plag-rich, skeletal laths 5-10 mm, not aligned; 5-7% cpx, euhedral, up to 7 mm
86.4
25
latite lava flow
dark blue-gray
Tstml 3
flow-top breccia
coherent, contorted flow banding
flow-bottom breccia
7% plag laths and round xtals, 2-5 mm, aligned; 1% cpx, subhedral 0.2-2 mm
61.4
33
latite lava flow
dark blue-gray
Tstml 2
elongate vesicles (40%)
cliff with shear faces
vesicular section
bulbous cliff former
flattened vesicles (20%) 2-20 mm
20-25% plag skeletal laths and round xtals, avg. 4-7 mm, not aligned; 3-5% cpx, sub-euhedral 2-5 mm
28.4
14
latite lava flow
dark gray-green
Tstml 1'
flow-top breccia with plastically deformed bombs and scoria
elongate vesicles
15-20%, plag laths and round xtals 8-10 mm, aligned; <1% cpx, <1 mm
14.4
latite lava flow
Tstml 1
vesiculated (20%) 5-7mm
columnar jointed, bulbous cliff
30% plag laths, 5-10 mm; 3-5% cpx, sub-euhedral avg. 2-3 mm
0
unconformity 3
andesitic debris flow deposits
brown
Trpdf
polymict andesitic debris flow deposits
section continues downward into Relief Peak Formation

The oldest palaeocanyon fill deposits consist of several Oligocene non-welded to welded rhyolite ignimbrites, referred to as the Valley Springs Formation (Figure 2; Slemmons 1953) which erupted from calderas in central Nevada and flowed westwards down palaeochannels across the present-day Sierra Nevada to the Sacramento Valley of central California (Garside *et al.* 2005; Henry 2008). Thus, surface elevations must have continuously decreased in that direction, from the drainage divide of the Nevadaplano in central Nevada westwards to central California, and the region could not have yet been significantly disrupted by normal faults (Busby and Putirka 2009). Oligocene ignimbrites of the central Sierra were deeply eroded in early Miocene time (unconformity 2, Figure 2; Busby *et al.* 2008a,b; Busby and Putirka 2009; Hagan *et al.* 2009), and overlain by middle Miocene andesitic volcanic and volcaniclastic rocks, referred to as the Relief Peak Formation in the Sonora Pass region (Figure 2; Slemmons 1953, 1966). In the eastern part of the map presented here (Figure 3), the Valley Springs Formation (Tvs) is preserved as an erosional remnant on a palaeoledge in the granitic basement (Kgu). Here, the Valley Springs Formation consists of light-coloured welded ignimbrite with fiamme and crystals of plagioclase, sanidine, and quartz. The Valley Springs Formation is overlain by andesitic debris-flow deposits of the Miocene Relief Peak Formation (Trpdf) along a steep buttress unconformity (Figure 3).

In general, Miocene andesitic strata pass gradationally westward from primary and vent-proximal volcanic deposits at the present-day Sierran crest into reworked volcaniclastic deposits exposed along modern west-flowing drainages; this, together with sparse palaeocurrent indicators, provides evidence for continued westward flow of material down the palaeocanyons in Miocene time (Busby *et al.* 2008b). In the area mapped in Figure 3, the Relief Peak Formation consists entirely of dark-tan-coloured, unsorted, matrix-supported, polymict, coarse pebble to small boulder debris-flow deposits composed of heterogeneous clasts of andesitic composition in a sandstone matrix. Basement granitic clasts are rare. Some blocks in the debris-flow deposits are prismatically-jointed or retain delicate breadcrust texture on their surfaces, indicating that they were derived from block-and-ash flows and not transported far from the vent area (Busby *et al.* 2008b). The debris-flow deposits were emplaced cold, as indicated by the presence of non-charred petrified wood fragments.

The Relief Peak Formation (as young as 10.39 ± 0.18 Ma; Table 1 and Figure 2) is separated from overlying high-K volcanic rocks of the 10.41–9.34 Ma (Table 1 and Figure 2) Stanislaus Group by a third erosional unconformity (Figure 2; Busby *et al.* 2008b). Measurements of elongate vesicles in lava flows from the map area (Figure 3) provide further evidence for the westward flow down the 'Cataract' palaeocanyon (Figure 6). The TML is the most widespread unit of the Stanislaus Group, extending from east of the Sierran crest to the Sierra foothills near Knight's Ferry (Figure 1; Gorny *et al.* 2009). The EVT consists of unwelded to densely welded ignimbrite that ranges in composition from trachydacite to dacite (Figure 7; King *et al.* 2007). Its basal member, the Tollhouse Flat Member, has been considered to be the most voluminous and widespread of the three ignimbrite members (Noble *et al.* 1974). Published descriptions of the Dardanelles Formation contradict one

Figure 4. Measured section through the Stanislaus Group at Slemmons' (1966) type section between Bald Peak and Red Peak (line of section plotted in Figure 2), measured by Alice Koerner in 2008. Although Slemmons described all of the formations and members measured here (see text for discussion), a detailed measured section or geologic map of the area was not provided. Plag, plagioclase; cpx, clinopyroxene; ol, olivine; avg., average; xtal, crystal; EVT, Eureka Valley Tuff.

A

Ransome (1898)	Slemmons (1966)		Noble et al. (1974)			Koerner et al. **(this study)**		
Dardanelle Flow	Stanislaus Group	Dardanelles Member	Stanislaus Group	Dardanelles Formation		Stanislaus Group	Dardanelles Formation	
		Eureka Valley Member		Eureka Valley Tuff	Upper Member		Eureka Valley Tuff	Upper Member
					By-Day Member			By-Day Member
								Lava Flow Member
Biotite-Augite Latite					Tollhouse Flat Member			Tollhouse Flat Member
Table Mountain Flow		Table Mountain Latite Member		Table Mountain Latite			Table Mountain Latite	

B

Locations									
Rattlesnake Hill[1]	McKays Point[1]	Whittakers Dardanelles[1]	Bald Peak[1]	**Bald Peak (this study)**	**Bald Peak-Red Peak area (this study)**	Golden Canyon[2]	Sonora Pass[1]	EVT, Reference Section, Sweetwater Mountains[1]	Bodie and Mono Lake[1]
		Dardanelles Formation	Dardanelles Formation	**Dardanelles Formation**	**Dardanelles Formation**		Dardanelles Formation		
					Upper Member, EVT	Upper Member, EVT		Upper Member, EVT	Upper Member, EVT
					By-Day Member, EVT			By-Day Member, EVT	
				Latite Flow Member, EVT	**Latite Flow Member, EVT**	Latite Flow Member, EVT			
	Tollhouse Flat Member, EVT	Tollhouse Flat Member, EVT	Tollhouse Flat Member, EVT	**Tollhouse Flat Member, EVT**	**Tollhouse Flat Member, EVT**	Tollhouse Flat Member, EVT	Tollhouse Flat Member,EVT	Tollhouse Flat Member, EVT	Tollhouse Flat Member,EVT
Table Mountain Latite	Table Mountain Latite	Table Mountain Latite		**Table Mountain Latite**	**Table Mountain Latite**	Table Mountain Latite	Table Mountain Latite	Table Mountain Latite	

Figure 5. (a) Evolution of the stratigraphic nomenclature of the Stanislaus Group, modified from King *et al.* (2007) to include the new data reported in this paper. (b) Columnar sections summarizing the distribution of various units of the Stanislaus Group: superscript '1' denotes stratigraphy summarized by King *et al.* (2007); superscript '2' denotes stratigraphy described by Hagan *et al.* (2008); and 'this study' refers to the stratigraphy mapped and measured in Figures 3 and 4 of this paper.

Table 1. Age controls on the Sonora Pass stratigraphy.

							Interpreted age (Ma)[a]		Nominal age (Ma)[b]		Preferred age (Ma)[c]		
Sample	Geochemistry	Mineral	Lat (°N)	Long (°W)	WMPA	IsoA	Age	± 2σ	Age	± 2σ	Age	± 2σ	Unit name
Sonora Pass geochronology													
BP068	Andesite	Hbl	38.37609	119.76975	7.12 ± 0.06	7.26 ± 0.16	7.12	0.06	7.22	0.06	7.28	0.06	Hbl Andesite Plug – Disaster Peak Fm
BP068	Andesite	Plag	38.37609	119.76975	7.04 ± 0.50	6.83 ± 0.94	7.0	0.5	7.11	0.5	7.15	0.5	Hbl Andesite Plug – Disaster Peak Fm
TF003	–	Plag	38.43096	119.44792	9.11 ± 0.04	9.10 ± 0.08	9.14	0.04	9.28	0.04	9.34	0.04	Upper Member, Eureka Valley Tuff – Stanislaus Gp
TF003	–	Bio	38.43096	119.44793	9.18 ± 0.04	9.20 ± 0.04	9.18	0.04	9.32	0.04	9.38	0.04	Upper Member, Eureka Valley Tuff – Stanislaus Gp
TF005b	–	Plag	38.43041	119.44805	9.19 ± 0.32	9.10 ± 0.52	9.2	0.3	9.34	0.3	9.4	0.3	By-Day Member, Eureka Valley Tuff – Stanislaus Gp
TF009	–	Plag	38.42891	119.44841	9.27 ± 0.04	9.30 ± 0.10	9.27	0.04	9.41	0.04	9.47	0.04	Tollhouse Flat Member, Eureka Valley Tuff – Stanislaus Gp
TF009	–	Bio	38.42891	119.44842	9.35 ± 0.04	9.32 ± 0.06	9.34	0.04	9.48	0.04	9.54	0.04	Tollhouse Flat Member, Eureka Valley Tuff – Stanislaus Gp
PC032	Shoshonite	Plag	38.35378	119.6344	10.14 ± 0.06	10.15 ± 0.08	10.14	0.06	10.30	0.06	10.36	0.06	Uppermost Table Mtn Latite Flow – Stanislaus Gp
PC005	Latite	Plag	38.34641	119.63263	10.19 ± 0.08	10.30 ± 0.16	10.19	0.08	10.35	0.08	10.41	0.08	Lowermost Table Mtn Latite Flow – Stanislaus Gp

Table 1 – *continued*

							Interpreted age (Ma)[a]		Nominal age (Ma)[b]		Preferred age (Ma)[c]		
Sample	Geochemistry	Mineral	Lat (°N)	Long (°W)	WMPA	IsoA	Age	±2σ	Age	±2σ	Age	±2σ	Unit name
PC-BA	Basaltic andesite	Hbl	38.34427	119.6340	10.10 ± 0.06	10.17 ± 0.18	10.17	0.18	10.33	0.18	10.39	0.18	Block-and-ash flow tuff – Upper Relief Peak Fm
PC-BA	Basaltic andesite	Plag	38.34427	119.6341	n.a.	n.a.	~10	n.a.	~10	n.a.	~10	n.a.	Block-and-ash flow tuff – Upper Relief Peak Fm
BP057	–	Plag	38.37824	119.7430	n.a.	n.a.	23.8	0.2	24.16	0.2	24.32	0.2	Uppermost welded ignimbrite – Valley Springs Fm

Interpreted ages as reported by Gans (Busby *et al.* 2008b) are recalculated here using improvements to decay constant (Renne *et al.* 1998; Kuiper *et al.* 2008), resulting in preferred ages plotted in Figure 2. Sample localities for samples collected and analysed from the field area (i.e. BP068) are plotted in Figure 3. WMPA is data reported by Busby *et al.* (2008b). IsoA is data reported by Busby *et al.* (2008b). Hbl, hornblende; Plag, plagioclase.

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

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

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

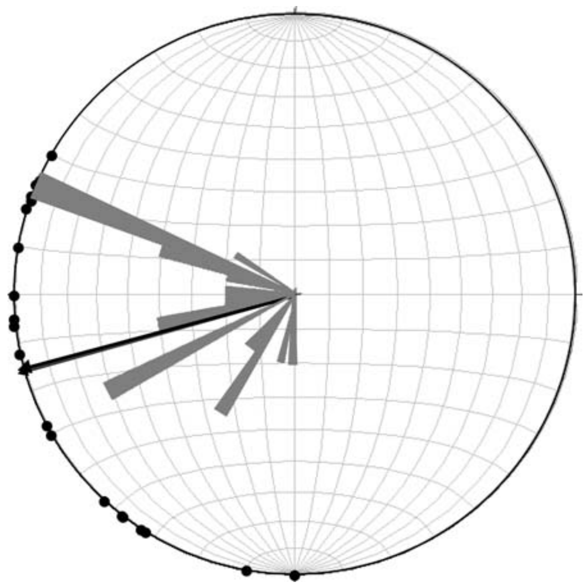


Figure 6. Rose diagram of trends of elongate vesicles within lava flows of the Stanislaus Group in the area mapped in Figure 3 ($n = 22$). The arrow denotes the average of the trends (255°), which is consistent with the general trend of the 'Cataract' palaeocanyon (Figure 1).

another, probably because it has been confused with the unit we call the Lava Flow Member of the EVT (see Discussion section).

The early late Miocene Stanislaus Group is in turn separated from the overlying late Miocene andesitic volcanic and volcaniclastic rocks of the Disaster Peak Formation by a fourth unconformity (Figure 2; Busby *et al.* 2008b; Busby and Putirka 2009). In the map area of Figure 3, strata of the Disaster Peak Formation are limited to a single small erosional remnant (Tpdf). Additionally, we assign 7.28 ± 0.06 Ma (Table 1 and Figure 2) hornblende–plagioclase–phyric andesite plugs that cut the Stanislaus Group to the Disaster Peak Formation, even though they are intrusions, because they clearly represent the subvolcanic parts of it (Table 1 and Figure 3).

Several previous workers inferred that the source for the EVT lies in the Little Walker Center (Noble *et al.* 1974; Priest 1979; see discussion in King *et al.* 2007). Slemmons (1966), however, portrayed the source of the TML as a 36 by 8 km, WNW-trending region of 'latite intrusives' that encompasses the Leavitt Peak–Sonora Peak–Bald Peak–Red Peak area (Slemmons 1953, 1966). His interpretation has been repeated in more recent publications (Noble *et al.* 1974; King *et al.* 2007). We have mapped this entire region in detail and found no evidence for the assertion by Slemmons – just a few small hornblende andesite plugs and dikes. The vent area for a lava flow field of the magnitude of the TML would likely be obvious in this very well-exposed area, just as it is for the 16 Ma Lovejoy basalt in the northern Sierra Nevada (Garrison *et al.* 2008). The fact that latite lava flows are interstratified with EVT in and around the Little Walker Center (Priest 1979) indicates to us that all of the high-K rocks vented there. The Little Walker Center/Caldera is interpreted to have formed along a releasing stepover of a dextral transtensional fault zone (Putirka and Busby 2007; Busby *et al.* 2008b; Busby and Putirka 2009). According to this explanation, the faults of this zone penetrated a thick crustal section into the lithospheric mantle, thereby providing a conduit for low-degree, high-K partial melts. We mapped the

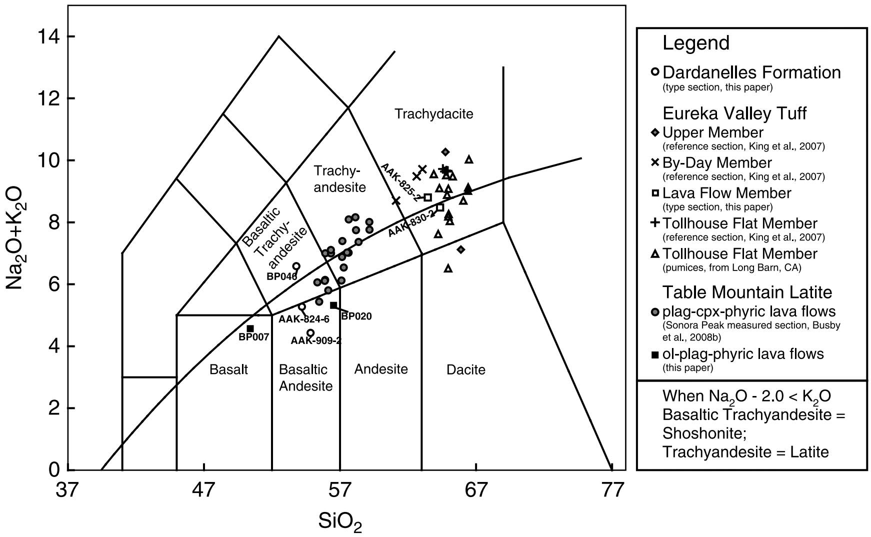


Figure 7. Le Bas *et al.* (1986) plot of high-K rocks and basalts of the Stanislaus Group from the Bald Peak–Red Peak and the Sonora Pass areas (locations given in Table 2; samples from the Bald Peak–Red Peak area plotted in Figure 3). This plot shows that the Lava Flow Member of the EVT plots in the same field as the ignimbrites of the EVT. Also, the Dardanelles Formation, which we show lies at the top of the Stanislaus Group above all members of the EVT, plots in the same field as the lava flows of the TML.

area in Figure 3, which lies ~10 km to the west of the Little Walker Center (Figure 1), to investigate this distinctive high-K pulse of magmatism.

Stanislaus Group stratigraphy

The purpose of this paper is to document field relations at the type section of the Stanislaus Group where exposure is nearly 100% (Figures 3 and 5).

Table Mountain Latite

The TML lava flows are easily recognized in the field by their clinopyroxene and skeletal plagioclase phenocrysts, up to 1 cm in size (Figure 4), accompanied by groundmass olivine. Geochemical analyses from a measured section through the TML at Sonora Peak 9 km to the ESE, presented by Busby *et al.* (2008b), show that it ranges from trachyandesite to basaltic trachyandesite (Table 2 and Figure 7). The TML is continuous across the map area (Figure 3), because much of the relief on the palaeocanyon floor was filled in by the underlying Relief Peak Formation. The unconformity between the Relief Peak Formation and the Stanislaus Group (unconformity 3; Figure 2) has less relief in the map area (Figure 3) than other areas (e.g. Sonora Pass, Busby *et al.* 2008b). On Red Peak in the east, the TML consists of seven or eight latite flows, 160 m thick with the top eroded. Five latite flows compose the 150 m-thick TML section between the two faults (Figure 4) and west of the Bald Peak fault the TML has four latite flows (Figure 3). Thus, the number of flows decreases westwards over a very short distance (just a few kilometres). This westward palaeoflow direction is consistent with the fact that only 9 km to the ESE on Sonora Peak, the TML section is 405 m thick and contains 26 flows (top eroded;

Table 2. Summary of sample localities and rock names for geochemical data plotted in Figure 7.

Sample	Fm	Map unit	Geochemistry	Igneous Fm	Lat (°N)	Long (°W)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3[a]	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Total alkalis
AAK-08-824-6	Dard[b]	Tsd[b]	Basaltic andesite	Lava	38.37145	119.76038	54.20	1.19	18.28	8.81	0.09	4.16	7.34	2.60	2.68	0.66	99.99	5.28
AAK-08-909-2	Dard[b]	Tsd[b]	Basaltic andesite	Lava	38.37735	119.74738	54.84	1.14	18.44	8.66	0.09	4.32	7.70	2.68	1.75	0.39	100.00	4.43
BP046	Dard[b]	Tsd[b]	Shoshonite	Lava	38.37413	119.75879	53.79	1.22	18.17	7.87	0.09	4.11	7.44	3.70	2.88	0.72	100.00	6.58
LWC 76G	EVT[c]	Tseu[c]	Dacite	Ash-flow tuff	38.43019	119.44800	65.88	0.91	17.34	3.71[a]	0.11	2.00	2.73	2.44	4.68	0.19	99.99	7.12
LWC 85	EVT[c]	Tseu[c]	Trachydacite	Ash-flow tuff	38.42990	119.45144	64.75	0.94	16.94	2.95[a]	0.08	0.95	2.99	3.52	6.75	0.13	100.00	10.27
LWC 65d	EVT[c]	Tseb[c]	Trachydacite	Ash-flow tuff	38.42951	119.44802	62.63	1.17	16.94	4.57[a]	0.09	1.46	3.23	3.73	5.75	0.42	99.99	9.48
LWC 70d	EVT[c]	Tseb[c]	Trachydacite	Ash-flow tuff	38.42992	119.44804	63.06	1.14	16.87	4.53[a]	0.09	1.19	3.01	4.31	5.4	0.4	100.00	9.71
LWC 59G	EVT[c]	Tseb[c]	Trachydacite	Ash-flow tuff	38.42947	119.44800	61.12	1.19	18.00	4.98[a]	0.10	1.72	3.73	4.22	4.48	0.46	100.00	8.70
AAK-08-825-2	EVT[b]	Tsel[b]	Trachydacite	Lava	38.37442	119.76389	63.46	1.12	17.10	4.93	0.04	1.24	2.94	3.46	5.34	0.37	100.00	8.80
AAK-08-830-2	EVT[b]	Tsel[b]	Trachydacite	Lava	38.37298	119.75229	64.36	1.10	17.20	4.73	0.05	1.06	2.70	3.18	5.30	0.37	100.02	8.48
LWC 83	EVT[c]	Tset[c]	Trachydacite	Ash-flow tuff	38.42865	119.44839	64.56	0.86	17.10	3.70[a]	0.07	0.99	2.70	4.53	5.19	0.30	100.00	9.72
LWC 52G	EVT[c]	Tset[c]	Trachydacite	Ash-flow tuff	38.42798	119.44791	64.92	0.85	17.08	3.55[a]	0.07	0.93	2.66	4.55	5.11	0.29	100.01	9.66
LWC 56G	EVT[c]	Tset[c]	Trachydacite	Ash-flow tuff	38.42845	119.44828	64.82	0.90	17.09	3.68[a]	0.05	0.86	2.62	4.42	5.25	0.30	99.99	9.67
LWC 82	EVT[c]	Tset[c]	Trachydacite	Ash-flow tuff	38.42785	119.44759	64.71	0.85	17.04	3.63[a]	0.08	1.08	2.69	4.60	5.04	0.29	100.01	9.64
LWC 54d	EVT[c]	Tset[c]	Trachydacite	Ash-flow tuff	38.42845	119.44828	64.89	0.87	17.08	3.82[a]	0.08	0.72	2.59	4.61	5.03	0.30	99.99	9.64
CMEVT-2R NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	66.39	0.79	16.69	3.60	0.12	1.03	2.00	3.71	5.31	0.35	100.00	9.02
CMEVT-3P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.31	1.01	16.95	4.11	0.11	1.34	2.77	4.54	4.56	0.30	100.00	9.10
CMEVT-5R NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.98	0.91	17.49	3.84	0.09	1.27	2.64	3.67	4.60	0.51	100.00	8.27

Table 2 – *continued*

Sample	Fm	Map unit	Geochemistry	Igneous Fm	Lat (°N)	Long (°W)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3[a]	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Total alkalis
LTEVT-P1 NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	65.29	0.91	16.80	3.59	0.10	1.11	2.47	4.62	4.86	0.25	100.00	9.48
LTEVT-P2 NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	65.08	0.94	17.07	4.27	0.10	1.31	2.75	3.36	4.69	0.44	100.00	8.04
LTEVT-P4 NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.96	0.93	17.23	3.77	0.10	1.17	2.51	4.36	4.72	0.25	100.00	9.08
MOEVT-2P 1NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	63.90	0.99	16.98	3.99	0.10	1.31	2.88	5.05	4.50	0.30	100.00	9.56
MOEVT-4P 1NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	66.48	0.73	16.70	3.10	0.10	0.83	1.85	4.74	5.29	0.18	100.00	10.03
MOEVT-3P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.96	1.00	17.12	4.25	0.09	1.31	2.78	3.65	4.54	0.30	100.00	8.19
SLEVT-1P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.80	0.93	17.05	3.56	0.09	1.18	2.61	4.73	4.79	0.26	100.00	9.52
SLEVT-4P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	66.06	0.91	17.01	3.42	0.07	1.13	2.46	3.73	4.97	0.25	100.00	8.70
SLEVT-5P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	66.42	0.84	16.77	3.42	0.10	0.95	2.16	3.80	5.33	0.22	100.00	9.13
TBEVT-1P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.22	1.00	16.84	5.57	0.11	1.42	2.90	3.24	4.38	0.32	100.00	7.62
TBEVT-2P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.95	1.08	18.62	4.59	0.10	1.21	2.68	2.79	3.72	0.25	100.00	6.52
TBEVT-3P NB	EVT[d]	Tset[d]	Trachydacite	Ash-flow tuff	38.34080	119.74430	64.87	0.96	17.03	3.94	0.10	1.20	2.73	4.16	4.73	0.28	100.00	8.89
SO-P-0107	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	56.30	1.31	18.36	6.40	0.13	2.05	7.78	3.67	3.34	0.67	100.00	7.00
SO-P-0201	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.27	1.31	17.48	7.47	0.05	2.31	6.95	3.44	3.10	0.62	100.00	6.54
SO-P-0305	TML[e]	Tstml[e]	Shoshonite	Lava	38.32160	119.68980	55.91	1.26	16.59	7.16	0.08	4.89	7.39	3.10	3.03	0.59	100.00	6.14
SO-P-0402	TML[e]	Tstml[e]	Shoshonite	Lava	38.32160	119.68980	55.88	1.25	16.62	6.86	0.11	4.43	8.15	3.14	2.97	0.59	100.00	6.11
SO-P-0505	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.11	1.30	17.09	5.96	0.12	2.36	9.34	3.24	2.88	0.61	100.00	6.12
SO-P-0602	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	55.92	1.52	18.02	6.36	0.16	1.48	8.63	3.60	3.40	0.91	100.00	7.00
SO-P-0708A	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.18	1.57	18.93	6.28	0.02	1.52	6.17	3.80	3.59	0.93	100.00	7.39
SO-P-0804B	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	56.14	1.21	16.72	6.87	0.10	3.68	8.95	2.78	3.03	0.53	100.00	5.80

Table 2 – *continued*

Sample	Fm	Map unit	Geochemistry	Igneous Fm	Lat (°N)	Long (°W)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3[a]	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Total alkalis
SO-P-0902	TML[e]	Tstml[e]	Shoshonite	Lava	38.32160	119.68980	55.34	1.15	16.57	6.92	0.14	5.41	7.85	3.08	2.98	0.56	100.00	6.06
SO-P-1001	TML[e]	Tstml[e]	Basaltic andesite	Lava	38.32160	119.68980	55.47	1.32	16.32	7.65	0.10	5.70	7.39	2.54	2.89	0.61	100.00	5.43
SO-P-1105	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	56.35	1.75	17.72	7.37	0.05	2.44	6.33	3.38	3.62	0.99	100.00	7.00
SO-P-1201	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	56.33	1.75	17.64	7.33	0.07	2.65	6.03	3.51	3.60	1.08	100.00	7.10
SO-P-1304	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.64	1.70	17.92	6.75	0.07	1.44	5.41	3.83	4.26	0.97	100.00	8.09
SO-P-1404	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.63	1.41	18.08	6.54	0.05	2.66	5.91	3.48	3.54	0.71	100.00	7.02
SO-P-1501	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	58.37	1.29	21.16	4.19	0.11	0.80	6.12	3.96	3.40	0.59	100.00	7.36
SO-P-1606	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	58.18	1.42	18.83	6.22	0.08	1.65	5.19	3.51	4.23	0.69	100.00	7.74
SO-P-1806	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	59.16	1.51	18.40	6.42	0.02	1.27	4.53	3.64	4.37	0.69	100.00	8.01
SO-P-1903A	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.15	1.27	17.20	7.51	0.34	2.61	6.48	3.43	3.45	0.55	100.00	6.88
SO-P-2106A	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	58.14	1.67	19.04	5.64	0.01	1.15	5.38	3.75	4.41	0.81	100.00	8.16
SO-P-2204A	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	57.52	1.19	17.69	5.99	0.15	3.58	6.32	3.32	3.70	0.55	100.00	7.02
SO-P-2301	TML[e]	Tstml[e]	Latite	Lava	38.32160	119.68980	59.17	1.38	18.32	6.26	0.02	1.30	5.20	3.57	4.19	0.60	100.00	7.76
BP007	TML[f]	Tstmb[f]	Basalt	Lava	38.36367	119.77765	50.40	1.65	14.94	8.54	0.10	10.15	9.18	2.65	1.91	0.47	100.00	4.57
BP020	TML[f]	Tstmb[f]	Basaltic andesite	Lava	38.37160	119.77208	56.53	0.89	16.55	6.39	0.07	6.61	7.39	3.70	1.62	0.25	100.00	5.32

Dard, Dardanelles Formation; TML, Table Mountain Latite; EVT, Eureka Valley Tuff. All coordinates reported using WGS 84. The samples[b],[d–f] shown in this table were generated from replicate analyses with initial totals between 99.5 and 100.5, and the replicates were averaged and renormalized.

[a] FeO was reported by [3]King *et al.* (2007), whereas Fe_2O_3 is reported in this study.

[b] Type section, Figure 4, this paper.

[c] Reference section, King *et al.* (2007).

[d] Pumices, from Long Barn, CA.

[e] Sonora Peak measured section, Busby *et al.* (2008b).

[f] See Figure 3, this paper.

Busby *et al.* 2008b). This eastward thickening of TML is compatible with an eruptive source in the Little Walker Caldera, which is 15 km east of the map area (Figures 1 and 3).

We subdivided the TML section in the Bald Peak–Red Peak area on the basis of outcrop characteristics (Figure 4). Future palaeomagnetic and geochemical analysis of these rocks may enable correlation of specific Bald Peak–Red Peak flows over long distances and provides additional age constraints by correlation to the magnetic polarity timescale (for examples see Busby *et al.* 2008b; Gorny *et al.* 2009; Pluhar *et al.* 2009). Most of the flows in the map area have prominent flow-top breccias, and some exhibit flow-bottom breccias, but some flows lack breccia and probably represent pahoehoe flows (Figure 4). Such variations are also present at Sonora Peak (Busby *et al.* 2008a,b).

The basal flow in the TML at Bald Peak–Red Peak has the best developed columnar jointing, probably due to quenching upon what was then the base of the palaeocanyon, perhaps in water. On Red Peak the basal TML flow is flow 2 rather than TML flow 1, because flow 1 is absent there. TML flow 1 consists of two flows (1 and 1′, Figure 4) but neither is continuous across the map area. Flow 1 has more crystals than flow 1′ and is marked by a vesicular top in the line of measured section, although the vesicular top passes laterally into a flow-top breccia. Flow 1′ has distinctive bombs and plastically-deformed spatter on its upper surface. Flow 2 has larger augite crystals than the underlying and overlying flows. Flow 3 has laterally-continuous contorted flow banding and a continuous flow-top breccia, but laterally variable plagioclase content. Flow 4 has the most abundant plagioclase of all the flows (30–35%) and flow 4′ has the largest plagioclase (up to 10 mm) and clinopyroxene phenocrysts (up to 7 mm) of all the flows; perhaps this is equivalent to the 'large plagioclase member' (Priest 1979), which is the second member from the base of the TML at the Little Walker Center. Flow 4 is restricted to Red Peak and extends east of Figure 3, whereas flow 4′ is continuous across the map area. Flow 5 displays a distinctive weathering pattern that yields jagged blocks.

Fluvial deposits intervene between flows 4 and 5 (Tstmf, Figure 4), exemplified by the one channelized body at the line of the measured section. As noted above, the fluvial deposits thicken dramatically onto the downthrown block west of the Bald Peak Fault (Figure 3). There, flow 5 lenses out within a minor channel cut into the fluvial deposits. The fluvial deposits consist of well-sorted, subrounded to rounded, pebble to boulder, conglomerate, and pebbly sandstone and lesser sandstone in thin to thick beds with planar lamination and cut and fill structures. They contain a mixture of andesite and latite clasts, and rare granitic clasts, with maximum particle sizes ranging from 15 to 200 cm.

Discontinuous, black, olivine–plagioclase–phyric basaltic and basaltic andesite lava flows lie between flows 3 and 4 (Figure 3). On the west side of the Bald Peak Fault, the geochemistry of the single flow there is basaltic, whereas the single, thicker flow on the east side of the fault is a basaltic andesite (Figure 7), indicating that two different olivine–plagioclase–phyric lava flows are present at this stratigraphic horizon.

Eureka Valley Tuff

Tollhouse Flat Member

The basal member of the EVT, the Tollhouse Flat Member, consists entirely of densely welded ignimbrite in the map area (Figures 3 and 4). It is dominated by black vitrophyre and large black fiamme up to 54 cm long with perlitic texture. It is distinguished from the By-Day Member by abundant biotite phenocrysts (in addition to plagioclase, present in both), and it has bigger and more abundant fiamme that weather out to form cavities. In the map area, the Tollhouse Flat Member also contains about 10–20% dominantly pebble-sized accidental rock fragments. The Tollhouse Flat Member is only 7 m thick in the line of the measured section (Figure 3), and lenses out abruptly to the west of it (Figure 4), reappearing abruptly on the west side of the Bald Peak Fault where it is about 25 m thick. It also thickens abruptly onto the downthrown block of the antithetic fault where it maintains an even thickness of about 25 m eastward.

Lava Flow Member

The Lava Flow Member of the EVT, which lies between the Tollhouse Flat and By-Day members, is mapped here for the first time in the Sierra Nevada. However, as mentioned above, a Lava Flow Member has been recognized at this stratigraphic position in the region of the Little Walker Center (Priest 1979) and in the Sweetwater Mountains (Brem 1977). At Bald Peak–Red Peak, the Lava Flow Member of the EVT is distinguishable from the TML by its smaller phenocrysts and the presence of plagioclase laths, rather than skeletal or resorbed plagioclase. The Lava Flow Member of the EVT at Bald Peak–Red Peak differs from all other units of the Stanislaus Group by having amphibole phenocrysts. As discussed below, its chemistry is quite distinct from that of all the other lava flows in the Stanislaus Group described to date, because it is a trachydacite, rather than a trachyandesite or basaltic trachyandesite. It has the same composition as pumice fragments from the Tollhouse Flat Member of the EVT (Figure 7). In the map area of Figure 3, the Lava Flow Member of the EVT has a very-highly-vesiculated top with a distinctive purple or orange colour, which passes laterally into a thick flow-top breccia in the line of the measured section (Figure 4). The Lava Flow Member is continuous wherever it is overlain by By-Day Member of EVT, but it is locally cut out along an erosional surface at the base of the Dardanelles Formation, 375 m west of the Bald Peak fault (Figure 3).

By-Day Member

The By-Day Member of the EVT lacks biotite phenocrysts, although it contains biotite in the groundmass, and consists of strongly welded vitrophyric (black) to weakly-welded devitrified (dark grey) ignimbrite. Its accidental lithic content is similar to that of the Tollhouse Flat Member. It locally has an orange top that was probably produced by vapour phase alteration. The By-Day Member thins from 30 m by the Red Peak fault to 20 m in the line of the measured section where it underlies Upper Member EVT; it is absent west of the Bald Peak fault (Figure 3).

Upper Member

The Upper Member of the EVT is preserved as erosional remnants on the ridge between the Red Peak and Bald Peak faults and consists of up to 8 m of unwelded biotite-bearing ignimbrite with 20–35% white unflattened pumices. It forms a distinctive soft white outcrop. In the line of the measured section, the ignimbrite is underlain by a fine-grained white tuff 20 cm thick that may be an ash fall deposit.

Dardanelles Formation

The Dardanelles Formation consists of a single lava flow up to 60 m thick, underlain by the Upper Member of the EVT or the Lava Flow Member of the EVT, and overlain by andesitic fluvial sandstones and conglomerates of the Disaster Peak Formation (Figures 3 and 4). In this section, the Dardanelles Formation contains microcrystalline olivine, pyroxene, and trachytic-textured plagioclase laths. It has extremely irregular jointing and a thick pink-red flow-top breccia injected by coherent lava from the flow's interior. Locally, it has a flow-bottom breccia. It is preserved as erosional remnants up to 60 m thick on the ridge between the Red Peak and Bald Peak faults, and is 40 m thick where it is intruded by the Bald Peak plug and where its flow-top breccia is mostly obliterated or eroded.

Stanislaus Group age controls

Age controls on the TML include an Ar/Ar age of 10.41 ± 0.08 Ma for the basal flow, and 10.36 ± 0.06 Ma for the top flow, of the 23 flows on Sonora Peak (Figure 2; Busby *et al.* 2008b). The Sonora Peak section is mainly composed of normal polarity lava flows, but contains two reversed polarity zones, each represented by a single lava flow (Busby *et al.* 2008b; Pluhar *et al.* 2009). The lower reversed lava flow exhibits what we call the 'Classic Table Mountain Latite' remanence direction, which is found widely in the TML, at sites from Sonora Peak to the foothills (see summary in Pluhar *et al.* 2009). This direction records an interlude that Pluhar *et al.* (2009) informally call the Table Mountain Event, which occurred between 10.36 ± 0.06 and 10.41 ± 0.08 Ma, around the time of subchron C5*n*.2*n* − 2 (10.309–10.313 Ma; Evans *et al.* 2007). In the foothills near Knight's Ferry (Figure 1), the TML consists of at least four flows, with palaeomagnetic results consistent with the 'Classic Table Mountain Latite' direction and inconsistent with directional results from any other Stanislaus Group lava flows published to date (Gorny *et al.* 2009). Assuming typical secular variation rates, the lava flows of the 'Classic Table Mountain Latite' were emplaced in less than four centuries (Pluhar *et al.* 2009).

Precise ages for the By-Day and Upper members of the EVT (9.42 ± 0.04 and 9.43 ± 0.02 Ma, respectively; Pluhar *et al.* 2009) coupled with their normal polarity (King *et al.* 2007) indicate that these units were emplaced early in subchron C4Ar.1*n* (9.443–9.351 Ma; Evans *et al.* 2007).

The Dardanelles Formation has a single whole rock K–Ar date of 9.3 ± 0.4, on a sample described as an aphyric basalt lava flow at an elevation of 9230' on Bald Peak by Dalrymple (1964). Our mapping (Figure 3) confirms that this is indeed the Dardanelles Formation, although the Dardanelles Formation is a shoshonite, not a basalt, as described below (Figure 7). Like the underlying By-Day and Upper members of the EVT, the Dardanelles Formation at Bald Peak displays normal polarity (Al-Rawi 1969; King *et al.* 2007). Taken together, these observations suggest that Dardanelles Formation erupted during one of two possible time periods: (1) during normal subchron C4Ar.1*n* (9.443–9.351 Ma), soon after EVT, or (2) during normal chron C4An (9.098–8.769 Ma; Lourens *et al.* 2004). Ar/Ar dating in progress will likely distinguish between these two possibilities.

Preliminary geochemical results

Geochemical analyses of the TML samples demonstrate that their compositions range from trachyandesite (latite) to basaltic trachyandesite (shoshonite; Figure 7). Trachyandesite is equivalent to a latite for these rocks (Figure 7; Ransome 1898; Slemmons 1953), but note that a few TML samples range in composition from andesite to basaltic trachyandesite. These samples might be considered the more mafic equivalents of the latite series and are still related to the latite lava flows of the TML. Basaltic trachyandesite is equivalent to shoshonite. The close relation of the TML data points suggests that these flows are part of the same magmatic event.

The Lava Flow Member of the EVT plots in the same field as the EVT ignimbrites and is markedly more silicic than all the other lava flows of the Stanislaus Group discovered to date (the TML and Dardanelles formations; Figure 7). This trachydacite Lava Flow Member is geochemically closely related to the Tollhouse Flat Member of the EVT (Figure 7), indicating that the lava flow must have erupted from the same magma chamber in which the EVT was developed, during the same magmatic event. Perhaps it records tapping of a lower, relatively volatile-poor part of the same magma chamber that erupted the Tollhouse Flat Member of the EVT, or tapping of the upper part of the chamber after the gas-rich part vented. In the second interpretation, the By-Day Member represents magma erupted when gases once again collected at the higher parts of the magma chamber.

As described above, Pluhar *et al.* (2009) have identified a lava flow with normal polarity in one locality and reversed polarity in another locality in the region of the Little Walker caldera, in the same stratigraphic position (between Tollhouse Flat and By-Day members of the EVT) as our newly-defined Lava Flow Member of the EVT. Preliminary geochemical data on the lava flows identified by Pluhar, however, indicate that they are indeed latites (with compositions ranging from trachyandesite/latite to andesite; Pluhar personal communication, 2009). Thus, Pluhar *et al.* (2009) follow Brem's (1977) nomenclature by referring to the lava flow as the Latite Flow Member of the EVT. In the type section (Figures 3 and 4), that member is instead a trachydacite, so we have dropped the term 'Latite' from the name of this unit and refer to it as the Lava Flow Member of the EVT. Our new geochemical data thus indicate that at least three lava flows are included in the Lava Flow Member: the trachydacite lava flow described here, and the two different trachyandesite (latite) lava flows recognized by Pluhar *et al.* (2009). Future work will determine whether the trachydacite lava flow has normal or reverse magnetization.

The Dardanelles Formation plots near the same geochemical field as the TML, although it is slightly more mafic in composition than most TML flows (Figure 7). The three samples from the Dardanelles Formation differ in the total alkali content; one is basaltic trachyandesite (i.e. shoshonite; BP046) and the others are basaltic andesite (AAK-08-824-6 and AAK-08-909-2; Table 2). However, the sample that is low in total alkalis (AAK-08-909-2) may have been altered.

As a final observation, regarding volcanic rock nomenclature, our geochemical data at Sonora Pass, the type locality for latite, provide something of a test of geochemical classification schemes. Le Bas *et al.* (1986), for example, propose that the term 'latite' be used to describe trachyandesites that have high K_2O, specifically where $K_2O > (Na_2O - 2.0)$. In their terminology, latite is a subdivision of trachyandesite, and rocks that have $Na_2O - 2.0 > K_2O$ are termed benmoreite. Lava flows that occur at Sonora Peak span a somewhat broad range of compositions, but all have $K_2O > (Na_2O - 2.0)$, and most are largely consistent with the Le Bas *et al.* (1986) definition. The Le Bas *et al.* (1986) definition is in turn largely consistent with the original intent of Ransome (1898), when he originated the term latite to describe the extrusive form of monzonite. These are rocks compositionally intermediate between trachyte and andesite, though Ransome (1898) perhaps did not foresee the subdivision of trachyandesites into high-Na and high-K suites. In any case, by these definitions, which we judge to be fully appropriate, not all (but most) samples at Sonora Peak within the TML are latites. Four samples (of the 21 total analysed flows) plot within the basaltic trachyandesite field (Figure 7); these samples, also having $K_2O > Na_2O - 2.0$, can be termed shoshonites (as opposed to mugearites, which have $K_2O < (Na_2O - 2.0)$; Le Bas *et al.* 1986). In addition, one flow from Sonora Pass also plots in the basaltic andesite field, so it is not trachytic. As for nomenclature, our data thus verify the usefulness and accuracy of the classification scheme as outlined by Le Bas *et al.* (1986), at least for use of the term latite. In addition, our data further show that latites, at their type locality at least, are a product of shoshonite fractionation, and that shoshonites can in turn be derived by fractionation of basaltic andesite parent magmas.

Discussion

Previous workers misidentified the Lava Flow Member of the EVT as part of the Dardanelles Formation. Slemmons (1966) reported multiple flows in the Dardanelles Formation (Tsd) but at the Bald Peak–Red Peak area, we recognize only one. Moreover, lava flows previously assigned to the Dardanelles Formation directly overlie the Tollhouse Flat Member of the EVT in many localities (Figure 5(b)). As a result, it is unclear whether some of the lava flows formerly attributed to the Dardanelles Formation are actually part of the Lava Flow Member of the EVT; since they do not have the By-Day Member in between to demarcate them. It is possible that they have been lumped together in the previous interpretations. Previous workers (Ransome 1898; Slemmons 1966) have described the Dardanelles Formation (Tsd) on the Dardanelles (Figure 1) as a rock that differs from the TML by lacking skeletal plagioclase texture and containing smaller phenocrysts**.** However, this description of the Dardanelles Formation is similar to our newly-recognized Lava Flow Member of the EVT at the Bald Peak–Red Peak area (Figure 4).

The Bald Peak–Red Peak area, where stratigraphic relationships are clear and stratigraphy is relatively complete, provides an excellent locale for clearly distinguishing between the TML, the Lava Flow Member of the EVT, and the Dardanelles Formation. The petrographic, geochemical, and outcrop characteristics defined here may be used to extend stratigraphic control into adjacent areas. All the lava flows are distinguishable on the basis of geochemical analyses. The TML consists of plagioclase–clinopyroxene–phyric (basaltic trachyandesite/shoshonite and trachyandesite/latite) lava flows, with minor interstratified basalt and basaltic andesite lava flows. In our study area, the Lava Flow Member of the EVT is plagioclase–pyroxene–amphibole–phyric, in contrast to all other previously described lava flows of the Stanislaus Group, which lack amphibole. Furthermore, the Lava Flow Member of the EVT has the same composition as the EVT ignimbrites it is interstratified with (trachydacite); this may record nearly coeval tapping of gas-rich and gas-poor parts of the magma chamber, or volatile-phase restratification processes within the magma chamber. Further age controls, in the form of palaeomagnetic work and high-precision Ar/Ar dating, together with detailed geochemical studies may resolve this question. The Dardanelles Formation is distinctive in that it appears to consist of one aphyric lava flow that is much darker in colour and more mafic in composition than most flows of the TML or the EVT.

Conclusions

In this paper, we present the first detailed geologic map and the first measured section of the type locality for the Stanislaus Group. These data demonstrate a complex stratigraphy, due to erosional surfaces between formations and members, but also demonstrate that the type locality contains the most complete stratigraphic section of the Stanislaus Group yet recognized in the Sierra Nevada. All formations and members of the Stanislaus Group were guided down the ‘Cataract’ palaeocanyon, which must have been an important palaeomorphological feature. This work thus refocuses attention on Slemmons’ type section (1966) and away from Noble *et al.*’s (1974) more convenient reference section.

Our work also recognizes the first known effusive equivalent of the EVT (i.e. the Lava Flow Member), with the same trachydacitic composition.

The Stanislaus Group records a distinctive high-K pulse of magmatism. Volcanism alternated between effusive and explosive eruptive styles, and complexly alternated between mafic, intermediate, and silicic compositions, over a period of at least 1 million years. Future work will determine how many of the outcrop, petrographic, geochemical, and palaeomagnetic characteristics of lava flows and ignimbrites discussed here can be used for regional-scale correlations.

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