International Geology Review
Vol. 51, Nos. 9–11, September–November 2009, 824–842

An in-depth look at distal Sierra Nevada palaeochannel fill: drill cores through the Table Mountain Latite near Knights Ferry

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(*Accepted 24 March 2009*)

The ~10.4 Ma Table Mountain Latite (TML) consists of high-K trachyandesite lavas that likely erupted from the Little Walker Center near Sonora Pass and flowed 80 miles (130 km) through the palaeo-Stanislaus river channel to Knights Ferry in the Sierra Nevada foothills. Complete sections through the proximal facies of the flow stratigraphy are common in the high-Sierra and along range-front faults, but in much of its distal facies in the Sierra Nevada foothills, the internal features of the unit are poorly exposed. Condor Earth Technologies offered us the opportunity to study three complete vertical sections through the distal facies of the TML through access to three drill cores. These cores, spaced 1500′ (457 m) apart and oriented oblique to inferred flow direction by 30°, are referred to here as cores A, B, and C, in a down-palaeoflow direction.

Previous outcrop studies of the distal TML over the past century have concluded that the distal TML consists of a single flow. This is true of core B, which is dominated by a single 144′ (44 m) thick flow, underlain by a thin (~5′, 1.5 m) flow with a vesiculated top, inferred to represent a toe of the thick flow, inasmuch as there is no baked zone or weathered contact between them. This contrasts sharply with core C, where the 50′ (15.2 m) thick TML consists of four flows 5–12′ (1.6–3.6 m) thick, each also defined by vesiculated tops, but differing in having weathered tops 1–2′ (0.3–0.6 m) thick, inferred to record an eruptive hiatus between each flow. The third flow in core C appears to be geochemically distinct from both overlying and underlying units, although all of the core samples are petrographically similar. The TML in cores C and B overlies coarse-grained andesitic volcaniclastic debris and fluvial deposits. By contrast, in core A, the TML overlies very fine-grained siltstones interpreted to record deposition in still water, probably a small lake produced by damming of the river by the thick flow in core B. The TML in core A is 20′ (6 m) thick, and is composed of eleven 1–3′ (0.3–1.0 m) thick couplets, each consisting of a clay-altered hyaloclastite breccia passing upwards into a relatively fresh, nonbrecciated, vesiculated top. We interpret these couplets to represent thin toes of a flow that generated steam explosions when they came into contact with a standing body of water.

Palaeomagnetic remanence data (inclination only) on lava flows from the cores are consistent with the Classic Table Mountain direction and inconsistent with directional results from any other Stanislaus Group lava flows published to date. Thus, by palaeomagnetic correlation, the lavas studied here were emplaced between 10.36 ± 0.06 and 10.41 ± 0.08 Ma. In addition, remanence results suggest that the three sampled flows from core C were erupted over a time period shorter than the secular variation rate (i.e. less than a few centuries) and the Knights Ferry portion of the TML was emplaced within several centuries of the average Classic TML age range

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ISSN 0020-6814 print/ISSN 1938-2839 online

DOI: 10.1080/00206810902944960
http://www.informaworld.com

spanning the Sierra Nevada. This indicates that the weathered flow tops at Knights Ferry formed very quickly.

Keywords: Sierra Nevada; Ancestral Cascades arc; high-K magmatism

Introduction

The 10.4 Ma Table Mountain Latite (TML) consists of voluminous high-K lavas that flowed westwards through palaeochannels across the central Sierra Nevada to the Central Valley (Figure 1; Ransome 1898; Slemmons 1953, 1966; Noble *et al.* 1974; Priest 1979; King *et al.* 2007; Busby *et al.* 2008a,b; Busby and Putirka 2009). It is the second largest known lava flow unit in California, after the 16 Ma Lovejoy Basalt (Garrison *et al.* 2008). The TML occupies the 'Cataract palaeochannel' of Ransome (1898) and Lindgren (1911), a palaeo-river valley that roughly coincides with the modern Stanislaus River. Like other palaeochannels of the Sierra Nevada, this palaeochannel is cut into Mesozoic rocks that were uplifted and deeply eroded in Late Cretaceous to Palaeocene time, and it is filled with Eocene to Miocene sedimentary and volcanic rocks (Lindgren 1911; Bateman and Warhaftig 1966; Wakabayashi and Sawyer 2001; Busby *et al.* 2008a,b).

In this paper, we report new stratigraphic, petrographic, and palaeomagnetic data from the distal facies of the TML, in the Sierra Nevada foothills near Knights Ferry. The proximal facies of the lava flow stratigraphy is very well exposed in the high Sierra and along range-front faults, due to glacial erosion and extension, respectively, but the internal stratigraphy of its distal facies in the Sierra Nevada foothills is poorly exposed, and therefore not well known. We took the opportunity provided by Condor Earth Technologies to study three complete drill cores through the distal facies of the TML, drilled for Oakdale Irrigation District in preparation for building a water tunnel under the latite. The lava flow stratigraphy revealed in the cores is much more complex than that exposed in outcrop, and is the main focus of this study.

Stratigraphy of Tertiary volcanic rocks in the Sonora Pass to Sonora region

Miocene andesitic volcanic and volcaniclastic rocks of the central Sierra Nevada are commonly referred to as the Merhten Formation (Figure 2; Curtis 1951, 1954). In the Sonora Pass region, however, distinctive high-K volcanic rocks of the Stanislaus Group lie within the andesite section; there, the underlying andesites are referred to as the Relief Peak Formation, and the overlying andesites are referred to as the Disaster Peak Formation (Figure 2; Slemmons 1953, 1966).

Ransome (1898) was the first to recognize some of the stratigraphic complexities of the high-K volcanic rocks, by mapping biotite augite latites between augite latite lava flows of the underlying TML and overlying Dardanelles Formation. Slemmons (1966) later recognized these biotite augite latites to be ash-flow tuffs/ignimbrites, and named them the Eureka Valley Tuff (EVT). Noble *et al.* (1974) divided the EVT into three members, the biotite-rich Tollhouse Flat Member, the By-Day Member, and the largely nonwelded Upper Member, and inferred that the Dardanelles Formation lay above the Upper Member (Figure 2). The TML was recently dated at 10.41 $\pm$ 0.08 Ma, and the EVT at 9.54 $\pm$ 0.04 to 9.34 $\pm$ 0.04 Ma, with the Upper and By-Day members overlapping within analytical uncertainty at ca. 9.4 Ma (Figure 2; Table 1; Busby *et al.* 2008b; Pluhar *et al.* 2009). The Dardanelles Formation was distinguished from the TML by its stratigraphic position above the EVT (Noble *et al.* 1974), although no maps or measured sections of this relationship

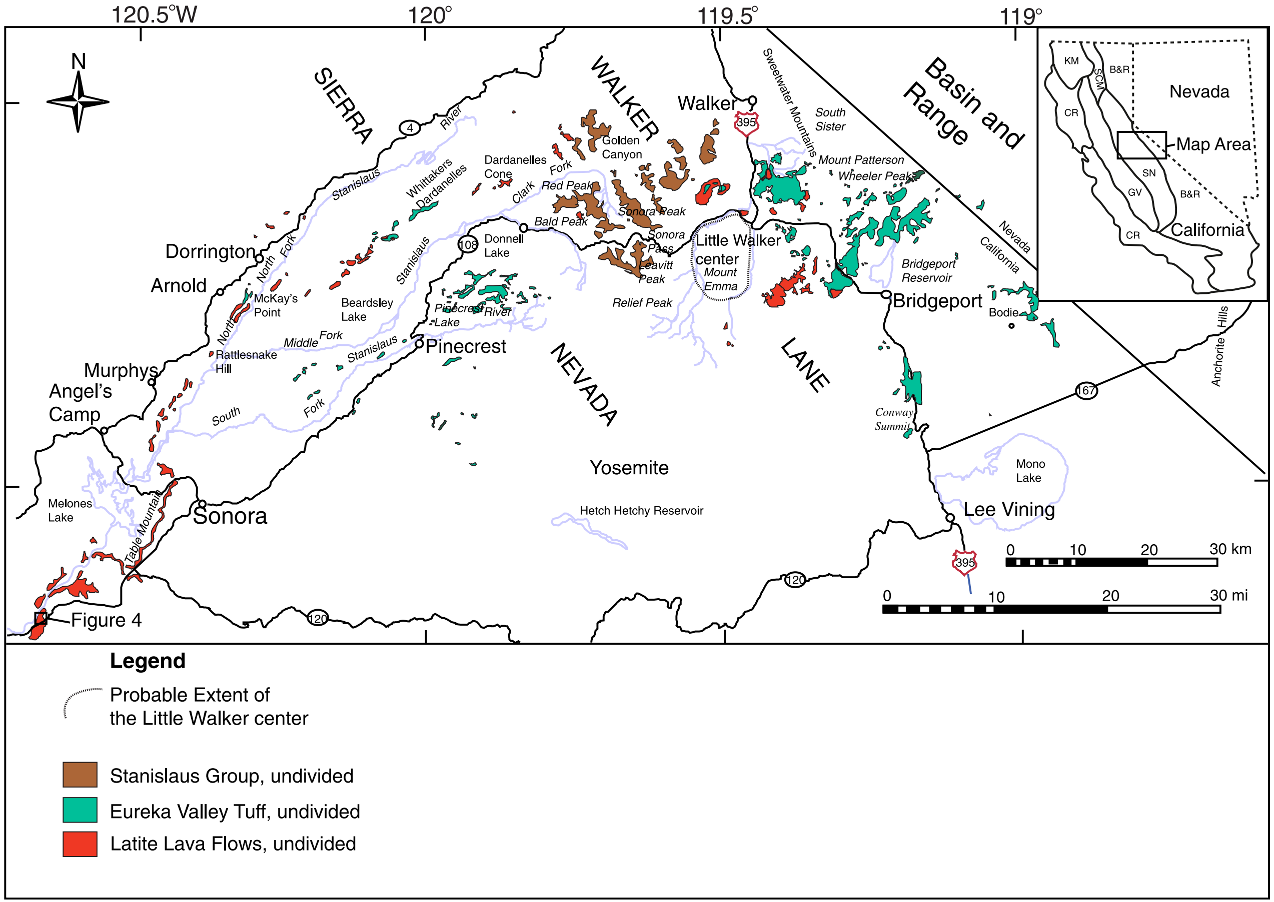
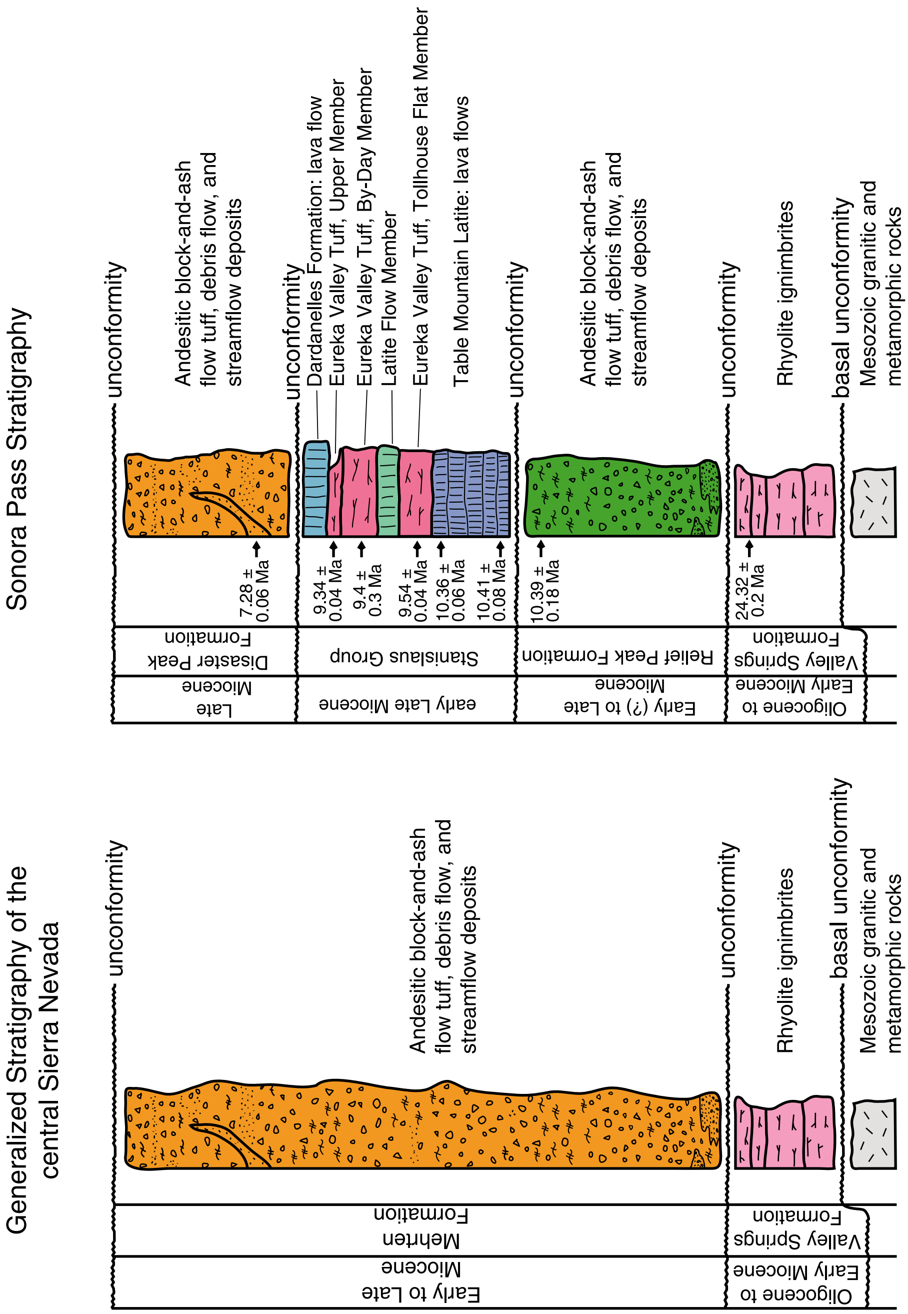


Figure 1. Distribution of high-K volcanic rocks of the central Sierra Nevada (Stanislaus Group), modified from King *et al.* (2007). Inset shows physiographic setting: B&R, Basin and Range; CR, Coast Ranges; GV, Great Valley; KM, Klamath Mountains; SCM, Southern Cascade Mountains; SN, Sierra Nevada.


Generalized Stratigraphy of the central Sierra Nevada
Early to Late Miocene
Mehten Formation
unconformity
Andesitic block-and-ash flow tuff, debris flow, and streamflow deposits
Oligocene to Early Miocene
Valley Springs Formation
unconformity
Rhyolite ignimbrites
basal unconformity
Mesozoic granitic and metamorphic rocks
Sonora Pass Stratigraphy
Late Miocene
Disaster Peak Formation
unconformity
7.28 ± 0.06 Ma
Andesitic block-and-ash flow tuff, debris flow, and streamflow deposits
early Late Miocene
Stanislaus Group
unconformity
9.34 ± 0.04 Ma
9.4 ± 0.3 Ma
9.54 ± 0.04 Ma
10.36 ± 0.06 Ma
10.41 ± 0.08 Ma
Dardanelles Formation: lava flow
Eureka Valley Tuff, Upper Member
Eureka Valley Tuff, By-Day Member
Latite Flow Member
Eureka Valley Tuff, Tollhouse Flat Member
Table Mountain Latite: lava flows
Early (?) to Late Miocene
Relief Peak Formation
unconformity
10.39 ± 0.18 Ma
Andesitic block-and-ash flow tuff, debris flow, and streamflow deposits
Oligocene to Early Miocene
Valley Springs Formation
unconformity
24.32 ± 0.2 Ma
Rhyolite ignimbrites
basal unconformity
Mesozoic granitic and metamorphic rocks

were presented to prove its existence. However, recent work in presumed vent-proximal areas of the Sierra Nevada range front and the Sweetwater Mountains shows that latite lava flows are present within the EVT, between the Tollhouse Flat and By-Day members (Hagan *et al.* 2008). This called into question whether the Dardanelles Formation actually exists as a formation that overlies all three members of the EVT (as defined by Noble *et al.* 1976), or whether it should be redefined as a member of the EVT (Hagan *et al.* 2008). As discussed by Koerner *et al*. (2009), we have recently mapped and measured a section, where a latite lava flow not only lies between the Tollhouse and By-Day members but also another flow overlies the Upper Member. We therefore retain the term ‘Dardanelles Formation’ for lava flows that are demonstrably younger than the Upper Member of the EVT, and propose the term ‘Latite Flow Member’ for lava flows between the Tollhouse and By-Day Members of the EVT (Koerner *et al*. 2009).

In summary, it appears that the high-K andesite lava flows erupted for >1 Ma. However, most stratigraphic sections are incomplete, due to a combination of original disparities in the distribution of lava flows and pyroclastic flows, as well as river channel reincision between eruptive events. Palaeomagnetic data can be useful for distinguishing between and correlating lava flows (King *et al.* 2007; Pluhar *et al.* 2009), as shown here.

Most studies of the TML have focused on its proximal facies, along the Sierra Nevada range crest and range front, and in the Sweetwater Mountains to the east, where exposures are excellent (Slemmons 1953, 1966; Noble *et al.* 1974; Priest 1979; King *et al.* 2007; Busby *et al.* 2008b; Pluhar *et al.* 2009). These studies have revealed the presence of up to 23 flows at the Sierra Nevada range crest on Sonora Peak (Busby *et al.* 2008b; Pluhar *et al.* 2009). The present study focuses on the stratigraphy, petrography, and palaeomagnetism of the TML at its most distal locality, just east of Knights Ferry, in the central Sierra Nevada foothills (Figures 1–4).

Methods

The core logging and petrographic analysis for this study were carried out by Gorny, under the supervision of Busby and Hagan, and the geochemical work was carried out by Gorny at CSU Fresno using methods described in Putirka and Busby (2007). Those results were reported in Gorny’s unpublished Senior Honors Thesis at the University of California in 2008. Subsequently, palaeomagnetic work was carried out by Pluhar (using the methods described below), who wrote that section, and Busby revised the Senior Honors Thesis text for publication, with Gorny’s assistance on figures.

Previous work on the TML at Knights Ferry

In the Knights Ferry area, the TML forms the sinuous Table Mountain and is a classic example of inverted topography (see aerial photo courtesy of Gary Hayes, Figure 3).

Figure 2. Stratigraphy of volcanic and volcaniclastic rocks in the central Sierra Nevada. (a) Undifferentiated andesite volcanic–volcaniclastic rocks are referred to as the Merhten Formation. (b) Sonora Pass area stratigraphy, modified from Busby *et al.* (2008a), using new stratigraphic data presented in Koerner *et al.* (2009). Where high-K volcanic rocks of the Stanislaus Group intervene, the andesites are divided into Relief Peak Formation (below) and Disaster Peak Formation (above). Details of the stratigraphy of the high-K volcanic rocks are given in Koerner *et al.* (2009) and Pluhar *et al.* (2009). Ages shown in this figure are summarized in Table 1.

Figure 3. Aerial photograph of Table Mountain, showing inverted topography produced by the TML, which flowed down a palaeochannel. Photograph courtesy of Gary Hayes.

Rhodes (1987) studied the morphology of the modern river and the palaeochannel, and showed that the lava flow backed up one tributary.

For over a century, numerous workers have proposed that only one lava flowed all the way to Knights Ferry (Ransome 1898; Slemmons 1953; Priest 1979; King *et al.* 2007). However, the internal characteristics of the TML are difficult to study in this area, because of incomplete exposure of the interior of the unit, as noted above. We present evidence from drill cores that multiple flows reached the area, although our palaeomagnetic data indicate that this happened in rapid succession.

Beck (1960) was the first to conduct palaeomagnetic analyses on the TML. Recent study of this formation (Pluhar *et al.* 2009) demonstrates that near the Sierra crest, TML spans two reversed polarity subchrons at ca. 10.3 Ma, informally named the Sonora Peak and Table Mountain Events. The time spanned by typical magnetic reversals (Clement 2004) suggests that the TML spans at least 28,000 kyr (Busby *et al.* 2008b). Thus far, palaeomagnetic results from the TML in the Sierra foothills (King *et al.* 2007) exhibit only one palaeomagnetic remanence direction, the distinctive 'Classic Table Mountain' direction ($D = 163.1°$, $I = -26.1°$, a95 $= 2.7°$; King *et al.* 2007). All TML west of about 120.125° west longitude (i.e. west of Whittaker's Dardanelles; Figure 1; King *et al.* 2007)

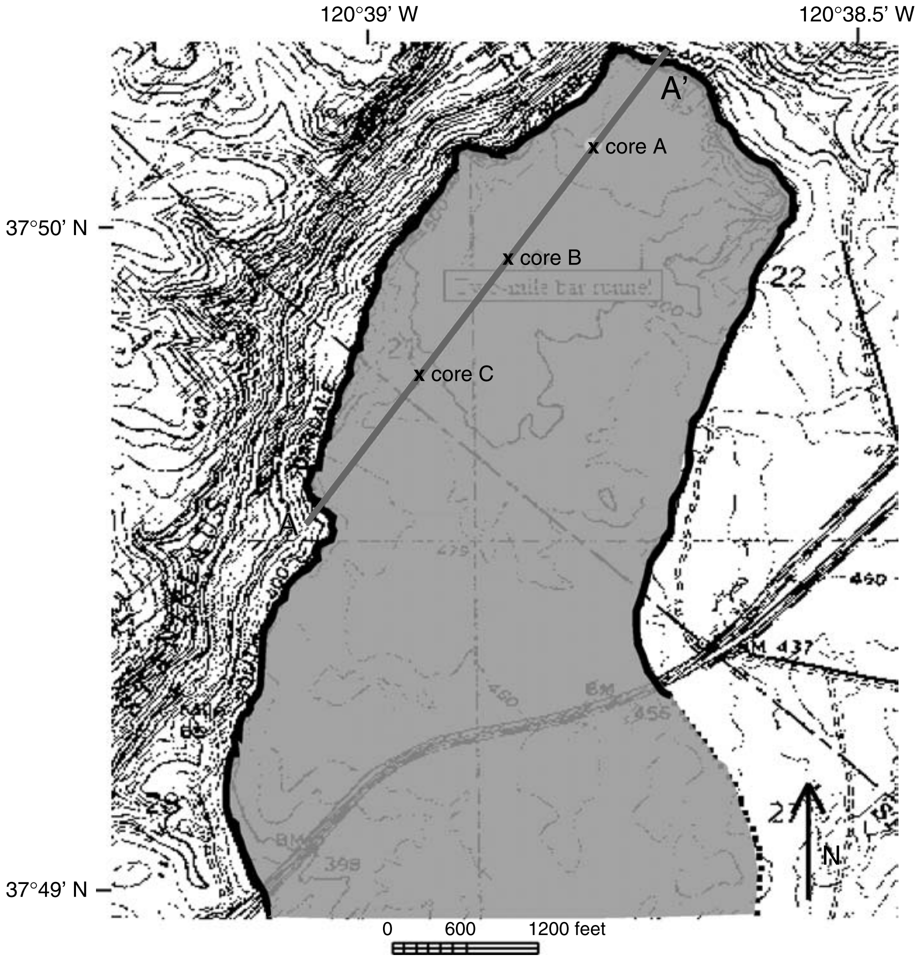


Figure 4. Outcrop map of TML (shaded grey) in the location shown in Figure 2, showing the positions of cores logged in Figure 6.

that has been palaeomagnetically analysed thus far exhibits this direction. This implies that the foothills portion of TML was emplaced during an interval shorter than secular variation – several centuries or less. The current study uses flow stratigraphy and palaeomagnetism to evaluate whether the several lava flows we describe here record a significant time interval, or were instead emplaced in rapid succession.

Field relations and core logs

In outcrops of the Sonora–Knights Ferry area, the TML is underlain by undated andesitic volcaniclastic rocks that we assign to the Relief Peak Formation, using regional correlation (Figure 2; Busby *et al.* 2008b). These rocks rest directly on Jurassic metavolcanic basement rocks. The Relief Peak Formation consists of fluvial and debris flow deposits, all dominated by intermediate-composition volcanic rock fragments. The fluvial deposits are very well-sorted, stratified, clast-supported pebble conglomerates, with scour and fill structures. The debris flow deposits are massive and poorly sorted, with angular pebble- to cobble-sized clasts supported in a granule sandstone matrix. Outcrops of the overlying TML consist of a single flow, with a columnar-jointed interior and a vesicular flow-top breccia (Figure 5).

Condor drilled three 2.5″ (6.35 cm) diameter cores through the TML, each spaced ~1500′ (457 m) apart, in a line trending about 040°–220°; this line appears to be oblique, at a low angle, to the flow direction which we estimate to have been parallel to the overall N–S trend of this part of the sinuous Table Mountain outcrop (Figures 1 and 4). Condor numbered these cores 2, 3, and 4, from south to north. For ease of reference for the reader, we relabel these cores to correspond to the position within the palaeocanyon. Core A is up-palaeocanyon, most proximal to the vent locality, core B is in an intermediate position, and core C is down-palaeocanyon, the most distal to the vent locality (Figure 6). The ground surface elevations for the cores are as follows: core A at 522′, core B at 479′, and core C at 362′. In this section, we describe core B first, because it is composed largely of the very thick flow that has been recognized in outcrop for over a century (Ransome 1898; King *et al.* 2007), and because it is the simplest in terms of stratigraphy. Second, we describe core A, a thin but very complex flow that we infer was emplaced in a lake created by damming of the river behind the very thick flow of core B. Last, we describe core C, which consists of four distinct flows that may have been deposited in a channel incised on the right bank of the thick flow after it was emplaced. The flows in cores A and C are much thinner, with a higher proportion of vesicles, than the flow that dominates core B (Figure 6); as a result, the flows in cores A and C are more easily weathered and eroded, which is probably why they are not recognized in outcrop.

Core B

All but the basal 5′ (1.5 m) of the 152′ (46.3 m) thick latite section in core B are composed of a single flow. We interpret the basal 5′ (1.5 m) of the latite in core B to represent a toe of the thick flow that broke out of the flow front and interacted with a wet substrate. We do

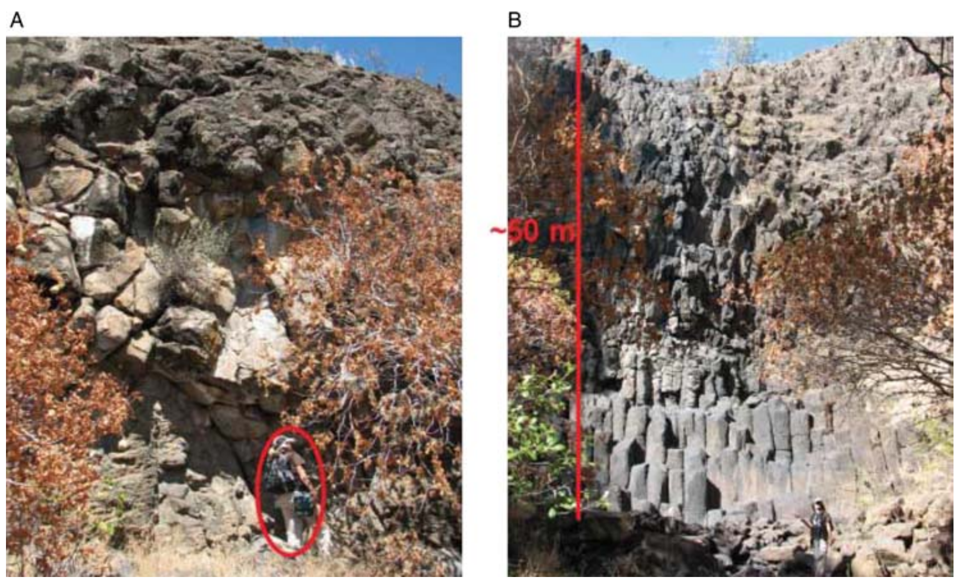


Figure 5. Outcrop photographs of the TML, taken 22 miles up the Stanislaus River from the drill site. (a) Flow-top breccia and (b) columnar-jointed interior of the single very thick flow that is exposed in outcrop.

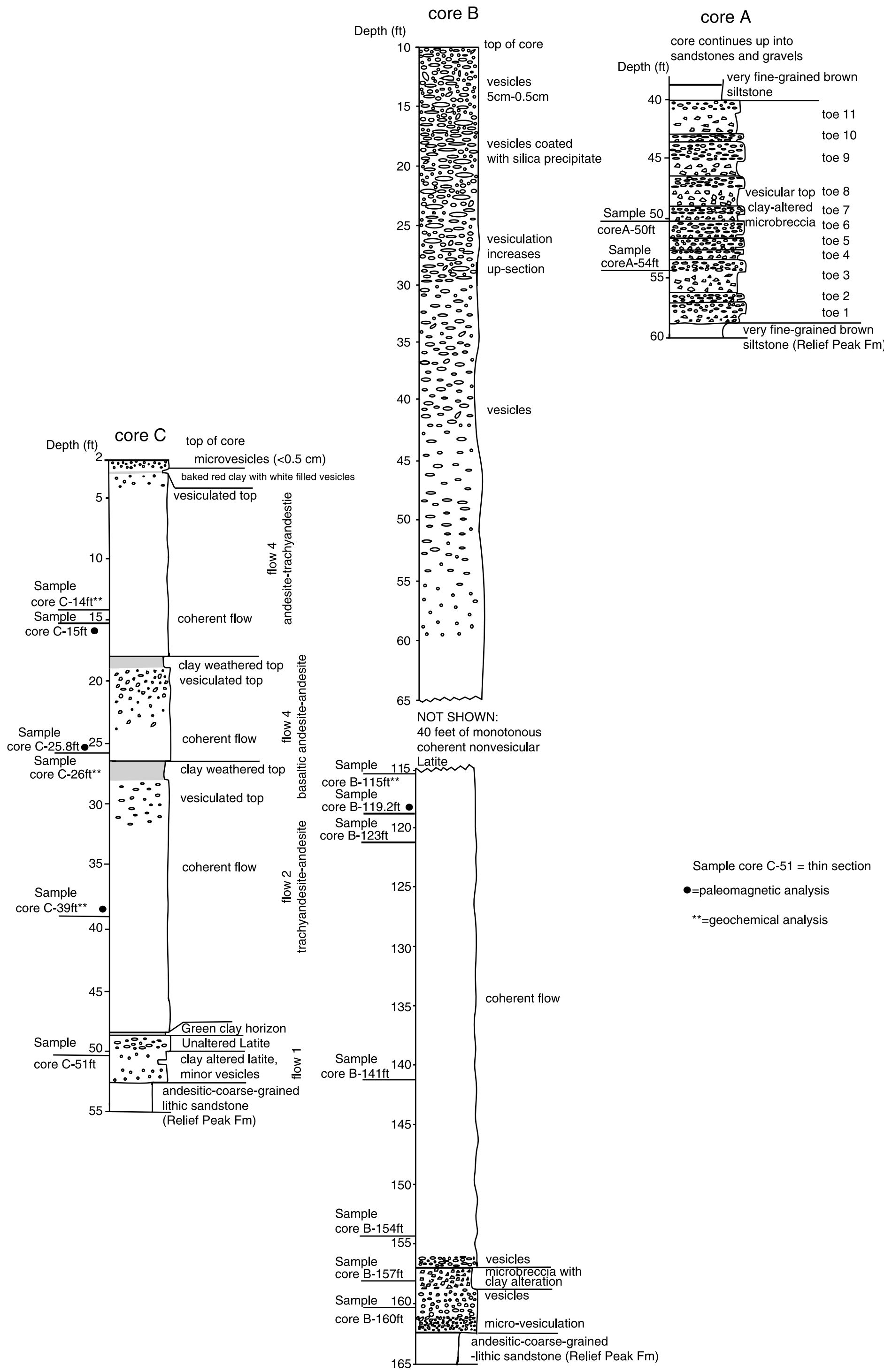


Figure 6. Core logs through the TML; positions of the three cores shown in Figure 4.

not interpret it to be a separate flow from the overlying thick latite, because it is not baked, nor does it have a weathered top (Figure 6). The toe has very small vesicles at the base and top, suggesting that it was quenched against a wet substrate and by water flowing over the top before the vesicles could grow. Furthermore, the top and bottom of the toe has a microbrecciated texture, consisting of angular, small pebble-sized pieces fitting together in jigsaw fashion, with clay minerals in the interstices, further supporting the interpretation that it quenched against a wet substrate in water.

The overlying 147′ (44.8 m) thick latite shows all the features typical of a single thick lava flow. The base is vesiculated, and passes rapidly upwards into a 95′ (29 m) thick section of dense (nonvesicular) coherent flow; this is equivalent to the columnar-jointed interior described in outcrop. Throughout the nonvesicular section, the plagioclase crystals show horizontal flow alignment. Vesicles gradually increase upwards in abundance and size through the upper 50′ (15 m) of the flow. At the top of the core, the vesicles range in size from 0.5 to 5 cm, and commonly show horizontal stretching. The top 10′ (3 m) of the core was not recovered, possibly because it consists of the flow-top breccia that is so obvious in outcrop.

We tentatively interpret the flow in core B to represent the oldest lava flow, because it is far thicker than any other flows (e.g. it is more than six times thicker than the second thickest flow, which is flow 2 of core C; Figure 6). This suggests that it filled the deepest part of the palaeochannel, and that the thinner flows in cores C and A were emplaced around it, in shallower parts of the palaeochannel. Furthermore, as discussed below, we infer that the flows in core A entered a lake or pond that formed upstream from the thick flow in core B immediately after it was emplaced. However, the possibility remains that some or all of the flows in core C were emplaced before the thick flow in core B.

Core C

Core C consists of four flows, 5–20′ (1.5–6 m) thick, with vesicles marking the upper part of each flow (Figure 5). Flow 1 is capped by a thin bed of green mudstone, recording a brief period of sedimentation, while the overlying two flows (flows 2 and 3) are weathered to clay in their upper 1–2′ (0.3–0.6 m; Figure 6), perhaps representing somewhat more time between them. We have considered the possibility that the flow-top clay alteration occurred long after emplacement of all of the flows, perhaps by fluids moving through the section along the contacts between lava flows; however, this process would have altered the base of each flow as well as its top, and the bases are fresh. The chemistry of flow 3 (discussed below) appears to be distinct from that of the underlying and overlying flows, supporting the interpretation that these are distinct flows, and not just toes of the thick flow in core B.

None of the flows in core C exhibit flow-top breccias, so they were likely pahoehoe flows, similar to some of the flows of the TML closer to the source (Busby *et al.* 2008b). Flow 1 is altered to clays at its base, perhaps because it was emplaced on a wet substrate. Flow 4 is capped by red clay, which in turn is overlain by a very thin (0.6 m) vesicular latite that represents the base of a fifth flow that has been eroded away.

Core A

Core A penetrated the thinnest but most complex latite section (Figure 6). The core penetrated sandstones and conglomerates, and then passed downwards through very fine-grained, brown siltstone that both overlies and underlies the latite. These siltstones contrast markedly with the typical coarse-grained nature of the andesitic volcaniclastic palaeochannel fills in the central Sierra. We interpret them to record deposition in quiet water, perhaps in a lake that was dammed up behind the thick lava flow of core B (as noted above). The siltstones lack the thin lamination one would expect in lake sediments, but this could be an artefact of the drilling process, as they are not very well consolidated.

Textural features of the latite in core A are consistent with deposition in water. Although it is only 28′ (8.5 m) thick, core A consists of 12 distinct layers, each with a base of clay-altered microbreccia and an unaltered vesicular top. Because each layer is so thin (1–3′; 0.3–1.0 m), and the layers are not separated by sediment or weathered tops, we interpret these layers to represent toes that broke out from the front of a lava flow into a standing body of water, rather than representing distinct lava flows. We interpret the clay-altered microbreccia of each toe to record quench fragmentation and shattering by steam explosions as each toe poured into the shallow lake; the fine-grained component of this shattered material was readily altered to clays.

Petrographic, modal, and geochemical analysis

Modal analysis of all of the flows in the cores shows relatively minor variation in crystal abundance between samples (Figure 7). We analysed two samples from the inferred toe of the thick flow in core B (160′/48.8 and 157′/47.8 m), four from different levels of the thick flow in core B (154′/46.9, 141′/43, 123′/37.5, and 115′/35 m; Figure 7), and a sample from each flow of the four flows in core C. It was difficult to find fresh material to sample from core A because of the brecciated and clay-altered nature of the thin toes, so we analysed only two of the inferred toes, from the vesicular parts of the couplets (Figure 7).

Perhaps the most distinctive feature of the TML is the well-developed sieve textures in the plagioclase (Figure 8; Ransome 1898). We also report less well-developed sieve textures in the clinopyroxene. The plagioclase laths are euhedral, range in size from 1–7 mm, and have albite and pericline twinning, with oscillatory zoning confined to the crystal rims. The clinopyroxene phenocrysts are 1–5 mm in size and are largely subhedral. The clinopyroxene displays deformation lamellae and dark brown alteration along the edges of broken crystals. Clinopyroxene crystals with embayed outlines are commonly rimmed by plagioclase laths. Although globular-shaped olivine is recognized as a minor phenocryst phase in the thick flow of core B, it is present in the groundmass of all samples, and is largely or completely altered to iddingsite in all samples; thus, we cannot reliably determine variations in olivine content. Other minor crystal phases include orthopyroxene, sphene, apatite, and oxides (Figure 7). The groundmass is composed of plagioclase laths, clinopyroxene, oxides, clay, and perhaps some relict glass.

Using observations of inclusions, the approximate crystallization history of the melt is inferred to be the same for all of the flows in all three cores. Inclusions of clinopyroxene, oxides, orthopyroxene, and olivine in some samples occur within plagioclase crystals. Inclusions of plagioclase, oxides, apatite, orthopyroxene, and olivine in some samples occur within clinopyroxene (Figure 8). Thus, the inferred crystallization sequence is that olivine, orthopyroxene, and oxides crystallized first, but not necessarily in that order, and then plagioclase and clinopyroxene crystallized cotectically. Furthermore, it appears that the olivine, orthopyroxene, and oxides continued to crystallize after the initiation of clinopyroxene and plagioclase crystallization. The sieve textures could be a result of decompression or melt disequilibrium (Kuscu and Floyd 1999), although they more likely

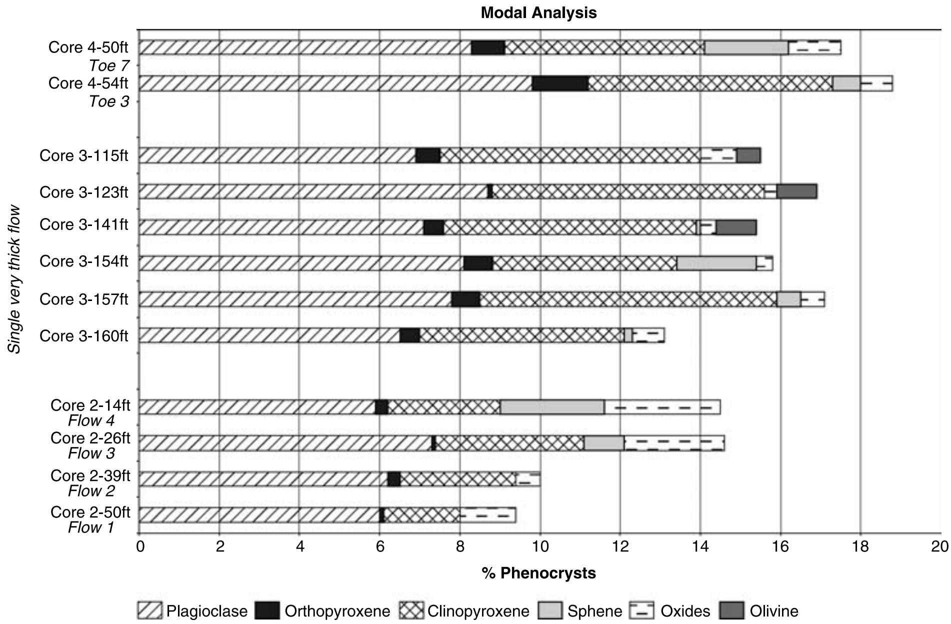


Figure 7. Modal analyses of samples from cores through the TML. Positions of samples are plotted on the core logs shown in Figure 6.

record magma mixing; thus, many of these phenocrysts may have crystallized from magmas with at least slightly different compositions and temperatures (Streck 2008). Variations in shape and grain size of plagioclase support the hypothesis that four flows are present on core C. In flows 1 and 2, the plagioclase phenocrysts are subhedral to anhedral, with a few euhedral grains in flow 2; however, the plagioclase crystals in flow 1 are smaller (1–6 mm) than they are in flow 2 (1–11.5 mm). In flows 3 and 4, the plagioclase phenocrysts are dominantly euhedral, with minor subhedral grains.

We analysed four samples for geochemistry (Figure 9): the thick flow in core B, and flows 2–4 in core C. We did not analyse flow 1 in core C, or the toe in core B, or any of the numerous toes in core A because they are vesicular (with amygdule fillings) or altered to clay. Similar to the modal analyses, the geochemical data cluster close together in the trachyandesite field, except for flow 3 of core C, which appears to be more mafic than the other flows (Figure 9).

Palaeomagnetic methods and results

We analysed one sample each from the four intervals indicated in Figure 6 (Figure 10). We avoided sampling core C flow 1 because emplacement of the much-thicker flow 2 on top likely remagnetized flow 1. Similarly, the core C flow 3 sample may have suffered partial remagnetization by emplacement of the 18′-thick overlying flow 4. However, the stratigraphic position of samples from core C flows 2 and 4 indicates that they should be free of the effects of baking. In practice, the results from flows 2 and 4 are indistinguishable from one another, so a secondary component or completely remagnetized flow 3 would not be noticeable.

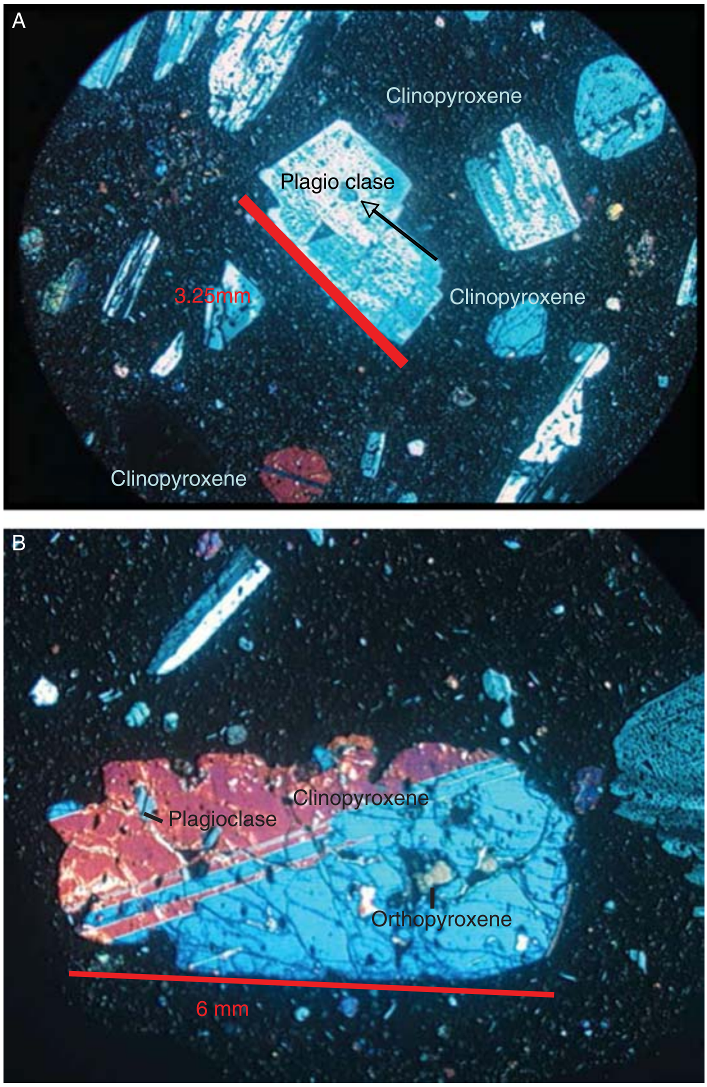


Figure 8. Photomicrographs of the TML, showing (a) plagioclase and clinopyroxene phenocrysts, and (b) mineral inclusions in clinopyroxene; inferred order of crystallization discussed in text.

Samples were oriented with respect to vertical to within a few degrees, but due to the drilling method employed, they were horizontally unoriented. For this reason, we compare only the inclinations of sample characteristic remanent magnetization (ChRM) directions (method of McFadden and Reid 1982; within Palaeomac – Cogné 2003).

Alternating field demagnetization experiments revealed sample ChRM directions by 50 mT and continued through 200 mT. Principal component analysis (Kirschvink 1980) of demagnetization data yielded maximum angular deviation (MAD) angles less than 10° for these samples. The up (reversed) and shallow inclinations in core C were indistinguishable from one another (Table 1), though the usual rigorous tests for this are not relevant because of our one-sample-per-flow sampling. Core C data yield a mean inclination of $-22.4° \pm 4.9°$ ($n = 3$). This result is statistically indistinguishable from the Classic

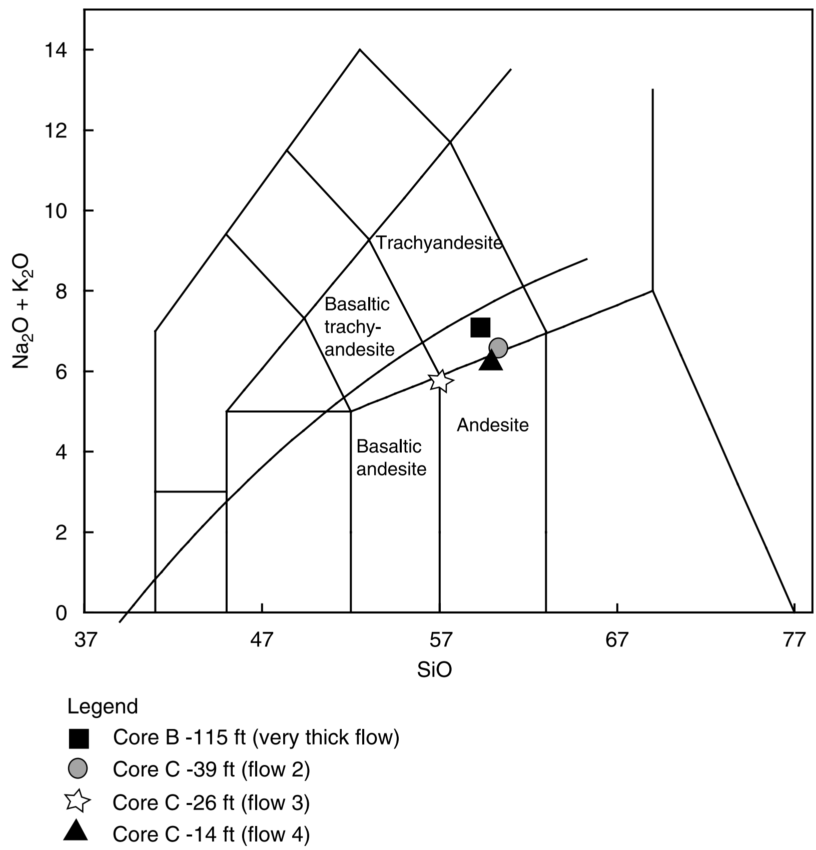


Figure 9. Alkali–silica classification diagram (Le Bas 1986) of four samples from the TML. The very thick flow of core B is indistinguishable from flow 2 of core C. However, flow 3 of core C appears to be geochemically distinct form the underlying and overlying flows. The very thin flow toes of core A and flow 1 of core C were not analysed due to clay alteration.

Table Mountain direction defined by King *et al.* (2007) ($D = 163.1°$, $I = -26.1°$, a95 $= 2.7°$). The core C mean ChRM inclination differs somewhat from the result for the core B sample. However, due to the small number of independently oriented samples available, and the expected random analytical and orientation errors of a few degrees on each sample, the difference between cores C and B samples is not deemed significant.

The distinctive mean inclination for all Knights Ferry samples ($I = -24.5° \pm 7.3°$) is indistinguishable from the Classic Table Mountain direction, which is found at sites from Sonora Peak to the foothills. This direction records an interlude that Pluhar *et al.* (2009) informally call the Table Mountain Event, which occurred between 10.36 $\pm$ 0.06 and 10.41 $\pm$ 0.08 Ma, around the time of subchron C5n.2n-2 (10.309–10.313 Ma; Evans *et al.* 2007). The age constraints stem from $^{40}Ar/^{39}Ar$ dating of the top and bottom flows at Sonora Peak locality (Table 1; Busby *et al.* 2008b); this section consists of 23 latite lava flows of dominantly normal polarity with one lava flow carrying the Classic Table Mountain direction.

It is possible to infer the duration of emplacement of the TML carrying the Classic Table Mountain direction, due to the similarity in remanence direction between sites. Palaeomagentic results from two sites that are statistically indistinguishable from one

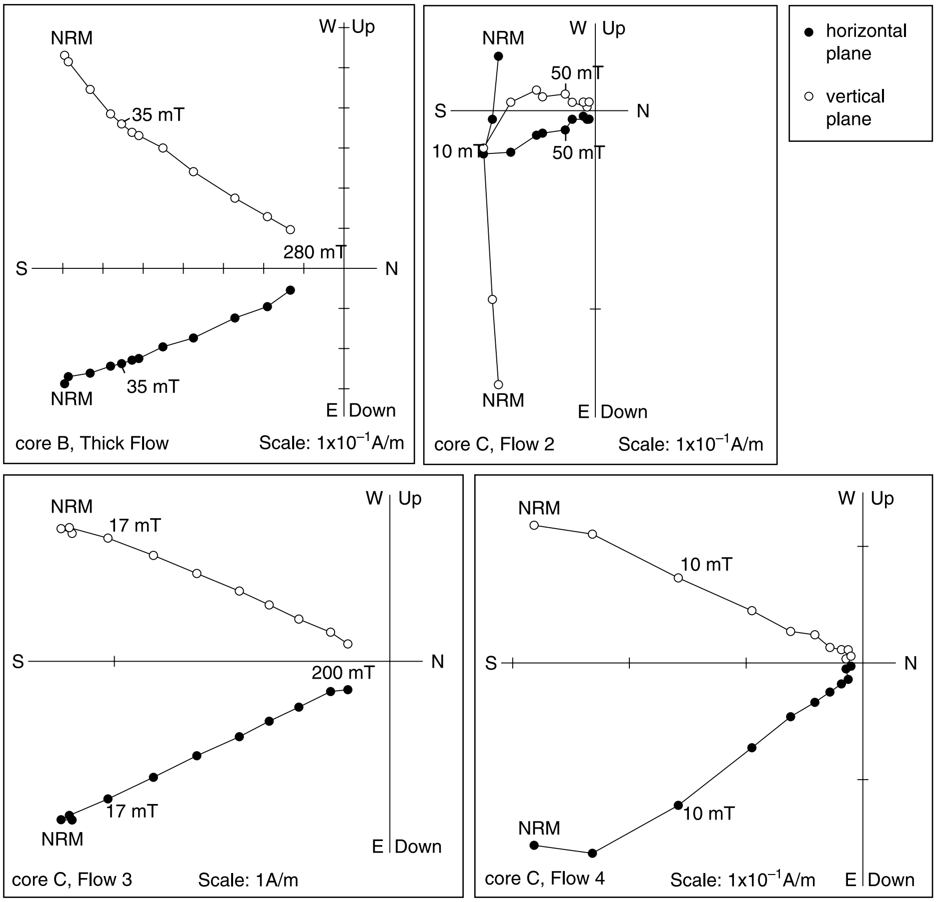


Figure 10. Zijderveld diagrams depicting alternating field demagnetization experiments. Stable ChRM directions are evident from the linear portion of each demagnetization path that is colinear with the origin.

another indicate eruption of the compared rocks within a period shorter than the secular variation of Earth's magnetic field, within the analytical error. A typical secular variation rate is 2° per century (Hagstrum and Champion 1995; Malin and Bullard 1981), while the Knights Ferry data yield a confidence interval of $\pm 7.3°$. Thus, differences in age of emplacement of about four centuries or more for these rocks would yield remanence directions that are statistically distinguishable from one another. More rapid emplacement would result in statistically identical remanence directions. By this logic, TML lavas at Knights Ferry were emplaced within about four centuries or less of TML carrying the Classic Table Mountain direction elsewhere in the Sierra Nevada and foothills. As would be expected, our data also suggest that flows within the Knight's Ferry study area were erupted within four centuries of one another, though the limited sampling prevents rigorous testing of within-site variability.

Several conclusions result from these data. (1) Elsewhere in the Sierra Nevada, only one unit within TML carries the Classic Table Mountain direction ($D = 163.1°$, $I = -26.1°$, a95 = 2.7°; King *et al.* 2007). Knights Ferry TML exhibits a statistically identical ChRM. Thus, we explicitly correlate flows 2–4 within core C and the thick flow

Table 1. Summary of age controls on Sonora Pass stratigraphy, summarized in Figure 2.

Sample	Geochemistry	Mineral	Latitude (°N)	Longitude (°W)	WMPA	IsoA	Interpreted age (Ma)[1]		Nominal age (Ma)[2]		Preferred age (Ma)[3]		Unit name
							Age	±2σ	Age	±2σ	Age	±2σ	
BP068	Andesite	Hbl	38.37609	119.7698	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	119.7698	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	119.4479	9.11 ± 0.04	9.10 ± 0.08	9.14	0.04	9.28	0.04	9.34	0.04	Upper Member, EVT – Stanislaus Gp
TF003	–	Bio	38.43096	119.4479	9.18 ± 0.04	9.20 ± 0.04	9.18	0.04	9.32	0.04	9.38	0.04	Upper Member, EVT – Stanislaus Gp
TF005b	–	Plag	38.43041	119.4481	9.19 ± 0.32	9.10 ± 0.52	9.2	0.3	9.34	0.3	9.4	0.3	By-Day Member, EVT – Stanislaus Gp
TF009	–	Plag	38.42891	119.4484	9.27 ± 0.04	9.30 ± 0.10	9.27	0.04	9.41	0.04	9.47	0.04	Tollhouse Flat Member, EVT – Stanislaus Gp
TF009	–	Bio	38.42891	119.4484	9.35 ± 0.04	9.32 ± 0.06	9.34	0.04	9.48	0.04	9.54	0.04	Tollhouse Flat Member, EVT – 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	119.6326	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
PC-AD	Latite	WR	38.34641	119.6327	10.34 ± 0.04	na	10.35	0.25	10.51	0.25	10.58	0.25	Subalkalic andesite dike – Upper Relief Peak Fm
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	na	na	~10	na	~10	na	~10	na	Block-and-ash flow tuff – Upper Relief Peak Fm
BP057	–	Plag	38.37824	119.7430	na	na	23.8	0.2	24.16	0.2	24.32	0.2	Uppermost welded ignimbrite – Valley Springs Fm

WMPA is the data reported by Busby *et al.* (2008a). IsoA is the data reported by Busby *et al.* (2008b).
[1]Interpreted age is calculated using 27.60 Ma for the FCs standard as reported by Gans (Busby *et al.* 2008b).
[2]Nominal age is calculated using 28.02 Ma for the FCs standard (Renne *et al.* 1998).
[3]Preferred age is calculated using 28.201 Ma for the FCs standard (Kuiper *et al.* 2008).

in core B to all other TML carrying the Classic Table Mountain direction, and infer that all Knights Ferry latites are similarly correlative. (2) Since, TML carrying the Classic Table Mountain direction has been dated at ca. 10.4 Ma elsewhere in the Sierra Nevada (Pluhar *et al.* 2009), the latites studied at Knights Ferry are dated by this correlation. (3) Since core C flows 2–4 yield the same inclination, within error, they were probably erupted in a short interval relative to secular variation – within four centuries of one another, and the Knights Ferry TML was also erupted within four centuries of the Classic TML elsewhere in the Sierra Nevada.

Conclusions

Previous work on the TML in its distal facies at Knights Ferry has concluded that Table Mountain is composed of a single lava flow (Ransome 1898; Slemmons 1953; Priest 1979; King *et al.* 2007) and that this lava flow reached the Sierra Nevada foothills through a palaeochannel that preserves 23 distinct flows in its more proximal reaches at the Sierra Nevada crest. Our work analysing a series of three cores through the latite in its distal facies reveals a more complex stratigraphy, with one core penetrating at least four flows. However, one very thick flow dominates one of the cores. We infer that thinner flows are not observed in outcrop because they have a higher proportion of vesiculated and clay altered material, and are thus more easily eroded. Additionally, the cores preserve a sedimentary record of a lake that was dammed behind the thick flow, and partly filled with a series of toes from a flow that quenched and shattered upon contact with the water. The petrographic and geochemical characteristics of the TML are all uniform, with the possible exception of flow 3 from core C, which may be more mafic. Palaeomagnetic results are consistent with the 'Classic Table Mountain' direction and inconsistent with directional results from any other Stanislaus Group lava flows published to date, thus indicating an age of ca. 10.4 Ma for these lavas. The remanence data exhibit no discernable secular variation and therefore constrain emplacement of TML at Knights Ferry to a several centuries or less. This indicates that the weathered tops on individual lava flows formed very quickly, perhaps due to the fact that they lay within a river valley.

Acknowledgements

A very special thanks to Dr Donald Bishop and Dr John Kramer and the rest of the crew at Condor, for supervising the senior author's senior thesis research during summer 2007, and for providing continued access to their cores and data during the 2007–2008 academic year. We also thank Dr Bishop and Dr Kramer for their reviews of this manuscript. We thank Gary Jernigan at the Oakdale Irrigation District for allowing access to the cores and property, and to Albert Conlin for allowing access to his land. We owe many thanks to Professor Frank Spera and to graduate students Duane DeVecchio, Sarah Fowler, and Emily Peterman (all at UC Santa Barbara) for the assistance and advice they gave the senior author. We thank Alice Koerner for assistance on drafting figures. Funding for this project was provided by National Science Foundation grants EAR-0711276 (to Busby and Putirka) and EAR-0711181 (to Busby), and by the Undergraduate Research and Creative Activities grant (to Gorny).

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