Ash-flow tuffs in the Nine Hill, Nevada, paleovalley and implications for tectonism and volcanism of the western Great Basin, USA

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ABSTRACT

Cenozoic ash-flow tuffs are key units for analyzing the tectonic and magmatic evolution of the Great Basin. The tuffs are commonly assumed to have spread nearly radially from source calderas and to have formed nearly continuous, flat-lying deposits. Based on detailed mapping and paleomagnetic investigations of the Nine Hill paleovalley in western Nevada and analysis of the regional distribution of the 27–23 Ma tuffs that crop out in the paleovalley, we find numerous features that differ markedly from these presumed characteristics.

Many individual ash-flow tuffs can be correlated from their source calderas in the central Nevada caldera belt westward into the Sierra Nevada of eastern California. Present-day distances from source to distal, primary tuff deposits are as much as ~295 km. Corrected for extension, original flow distances were as much as ~200 km. The tuffs flowed, were deposited, and are preserved primarily in deep (as much as 1.2 km) but wide (8–10 km) paleovalleys. The tuffs were able to flow these great distances because they were channelized, did not disperse, and did not mix with air as much as would tuffs that spread more radially. Tuffs probably spread more radially only within a few tens of kilometers of source. The paleovalleys held major rivers that drained from a “high” plateau in the present Basin and Range Province and Walker Lane and flowed across the Sierra Nevada to the Pacific Ocean in what is now the Great Valley. The Basin and Range–Sierra Nevada structural and topographic boundary did not exist before 23 Ma, the age of the youngest tuff in the Nine Hill paleovalley. Any faulting in western Nevada before 23 Ma was insufficient to disrupt the paleodrainages other than temporarily.

Deposition of tuffs in paleovalleys produced several features relevant to interpreting the tectonic evolution of the region. Most tuffs show primary dips, commonly up to ~20° and locally up to near vertical, because they compacted against gentle to steep paleovalley walls. Angular unconformities, unrelated to tectonism, are common where tuffs were deposited on eroded tuffs that had primary dips. The tuffs are commonly interbedded with coarse clastic deposits that originated either as channel deposits in high discharge, possibly high gradient rivers, or from floods induced by failure of dams, whereby a tuff temporarily blocked drainage.

Tuffs show highly asymmetric, elliptical distributions, preferentially west of their source calderas, because they flowed in the westward-draining paleovalleys. Although deposited continuously along the paleovalleys, tuffs were subsequently eroded by the rivers, so that tuff distributions are highly discontinuous both between and along individual paleovalleys. Thicknesses of tuffs vary irregularly with distance from source, and some tuffs are as much as 300 m thick even 150 km (primary distance) from source. Thickness variations probably are in part due to variations in width and depth along paleovalleys. Estimates of tuff volumes should not assume radial distribution or continuous deposition between paleovalleys, which give unreasonably large volumes. In ideal cases where the source caldera is well understood, the best way to estimate erupted volume can be from the volume of caldera collapse (i.e., area within ring fracture × amount of subsidence).

INTRODUCTION

Cenozoic ash-flow tuffs of the Great Basin and many other regions are key indicators of both tectonic and magmatic processes. The tuffs are commonly used as the dominant structural markers to measure extension with the assumptions that their compaction foliation records paleohorizontality and that any divergence from horizontal reflects tilting and/or vertical-axis rotation during later deformation (Anderson, 1971; Proffett, 1977; Geissman et al., 1982; Chamberlin, 1983). An obvious corollary is that any angular discordance between different tuffs must result from deformation that occurred between their depositions. Because ash-flow tuffs are the most voluminous volcanic rocks of the Great Basin, especially during the mid-Cenozoic “ignimbrite flare-up” (Best et al., 1989), estimates of their volumes are major factors in evaluating magmatic processes such as mass and heat flux from the mantle, interaction with the crust, and assembly of crustal magma chambers (e.g., Best and Christiansen, 1991; Johnson, 1991; Perry et al., 1993; Lipman, 2007; Farmer et al., 2008). Volume estimates commonly assume that the tuffs were deposited as essentially continuous sheets with a near radial distribution around their sources, both in the Great Basin and worldwide (Ekren et al., 1980; Cas and Wright, 1987; Best et al., 1995). Distribution can, in turn, be used to infer displacements on strike-slip faults (Faulds et al., 2000, 2005a, 2005b; Henry et al., 2002; Hardeman et al., 2003), and asymmetric distributions have been used to evaluate the amount and direction of regional extension (Gans et al., 1989; Colgan et al., 2008).

The assumptions of “paleohorizontality” and essentially continuous, semiradial sheets are true as long as ash-flow tuffs flowed over surfaces with little relief. However, volcanologists have long recognized that tuffs are density currents whose flow is strongly influenced by topography and that tuffs drape topography and compact against the underlying surface (Ross and Smith, 1961; Chapin and Lowell, 1979; Walker, 1983).
Such relations are particularly well established around Quaternary calderas, where tuffs flowed down surrounding drainages, and present-day topography is little changed since the time of tuff eruption (e.g., Aso, Japan; Matumoto, 1943; Lipman, 1967; Long Valley, California, Bailey et al., 1976, Bailey, 1989; Taupo, New Zealand, Wilson and Walker, 1985). Matumoto (1943) described the distribution of the Aso Tuff as “likened to the pseudopods of an amoeba... branching away on account of pre-existing mountain masses and projecting radially, far along the rivers and valleys.” Tuffs can have significant primary dips where deposited against slopes (Chapin and Lowell, 1979; Geissman et al., 1982; Hagstrum and Gans, 1989; Henry et al., 2003; Brooks et al., 2008). Many geologists recognized that ash-flow tuffs and interbedded sedimentary deposits in western Nevada and elsewhere were deposited in large paleovalleys with up to 1.2 km of relief and that thicknesses of individual ash-flow tuffs varied from as much as 400 m to 0 across short distances (Proffett and Profett, 1976; Bingler, 1977, 1978a; Geissman et al., 1982; Profett and Dilles, 1984; Baer et al., 1997; Henry et al., 2004; Eckberg et al., 2005; Faulds et al., 2005a, 2005b; Henry, 2008; McGrew and Vance, 2008). What is now the Great Basin was a high plateau or moderate-relief upland drained by major paleovalleys in the middle Cenozoic (Christiansen and Yeats, 1992; Dilek and Moores, 1999; DeCelles, 2004; Faulds et al., 2005a, 2005b; Cecil et al., 2006; Mulch et al., 2006; Henry, 2008; McGrew and Vance, 2008; Best et al., 2009; Cassel et al., 2009b). Despite the early recognition of major synvolcanic paleotopography in the Great Basin, the implications for ash-flow tuffs and tectonics do not seem to be widely appreciated.

The classic work of Chapin and Lowell (1979) on the 36 Ma Wall Mountain Tuff in the ~300-m-deep Gribbles Run paleovalley of central Colorado documented a wide range of volcanological features of the flow, such as deposition (including primary dip), welding, and secondary flow. The Gribbles Run paleovalley is in a region that has undergone relatively minor post–ash-flow tuff deformation, so Chapin and Lowell (1979) were not concerned about implications of these features for extension. Other studies (e.g., Ort et al., 2003) have also focused on volcanological implications.

This paper, although discussing volcanological aspects, emphasizes implications of ash-flow tuffs and paleovalleys on tectonic reconstructions, paleotopography, and volume estimates. Our work is primarily based on detailed geologic mapping, 40Ar/39Ar dating, and paleomagnetic analysis of ash-flow tuffs and interbedded sedimentary deposits that fill the Nine Hill paleovalley, a well-exposed segment of a paleovalley in western Nevada. We use the geology of the Nine Hill paleovalley, supplemented with published and our new regional data about the tuffs, to document that (1) ash-flow tuffs in western Nevada generally flowed in and were deposited in paleovalleys, (2) the tuffs compacted against sloping paleovalley walls, so commonly have primary dips, as much as 80° in extreme examples, (3) deposition of subsequent tuffs on variably eroded tuffs with primary dips generated angular unconformities that are unrelated to tectonism, (4) a combination of normal fluvial processes and “dam-burst” type floods resulting from blockage of drainages by ash-flow tuffs generated coarse clastic deposits without tectonism, (5) tuffs are generally laterally discontinuous, both between and along valleys, because they were deposited and rapidly eroded in paleovalleys, (6) tuffs generally have elliptical distributions, offset to the west from their source calderas because they flowed preferentially westward down the paleodrainages, and (7) tuff volumes, although commonly ≥1000 km³, are much less than would be calculated under the common assumption of radial distribution and continuity.

**ASH-FLOW TUFTS AND CALDERAS OF THE GREAT BASIN**

Ash-flow tuffs are abundant and widespread in the Great Basin, mostly erupted from a belt of calderas from central Nevada into western Utah (Fig. 1). Tuffs in western Nevada and the eastern Sierras Nevada erupted from calderas in central Nevada and flowed in paleovalleys that drained to the Pacific Ocean (Deino, 1985, 1989; John, 1992b, 1995; Garside et al., 2002, 2005; Henry et al., 2003, 2004; Faulds et al., 2005a, 2005b; Busby et al., 2008a, 2008b; Henry, 2008; Cassel et al., 2009b; Hinz et al., 2009). Best et al. (1989) and Best et al. (1995) listed 71 known or postulated calderas and more than 100 major ash-flow tuffs, and identification of several tens of additional major tuffs that lack identified caldera sources require many additional calderas (e.g., Faulds et al., 2005a; Brooks et al., 2008; Henry, 2009). Correlation of ash-flow tuffs beyond individual ranges has been hampered by the abundance of tuffs, primary stratigraphic complexity (which we attribute partly to deposition in paleovalleys), structural complexity from both normal and strike-slip faulting, cover beneath intervening basins, similarity in phenocryst assemblages among different tuffs, and lateral and vertical compositional and petrographic variation within individual tuffs (e.g., Best et al., 1995; John et al., 2008b). On the one hand, all Oligocene–Miocene ash-flow tuffs in western Nevada were initially combined into a single unit (Hartford Hill Rhyolite; e.g., Bingler, 1978a); on the other, Best et al. (1995) point out that the same ash-flow tuff in central Nevada had been assigned four different names in different ranges, a common problem for western Nevada tuffs also.

Work for this study shows that the six ash-flow tuffs present in the Nine Hill paleovalley (and one just outside) are regional units widespread in western and central Nevada (Table 1; Fig. 1). The tuffs were initially subdivided and partly correlated between Yerington (Profett and Profett, 1976; Profett and Dilles, 1984) and the Nine Hill paleovalley (Bingler, 1977, 1978a). We recognize further correlations based on geologic mapping, stratigraphy, petrography, and especially on new 40Ar/39Ar ages. Distal, paleovalley deposits and intracaldera or near source tuffs have the same stratigraphic position, indistinguishable ages, the same phenocryst assemblages, and distinctive petrographic features (Table 1). The overall distributions of the seven tuffs are variably known because of variable coverage by geologic mapping and because tuffs were commonly given local names and not correlated beyond each map area.

That ash-flow tuffs are confined to paleovalleys in western Nevada and the eastern Sierra Nevada is readily apparent from examination of many geologic maps (Profett and Profett, 1976; Bingler, 1977; Henry et al., 2004, 2009; Brooks et al., 2008; Sylvester et al., 2007). For example, Plate 1 shows the geology of an ~100 × 40 km area in western Nevada and eastern California around the Nine Hill paleovalley. Throughout this area, tuffs crop out in curvilinear belts set topographically into pre-Cenozoic rocks, and individual tuffs pinch out abruptly against paleovalley walls. The Soda Springs paleovalley segment in the northwestern part of Plate 1 is particularly illustrative because erosion in the headwaters of the American River exposed a cross section through the paleovalley, and the area is essentially unfaulted and untilted. Total relief on the Soda Springs paleovalley was at least 450 m, and the moderately steep eastern wall climbs ~300 m in a lateral distance of 1.5 km (Plate 1). As many as eight individual ash-flow tuffs are present, and each pinches out against the eastern wall (Sylvester et al., 2007). Outside the paleovalleys, Pliocene–Miocene volcanic rocks, dominantly intermediate to mafic lava flows and breccias, rest directly on pre-Cenozoic rocks.

Tuffs probably made at most a thin, nonwelded veneer that was quickly eroded from these interfluves. Little ash-flow tuff is preserved on these interfluves throughout western Nevada and eastern California.
Figure 1. Digital elevation map of the western Great Basin showing the distribution of known paleovalleys and a few segments (from Lindgren, 1911; Jenkins, 1932; Faulds et al., 2005a, 2005b; Garside et al., 2005; this study), a proposed paleodivide (Henry, 2008), known locations of tuffs of the Nine Hill paleovalley (locations with ? are uncertain correlations), and known or suspected calderas for six of the paleovalley tuffs. The paleovalley system drained to the Pacific Ocean, in the Great Valley at the time. The discontinuously exposed paleovalleys in western Nevada probably were more irregular than shown, similar to those in the Sierra Nevada, which are continuously exposed and were mapped in detail.
### Table 1. $^{40}\text{Ar}^{39}\text{Ar}$ Ages and Phenocryst Abundances of Ash-Flow Tuffs of the Nine Hill Paleoalvalley and Correlative Intracaldera or Near-Source Tuffs in Central Nevada.

<table>
<thead>
<tr>
<th>Sample Tuff</th>
<th>Location</th>
<th>Age ± 2$\sigma$ (Ma)</th>
<th>K/Ca ± 1$\sigma$</th>
<th>n$^1$</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Phenocrysts (%)</th>
<th>Distinctive</th>
<th>Step heating: matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>86-DJ-107</td>
<td>tuff of Poco Canyon, upper unit</td>
<td>Poco Canyon caldera, Stillwater Range</td>
<td>25.10 ± 0.07</td>
<td>49.4 ± 7.3</td>
<td>10/15</td>
<td>39.61111</td>
<td>-118.25972</td>
<td>Plag: 40, Qtz: 19, Biot: 18, Px: 1</td>
<td>sanidine; smoky</td>
</tr>
<tr>
<td>H00-66</td>
<td>Mickey Pass Tuff, lower unit</td>
<td>Nine Hill paleovalley</td>
<td>27.30 ± 0.07</td>
<td>65.1 ± 12.4</td>
<td>15/15</td>
<td>39.21666</td>
<td>-119.78415</td>
<td>Plag: 15, Qtz: 3, Biot: 2</td>
<td>sanidine</td>
</tr>
<tr>
<td>H01-86</td>
<td>Mickey Pass (Guld Mine unit 1)</td>
<td>Nine Hill paleovalley</td>
<td>27.19 ± 0.08</td>
<td>46.1 ± 11.5</td>
<td>16/16</td>
<td>39.87729</td>
<td>-119.20519</td>
<td>Plag: 25, Qtz: 2</td>
<td>abundant</td>
</tr>
<tr>
<td>H99-29</td>
<td>unnamed tuff</td>
<td>Soda Springs paleovalley</td>
<td>29.02 ± 0.08</td>
<td>72.1 ± 10.2</td>
<td>15/15</td>
<td>39.26750</td>
<td>-120.37133</td>
<td>Plag: 10, Qtz: 3</td>
<td>sanidine</td>
</tr>
<tr>
<td>H99-27</td>
<td>tuff of Sutcliffe</td>
<td>Soda Springs paleovalley</td>
<td>30.48 ± 0.08</td>
<td>32.0 ± 2.4</td>
<td>14/14</td>
<td>39.27333</td>
<td>-120.36500</td>
<td>Plag: 15, Qtz: 4</td>
<td>sanidine; quartz</td>
</tr>
<tr>
<td>H00-66</td>
<td>Mickey Pass Tuff, upper unit</td>
<td>McClellan Peak, east of Nine Hill</td>
<td>27.12 ± 0.10</td>
<td>62.6 ± 8.6</td>
<td>17/17</td>
<td>39.25176</td>
<td>-119.70994</td>
<td>Plag: 20, Qtz: 10</td>
<td>abundant</td>
</tr>
<tr>
<td>H00-66</td>
<td>Mickey Pass Tuff, lower unit</td>
<td>Nine Hill paleovalley</td>
<td>27.30 ± 0.07</td>
<td>65.1 ± 12.4</td>
<td>15/15</td>
<td>39.21666</td>
<td>-119.78415</td>
<td>Plag: 15, Qtz: 3, Biot: 2</td>
<td>sanidine</td>
</tr>
<tr>
<td>H01-82</td>
<td>Mickey Pass Tuff (Guld Mine unit 2)</td>
<td>Nine Hill paleovalley</td>
<td>27.12 ± 0.06</td>
<td>63.9 ± 5.8</td>
<td>15/15</td>
<td>39.87393</td>
<td>-119.20597</td>
<td>Plag: 28, Qtz: 12</td>
<td>quartz</td>
</tr>
<tr>
<td>H99-31</td>
<td>Mickey Pass Tuff, Guild Mine Member</td>
<td>Soda Springs paleovalley</td>
<td>26.98 ± 0.07</td>
<td>68.3 ± 6.7</td>
<td>15/15</td>
<td>39.27667</td>
<td>-120.37133</td>
<td>Plag: 20, Qtz: 9</td>
<td>sanidine</td>
</tr>
<tr>
<td>H94-14</td>
<td>tuff of Moores Ck</td>
<td>Toquima caldera complex</td>
<td>27.12 ± 0.08</td>
<td>65.6 ± 6.7</td>
<td>9/10</td>
<td>38.68903</td>
<td>-116.86655</td>
<td>Plag: 21, Qtz: 8</td>
<td>sanidine</td>
</tr>
<tr>
<td>H00-100</td>
<td>tuff of Toyabe</td>
<td>Paradise Range</td>
<td>23.16 ± 0.06</td>
<td>77.3 ± 8.7</td>
<td>14/17</td>
<td>38.87278</td>
<td>-117.73583</td>
<td>Plag: 30, Qtz: 8</td>
<td>titanite</td>
</tr>
</tbody>
</table>

Note: $^1$ number of single grains used in age calculation/total number of grains analyzed.

Sanidine was separated from crushed, sieved samples by standard magnetic and density techniques, leached with dilute HF to remove matrix, and handpicked.

All analyses at New Mexico Geochronological Research Laboratory, New Mexico Institute of Mining and Technology, Analytical methods in McIntosh et al. (2003).

Weighted mean $^{40}\text{Ar}^{39}\text{Ar}$ ages of sanidine calculated by the method of Samson and Alexander (1987). Samples were irradiated in Al discs for 7 hours in D-3 position, Nuclear Science Center, College Station, TX. Neutron flux monitor Fish Canyon Tuff sanidine (FC-1); assigned age = 28.02 Ma (Renne and others, 1998).

Decay constants and isotopic abundances after Steiger and Jäger (1977); $\lambda_\text{t} = 4.963 \times 10^{-10}$ yr$^{-1}$; $\lambda_\text{c} = 0.581 \times 10^{-10}$ yr$^{-1}$; $^{40}\text{K/_{39}} \text{Ar} = 1.167 \times 10^4$

David John (USGS, Menlo Park) provided sample 86-DJ-107.
Plate 1. Geology of the region around the Nine Hill paleovalley from Saucedo and Wagner (1992), Stewart (1999), Saucedo (2005), Garside et al. (2005), and this study. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00548.SI or the full-text article on www.gsapubs.org to view the full-size PDF file of Plate 1.
In the area of Plate 1, two large tributaries joined at Nine Hill. The Soda Springs paleovalley segment is a separate major paleodrainage from the north that joined the Nine Hill segment west of Lake Tahoe. This grand paleovalley is thought to be part of the Tertiary American River or the south branch of the Tertiary Yuba River (Lindgren, 1911).

The Nine Hill paleovalley is part of an extensive paleodrainage network that drained westward from a high plateau or upland in central Nevada during the Eocene and Oligocene (Fig. 1). In the Sierra Nevada, the paleovalleys were recognized in the 1800s and mapped in great detail because they hosted substantial paleoplacer gold deposits, the auriferous gravels (Lindgren, 1911; Jenkins, 1932). Although many geologists (e.g., Bateman and Wahrhaftig, 1966; Yeend, 1974) recognized that the paleovalleys continued into Nevada, the paleovalley system in western and central Nevada and its connection across the Sierra Nevada are only now being documented (Davis et al., 2000; Garside et al., 2002, 2005; Henry et al., 2003, 2004, 2009; Faulds et al., 2005a, 2005b; Henry, 2008; John et al., 2008a; Cassel et al., 2009a; Hinzelin et al., 2009). An obvious implication is that the present Basin and Range—Sierra Nevada structural-topographic boundary did not exist when these paleovalleys were major, regional drainages and the tuffs were deposited in them. Instead, the Great Basin was a topographic high, although how high cannot be resolved from our data, and the Sierra Nevada was the western flank of that high.

Where sufficiently well exposed and mapped, paleovalleys in western Nevada and easternmost California are typically 7–10 km wide by 400–1200 m deep. For example, the western continuation of the Nine Hill paleovalley just west of Lake Tahoe was 7 km wide by at least 600 m deep (Saucedo and Wagner, 1992; Davis et al., 2000). The Soda Springs paleovalley is 9 km by more than 450 m deep (Sylvester et al., 2007). Paleovalleys north of Reno that are well exposed in cross section are 5–8 km wide and 300–800 m deep (Henry et al., 2004, 2009; see especially figure 8 in Faulds et al., 2005b and figure 8 in Hinz et al., 2009)). The deepest known paleovalley is the southeastern tributary of the Nine Hill paleovalley in the Singatse Range (Fig. 1). Mapping at 1:12,000 supplemented by more than 30 km of drillhole data in the Yerington mining district document the paleovalley geometry, pinch outs of tuffs against topographic walls, 10 km width, and 1200 m depth (see figures 2, 4, and 5 in Proffett and Proffett [1976]; Proffett and Dilles [1984]). The paleovalleys narrow and total relief decreases westward, where an inner, V-shaped channel 50–80 m deep is cut into the broad paleovalley (Lindgren, 1911; MacGinitie, 1941; Yeend, 1974). The paleovalleys emptied into shallow marine basins along the western edge of the present Sierra Nevada (Allen, 1929; Creely and Force, 2007).

**GEOLOGY OF THE NINE HILL PALEOVALLEY**

**Geometry and Wall Rocks of the Paleovalley**

The Nine Hill paleovalley is an east-northeast–trending, 7.5-km-long by as much as 2-km-wide segment of one of these major paleodrainages. The width and depth of the Nine Hill paleovalley at the time of ash-flow deposition are uncertain because it is cut off along its northwest side by faulting and has been partly eroded.

The Nine Hill paleovalley is in the hanging wall of the north-striking, east-dipping Carson Range normal fault system (Plate 1, Fig. 2A). The paleovalley occupies part of a structural high that separates the relatively deep Washoe Valley basin on the north from the shallow Eagle Valley basin to the south. The Carson Range fault system steps 2 km to the left at the paleovalley and accommodates a 1 km of down-to-the-east displacement from the Carson Range to the western end of Nine Hill. The northwestern edge of the paleovalley is cut off by a northwestern-facing fault, presumably antithetic to the major basin-bound fault (Fig. 2A).

Probably Jurassic metasedimentary and metavolcanic rocks (Jms and Jmv) that are intruded by a Cretaceous biotite-hornblende granodiorite (Kg) make up the wall rocks of the paleovalley. Ash-flow tuffs rest depositionally on the Mesozoic rocks all along the southeast wall and along part of the northwest wall. Mesozoic rocks are exposed only along a short segment of the northwest wall, where they underlie Nine Hill Tuff in the most eastern, upstream part, and Santiago Canyon Tuff, the youngest ash-flow tuff recognized in this area, just to the west. The northeast-striking, down-to-the-northwest fault cuts off tuff along most of the northwestern edge.

The granodiorite is noticeably weathered near the contact with tuffs (Figs. 2B and 2C). More than 20 m perpendicular from the contact, granodiorite displays a typical, nonweathered, salt and pepper appearance. Toward the contact, granodiorite becomes progressively iron stained and disaggregated to grus. Biotite is black but appears to have expanded, probably from absorption of water and possibly minor clay alteration. Hornblende is weathered to clay, and titanite (sphere) is altered to leucoxene. A similar paleoweathering zone beneath Tertiary rocks is common in paleovalleys in western Nevada (Proffett and Proffett, 1976; Henry et al., 2004; Eckberg et al., 2005; Faulds et al., 2005b) and in the Sierra Nevada (Bateman and Wahrhaftig, 1966; Cecile et al., 2006; Mulch et al., 2006). Weathering occurred before 27.3 Ma, the age of the oldest tuff in the Nine Hill paleovalley, and before 31.3 Ma in other paleovalleys in western Nevada (Henry et al., 2004, 2009). Continuity of the Nine Hill and other Nevada paleovalleys with the Eocene, auriferous-gravel bearing paleovalleys in the Sierra Nevada (Lindgren, 1911; Bateman and Wahrhaftig, 1966; Faulds et al., 2005a, 2005b; Garside et al., 2005) indicates that the Nevada paleovalleys existed at least in the Eocene. Most weathering probably occurred during the Eocene, when the climate was warm and humid and intense weathering occurred in the Sierra Nevada gold belt (MacGinitie, 1941; Bateman and Wahrhaftig, 1966; Kelly et al., 2005; Cecile et al., 2006; Mulch et al., 2006).

**Ash-Flow Tuff Stratigraphy**

The Nine Hill paleovalley contains a sequence of seven Oligocene to lower Miocene ash-flow tuffs that are complexly interbedded with sedimentary deposits and all inset into the Mesozoic rocks (Plates 1 and 2; Table 1, which lists 40Ar/39Ar ages and phenocryst assemblages used to correlate tuffs). The tuffs dominantly strike parallel to the paleovalley and dip to the northwest. However, attitudes vary considerably, most notably for the Nine Hill Tuff, which dips steeply into the paleovalley on opposite sides separated by ~700 m (Figs. 3A–3D). None of the tuffs are continuous for more than a few kilometers along the paleovalley, a continuous section of more than three tuffs is not present anywhere, and all tuffs locally rest directly on basement. This discontinuity resulted from irregular deposition and erosion in the paleovalley (see Discontinuity of Tuffs and Sedimentary Deposits). Nevertheless, relative ages that are consistent with regional relations can be determined between most tuffs from exposures in different locations. 40Ar/39Ar dates confirm these relations (Table 1).

The oldest tuffs in the Nine Hill paleovalley are two units of the Mickey Pass Tuff, which were combined into a single unit in previous mapping (Bingler, 1977; Trexler, 1977). The 27.3 Ma, lower Mickey Pass Tuff is a single cooling unit that crops out discontinuously along the southern edge of the paleovalley (Ttm1, Plate 1). It is as much as 20 m thick and has a thin, black basal vitrophyre overlain by densely welded, devitrified rock.

The 27.1 Ma, moderately porphyritic, upper Mickey Pass Tuff at Nine Hill (Ttm2, Plate 2)
Figure 2. (A) View to west down axis of Nine Hill paleovalley across Carson Range, showing range-front fault, paleovalley in Carson Range, and fault along northwest edge of paleovalley. (B) View to east of paleovalley margin showing typical paleoweathering of Cretaceous granodiorite in the paleovalley wall, overlain by Nine Hill Tuff. Granodiorite is not weathered in foreground, away from paleovalley wall, but becomes increasingly weathered toward the wall. (C) Granodiorite at the wall is highly weathered and partly disaggregated to grus. Rock hammer in this and all other photos is 42 cm long.
Plate 2. Geologic Map of the Nine Hill Paleoavlley: Carson City and New Empire Quadrangles, Western Nevada. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00548.S2 or the full-text article on www.gsapubs.org to view the full-size PDF file of Plate 2.
Figure 3 (Continued on following page). Photos of Nine Hill paleovalley and tuff units. (A) Panoramic view east-northeast up paleovalley, with inward-dipping Nine Hill Tuff on basement on opposite sides. Locations shown in B and C are ~700 m apart. (B) Steeply northwest-dipping Nine Hill Tuff along southeast wall of paleovalley. (C) Steeply southeast-dipping Nine Hill Tuff along northwest wall of paleovalley. (D) Close-up of B showing dense welding to within ~20 cm of the base.
Figure 3 (Continued). (E) Gently north-dipping, densely welded ledge of Eureka Canyon Tuff in the southwestern part of the Nine Hill paleovalley. (F) Three cooling units of Santiago Canyon Tuff in the northeastern part of the paleovalley consisting of a thick, basal, poorly welded zone (light-colored area of poor exposure making slope), overlain by three, dark resistant ledges of densely welded tuff separated by two, nonresistant poorly welded zones. (G) Nontectonic angular unconformity where the Nine Hill Tuff overlies poorly welded tuff near Soda Springs in the Sierra Nevada, California (Plate 1). Angularity results from moderate primary dip of the Nine Hill Tuff where it was deposited on a moderately dipping paleosurface eroded into the underlying tuff, which is flat-lying, not from tilting of the underlying tuff. Note that the entire Nine Hill Tuff dips the same way and that it is not rheomorphic here. Upper, less welded Nine Hill Tuff may have had more horizontal compaction foliation but has been eroded. (H) View to east of regularly layered ash-flow tuffs, including the tuff of Chimney Spring, in the middle of a paleovalley in the Virginia Mountains, ~43 km north of Reno (Fig. 1).
is distinguished from the lower unit by both age and a phenocryst assemblage dominated by quartz and sanidine. It crops out in two small areas along the southern edge of the paleovalley, where it is ~15 m thick. However, it thickens abruptly into the southeastern tributary, where the combined Mickey Pass Tuffs total as much as 300 m thick and are probably dominantly the younger tuff (Plate 1). The 27.1 Ma tuff is ~400 m thick in the Singatse Range, where the paleovalley is 1.2 km deep (Proffett and Proffett, 1976; Table 1). Also, clasts of 27.1 Ma Mickey Pass Tuff are abundant in conglomerate interbedded with the tuffs in the Nine Hill paleovalley (Fig. 4A).

The 26.8 Ma Lenihan Canyon Tuff crops out in the northeast and southeast tributaries and in the Carson Range west of Nine Hill but is absent in the Nine Hill segment (Plates 1 and 2). The most distinctive characteristics of this tuff are fine (<1 mm) plagioclase, ubiquitous hornblende, and lack of sphene compared to the somewhat similar Santiago Canyon Tuff. Despite its absence at Nine Hill, Bingler (1978) reported that it is 300 m thick, probably in the southeast tributary (Plate 1).

The 25.3 Ma, densely welded, and commonly rheomorphic Nine Hill Tuff is the most resistant rock in the area and crops out along most of the Nine Hill paleovalley (Plate 2; Bingler, 1977). The tuff has lower sparsely porphyritic and upper moderately porphyritic phases (Deino, 1985), both of which are present in the paleovalley. The lower phase crops out mostly close to depositional contacts with the paleovalley wall, whereas the upper phase is mostly in the middle of the paleovalley. Lag of basal vitrophyre occurs north of paleomagnetic site NH-1 (Plate 2), and clay-altered tuff at site NH-2 was probably former vitrophyre. However, the rest of the tuff is devitrified. The distinctive, easily correlated Nine Hill Tuff contains three feldspars (sanidine, plagioclase, and anorthoclase), common large pumice as much as 1 m long, and common rheomorphic features (Deino, 1985). The Nine Hill Tuff is at least 120 m thick in the paleovalley.

The 25.1 Ma tuff of Chimney Spring crops out in the central part of the Nine Hill paleovalley, where it is as much as 20 m thick and everywhere densely welded and devitrified. The petrographically distinctive tuff contains abundant phenocrysts of adularescent sanidine and smoky quartz.

The 24.9 Ma Eureka Canyon Tuff crops out extensively in the southwestern part of the paleovalley but is mostly absent in the northeastern part. The Eureka Canyon Tuff commonly has a light to dark gray basal vitrophyre overlain by light yellowish, densely welded,
devitrified rock (Fig. 3E). The tuff is as much as 40 m thick in the southwestern part of the paleovalley, thickens to as much as 130 m to 10 km to the southeast in the southeastern tributary (Plate 1; Bingler, 1978a), but wedges out within a few kilometers northeastward into the northeastern tributary. The sparsely porphyritic tuff contains distinctive, highly resorbed quartz phenocrysts.

The 23.1 Ma Santiago Canyon Tuff, the youngest tuff at Nine Hill, crops out in two areas along the northwest edge of the Nine Hill paleovalley, resting directly on granodiorite in the eastern area (Plate 2). The well-exposed, eastern outcrop is ~60 m thick and consists of three densely welded, devitrified ledges separated by poorly to moderately welded, vitrophyric zones (Fig. 3F). The Santiago Canyon Tuff thickens to as much as 120 m to 5 km to the northeast in the northeastern tributary and to as much as 300 m to 10 km to the southeast in the southeastern tributary (Plate 1; Bingler, 1978a; Hudson et al., 2008). The ubiquitous presence of titanite (sphe re) is a distinguishing characteristic of the crystal-rich tuff (Table 1).

Coarse conglomerate and sedimentary breccia are interbedded with the ash-flow tuffs and divided into four units on the basis of stratigraphic position and type of clasts. Sedimentary breccia, the oldest unit, crops out along an ~600 m length of the southern paleovalley wall. It consists of angular to moderately rounded clasts of the upper Mickey Pass Tuff up to 4 m in diameter in an indurated matrix of finer tuff clasts (Fig. 4B). Conglomerates, which occur throughout most of the paleovalley, are marked by a lag of moderately to well-rounded cobbles to boulders (Fig. 4A); matrix is nowhere exposed. Clasts include ash-flow tuffs and granodiorite, both up to ~2 m in diameter, and metavolcanic and metasedimentary rocks, generally no more than ~50 cm in diameter. The lack of exposed matrix precludes measuring attitudes in the sedimentary deposits, but their topographic expression suggests that the paleovalley is tilted moderately to the northwest.

Locally derived volcanic rocks consist of andesite lava and two units of basaltic andesite. Andesite crops out in a small area in the western part of the paleovalley where it overlies Eureka Canyon Tuff. Miocene basaltic andesite lava erupted over part of the paleovalley at ca. 9 Ma (Table 1). Its topographic distribution, lower to the northwest, suggests that it is tilted to the northwest, and it is cut along its western edge by a north-striking, down to the east fault. These relationships suggest that the basaltic andesite has undergone the same amount of faulting and tilting as the ash-flow tuffs, which is consistent with regional relationships that indicate major Basin and Range faulting is younger than ca. 10 Ma and possibly no older than 3 Ma here (Dilles and Gans, 1995; Henry and Perkins, 2001; Surless et al., 2002). Quaternary basaltic andesite (McClellan Peak Basalt) forms a cinder cone and lava flow complex along the eastern edge of the map area. Bingler (1977) reported an apparent whole-rock K/Ar age of 1.36 ± 0.29 Ma from a flow ~1 km east of the area of Plate 2 but provided no analytical data. Several flows from the cinder cone extend southward into Eagle Valley, where they flowed around hills of resistant Mesozoic rocks. The Quaternary flows apparently erupted onto topography much like that of today.

Regional Ash-Flow Tuff Correlation and Distant Calderas

Figure 1 shows known and probable outcrop locations and known or postulated caldera sources for most of the tuffs, and Figures 5–7 show distributions of individual tuffs. Correlations are based on stratigraphy, petrography including the distinctive features discussed above, and 40Ar/39Ar age, including K/Ca of analyzed sanidines, which is an additional and commonly useful correlation tool (e.g., the very low ratio of sandine in the Nine Hill Tuff; Table 1). It is apparent that all but the Nine Hill Tuff have distinctly elongate distributions preferentially west of their source calderas. Because the two Mickey Pass Tuffs were combined in most mapping to the east and a third, younger part of the Mickey Pass Tuff is present in the Singate Range (Proffett and Proffett, 1976; Gard ne et al., 2002), distribution of individual tuffs is variably known. The 27.3 Ma tuff is present in the Singate Range (Fig. 5; Proffett and Proffett, 1976; Table 1), where it is commonly the oldest tuff in the paleovalley there. Descriptions by Bingler (1978b), Ekren et al. (1980), and Hard myan (1980) indicate that the 27.3 Ma tuff also crops out in the Wassuk, Gabbas Valley, and Gillis Ranges. The 27.3 Ma Mickey Pass Tuff probably correlates with the indistinguishably aged, intracaldera tuff of Ryecroft Canyon in the Toquima Range (Fig. 6; Boden, 1992; Henry et al., 1997; Gard ne et al., 2002). Intracaldera tuff is more than 2000 m thick (Boden, 1992). The Lenahan Canyon Tuff has not been identified other than in the Toquima Range and near Nine Hill, which may possibly reflect its relatively nondistinctive character.

Deino (1989) demonstrated that the Nine Hill Tuff correlates with the D unit of the Bates Mountain Tuff in central Nevada (Gromme et al., 1972). The Nine Hill Tuff crops out from near Ely, Nevada on the east to the western foothills of the Sierra Nevada on the west, a present-day distance of ~500 km, which probably makes it the most extensive tuff in the Great Basin. Deino (1989) postulated a caldera source beneath the Carson Sink (Fig. 1), in part because that was close to the center of its distribution. If correct, outflow tuff in the Nine Hill paleovalley is only ~110 km away.

Unlike the other paleovalley tuffs, the tuff of Chimney Spring occurs mostly in paleovalleys to the north and east (Fig. 7; Henry et al., 2004; Faulds et al., 2005a, 2005b). Outcrops in the Nine Hill paleovalley are its southernmost known occurrence. Its overall distribution and source caldera are particularly well understood. Deino (1989) correlated the tuff of Chimney Spring with the New Pass Tuff of central Nevada (McKee and Stewart, 1971), and John (1992a, 1995) recognized that the combined tuff erupted from the Poco Canyon caldera in the Stillwater Range ~140 km to the east. Intracaldera tuff of Poco Canyon is at least 1500 m thick and contains abundant megabreccia of blocks
Figure 5. Distribution and ages of the 27.3 Ma Mickey Pass Tuff and correlative tuff of Ryecroft Canyon (source caldera in the Toquima Range), the Lenihan Canyon Tuff and correlative upper tuff of Mount Jefferson, the Nine Hill Tuff (possible source caldera beneath Carson Sink; Deino, 1989), the Eureka Canyon Tuff and correlative Blue Sphinx Tuff, and the Santiago Canyon Tuff and correlative tuff of Toiyabe (source caldera in the Toiyabe Range).
Figure 6. Distribution, thicknesses (m), and ages of the 27.1 Ma Mickey Pass Tuff and the correlative lower tuff of Mount Jefferson. Intracaldera lower tuff of Mount Jefferson in the Toquima Range is at least 1300 m thick. Thicknesses in italics are for the combined 27.3 and 27.1 Ma parts of the Mickey Pass Tuff where they were not mapped separately; most of the thickness is probably the 27.1 Ma part. Ellipse shows the tuff’s elongate distribution, preferentially westward from the source caldera.
Figure 7. Distribution, thicknesses, and ages of the correlative tuff of Chimney Spring, tuff of Poco Canyon (intracaldera tuff in the Stillwater Range; John, 1995), and New Pass Tuff. Ellipse shows the tuff’s elongate distribution, preferentially westward from the source caldera.
The Eureka Canyon Tuff is widespread in western Nevada in the Singatse Range (Fig. 5; where it is the upper ash-flow tuff in the Bluestone Mine Tuff of Proffett and Proffett [1976]) and in the Wassuk, Gillis, and Gabbs Valley Ranges (where it is called the Blue Sphinx Tuff; Bingler, 1978b; Ekren et al., 1980; Hardyman, 1980; Eckberg et al., 2005). An unnamed, petrographically similar and probably correlative tuff of similar age is also present in the Sand Springs Range (H00–58, Table 1; Satterfield, 2002). Although the source of the Eureka Canyon Tuff is unknown, this distribution suggests a source in the central part of the central Nevada caldera belt.

The Santiago Canyon Tuff erupted from a caldera ~200 km to the east in the Toiyabe Range in central Nevada, where the correlative unit is called the tuff of Toiyabe (Fig. 5; Table 1; Brem et al., 1991; John, 1992b). Reconnaissance mapping identified thick intracaldera tuff of Toiyabe and part of the caldera wall in the Toiyabe Range (Brem et al., 1991; John, 1992b). John (1992b) recognized the tuff of Toiyabe and another separately named equivalent, the tuff of Copper Mountain in the Gillis and Gabbs Valley Ranges (Ekren et al., 1980; Hardyman, 1980), as much as 100 km west of the caldera. The Santiago Canyon Tuff has not been recognized in the Singatse or Wassuk Ranges (Proffett and Dilles, 1984; Bingler, 1978b).

As shown here, the tuffs in the Nine Hill paleovalley are distal outflow deposits from sources that are currently 100–265 km to the east. Bingler (1978a) and Ekren et al. (1980) thought that the caldera sources for several of the tuffs lay in the Nine Hill area or between the Singatse and Gabbs Valley Ranges, respectively, based on thicknesses of individual tuffs of up to several hundred meters and of composite sections of numerous tuffs of up to 2000 m. However, several hundred meters is small compared to intracaldera thicknesses of the same tuffs discussed above and of intracaldera tuffs in general. The moderate thicknesses in western Nevada and the eastern Sierra Nevada are consistent with their deposition in paleovalleys (Deino, 1985; Brooks et al., 2003; Henry et al., 2004; Faulds et al., 2005a, 2005b).

Even geologists who did not identify paleovalleys or any significant paleotopography recognized that tuff thicknesses varied abruptly over short distances (Ekren et al., 1980; Hardyman, 1980; Petronis and Geissman, 2009). Contacts in the Gillis Range interpreted by Hardyman (1980) as low-angle faults between Cenozoic and Mesozoic rocks were reinterpreted by Eckberg et al. (2005) to be paleovalley walls based on the configuration of erosion surfaces, local basalt Tertiary stream conglomerate, red weathered paleosurfaces on Mesozoic intrusions, and paleosols containing root casts and petrified wood. Based on all these data, we suggest that tuffs in the Gillis and Gabbs Valley Ranges generally are in paleovalleys. Figure 1 shows a likely paleovalley axis, which has been displaced by strike-slip faults of the central Walker Lane.

Two other ash-flow tuffs identified in the Soda Springs paleovalley segment are not present at Nine Hill or anywhere that we know of along the Nine Hill paleovalley system (Plate 1; Table 1). These two tuffs are widespread in the paleovalley upstream from Soda Springs and in other northern paleovalleys (Faulds et al., 2005a; Brooks et al., 2008), which indicates they probably erupted from a northern caldera and flowed and were deposited only in northern paleovalleys. From geochemical comparisons, Brooks et al. (2008) suggested the caldera for the unnamed tuff (H99–29, Table 1) was in the Desatoya Mountains, and the caldera for the tuff of Sutcliffe was in the Stillwater Range. Only two ash-flow tuffs in the Nine Hill paleovalley system are also present in northern paleovalleys: the Nine Hill Tuff, which is extremely widespread, and the tuff of Chimney Spring, for which Nine Hill is its southernmost occurrence (Henry et al., 2004, 2009; Faulds et al., 2005a). The lack of overlap between tuff sequences is a powerful indication that tuffs were strongly channelized.

**TECTONIC TILT, PALEOHORIZONTAL, AND PRIMARY DIPS**

**Regional Fault and Tilt Relations**

The large variation in direction and amount of dip within individual tuffs over a small area that has undergone relatively minor deformation requires that they were deposited with some primary dip, regardless of tilt correction. Variations in dip are apparent both in the Nine Hill paleovalley segment and in the southeastern tributary (Plate 1). Nevertheless, a key question in discussing the Nine Hill paleovalley is the amount and direction of tilt that postdates ash-flow deposition. Measured attitudes of the tuffs cannot be used to interpret tectonic tilt because the attitudes vary so widely, and sedimentary units are insufficiently exposed. Variation within individual tuffs is most notable for the Nine Hill Tuff, which dips steeply into the paleovalley on opposite sides separated by ~700 m. Therefore, we use paleomagnetic data and measured dips of sedimentary rocks in surrounding areas to evaluate tilt.

The Nine Hill paleovalley lies in the hanging wall of the moderately large displacement, east-dipping, Carson Range normal fault that bounds the west side of Washoe Valley. The paleovalley is presumably tilted westward, but the amount and exact direction are uncertain. Displacement on the Carson Range fault reaches a probable maximum of ~3 km in the middle of Washoe Valley (~6 km north of Nine Hill) and decreases both to the north and south, past Nine Hill. This displacement gradient suggests the paleovalley is tilted toward the west-northwest. The paleovalley segment is small and cut only by small-displacement, north-striking normal faults; therefore the whole segment has probably undergone the same amount and direction of tilt.

The nearest pretilt sedimentary rocks to the Nine Hill paleovalley, along the northeast flank of Washoe Valley (Plate 1), generally strike north-northeast and dip 20°–25° to the west (Hudson et al., 2008). The west-northwest dip seems inconsistent with decreasing displacement on the Carson Range frontal fault in the northern part of Washoe Valley. However, two north-striking, west-dipping normal faults lie east of but parallel to the range front fault at the north end of Washoe Valley. These faults may have accommodated tilting of the sedimentary deposits.

**Paleomagnetic Data**

The paleomagnetic investigation focused on the Nine Hill Tuff, which has a well-determined reference direction (Deino, 1985; Faulds et al., 2004). Conventional paleomagnetic methods (e.g., Knight et al., 1986; Hudson et al., 2000) were employed in this study. A portable drill and Pomeroy orienting fixture were used to collect oriented cores from each site. All analyses were carried out at the Keck Paleomagnetic Laboratory at the University of Nevada, Reno. Remanent magnetizations were measured on an Agico JR-5A magnetometer. To isolate components of natural remanent magnetization, all samples were subjected to either alternating field or thermal demagnetization. Demagnetization trajectories were evaluated on orthogonal demagnetization diagrams (Fig. 8). Characteristic remanent magnetizations (ChRMs) were calculated using standard methods such as the multivariate technique of principal component analysis (e.g., Kirchvink, 1980). Conventional statistical analyses on a sphere (e.g., Fisher, 1953) were employed to determine site means and dispersion parameters (Table 2).

The Nine Hill Tuff was sampled at 14 sites throughout the paleovalley segment in areas having both northwest and southeast dips. Of these, six showed significant rheomorphism
Ash-flow tuffs in the Nine Hill, Nevada, paleovalley

Twelve of the 14 sites yielded well-grouped site means, with an $\alpha_{95} < 10^\circ$ and $k > 45$ ($k$ is a precision parameter denoting the concentration of the distribution about the mean direction; Fisher, 1953). However, two sites (NH7 and NH14) yielded highly dispersed site means. Site NH7 appears to have been lightening struck. Site NH14, which is in the deepest part of the paleovalley, has undergone considerable planar rheomorphism, appears to be partly silicified, and thus yielded poor demagnetization results. In all other sites, a single ChRM was first recognized at low inductions between 0 and 35 mT (milliTesla) and by 250 °C. Most samples behaved simply during demagnetization (Fig. 8). At moderate to high temperatures and inductions, demagnetization trajectories typically continued straight to the origin.

Demagnetization behaviors suggest that fine-grained, pseudo-single domain titanomagnetite is the principal carrier of the ChRMs in the Nine Hill Tuff. Alternating field demagnetization commonly removed 40%–80% of the magnetization by 100 mT and nearly all magnetization by 200 mT. Thermal demagnetization removed most of the magnetization by ~590 °C and nearly all magnetization by 610–645 °C, with a few sites retaining a small amount of magnetization to 690 °C. Titanomagnetite typically loses most magnetization by 100 mT and 590 °C (Butler, 1992). Magnetizations removed at higher inductions and temperatures probably reside in small amounts of hematite or fine-grained maghemite.

In situ site means cluster well, whereas tilt-corrected means based on measured attitudes at each site significantly increase dispersion (Fig. 9). Two of the rheomorphic sites showed the greatest dispersion from the mean (NH6 and NH11), but all other rheomorphic sites clustered closely with all others. This suggests secondary flow may have continued below the blocking temperature (~580–590 °C) of fine-grained titanomagnetite in parts of the Nine Hill Tuff, similar to results for the Kalamazoo Tuff of eastern Nevada where dispersion of paleomagnetic data indicate some rheomorphic flow continued below the blocking temperature (Hagstrum and Gans, 1989).

A mean of the 12 sites ($D = 29$ and $I = 65$) differs from the Nine Hill reference direction ($D = 341$ and $I = 55$; Fig. 9A) and could indicate either 28° of westward tilt about a NNE–trending axis (i.e., 28° tilt toward 294°) or ~40°–45° of clockwise rotation. West-northwest tilt of this magnitude is consistent with the orientation and displacement gradient along the Carson Range normal fault, with the measured attitudes in sedimentary rocks northeast of Washoe Valley and the dominant attitude of tuffs in the southeastern tributary (Plate 1), and with the

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Figure 8. Orthogonal demagnetization plots of representative samples of the Nine Hill Tuff. Squares and triangles are projections on the horizontal (declination) and vertical (inclination) planes, respectively. C—Celsius; mT—millitesla; $I_0$—intensity of the natural remanent magnetization prior to demagnetization. Coordinates are not corrected for tilt of strata. (A) Site NH6, sample H, alternating field demagnetization. (B) Site NH16, sample H, alternating field demagnetization. (C) Site NH3, sample G, thermal demagnetization. (D) Site NH9, sample I, thermal demagnetization.
# TABLE 2. CHARACTERISTIC REMANENT MAGNETIZATIONS

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| Group mean | Tnh | -- | -- | 28.2 | 65.1 | 27.0 | 8.5 | 12/14 | -- | -- |
| Group mean corrected | Tnh | -- | -- | 40.2 | 54.2 | 5.2 | 21.0 | 12/14 | -- | -- |
| Tnh reference | Tnh | -- | -- | 341.0 | 55.2 | 121.5 | 4.4 | 10/10 | -- | -- |
| Tnh reference corrected | Tnh | -- | -- | 335.1 | 57.5 | 121.5 | 3.0 | 20/20 | -- | -- |

*Note: Paleomagnetic data, Nine Hill Tuff from the Nine Hill area (see Plate 1 for site localities). Sites NH5 and NH15 were not collected from the Nine Hill Tuff and are therefore not shown due to lack of relevance to this study. Tnh—Nine Hill Tuff; Tnhl—lower Nine Hill Tuff; $k$—precision parameter (Fischer, 1953); $\alpha_{95}$—cone of 95% statistical confidence about the site mean; N/N₀—number of demagnetized samples used in statistical analysis versus number of total samples analyzed, or number of sites used in site mean calculations versus total number of sites analyzed. Tnh reference refers to calculated reference directions for the Nine Hill Tuff from Deino (1985) and Faulds et al. (2004). Regional tilt correction of 28° west about a N24°E axis restores in situ, group site mean to approximate reference direction (within 95% confidence level).*
topographic expression of conglomerate beds in the paleovalley (Plate 2). Consistency of the data between the eastern and western ends of the paleovalley segment (e.g., sites NH1 and NH2 versus NH3) also support the interpretation of negligible internal deformation within the paleovalley. Clockwise rotation cannot be precluded, but 40°–45° of rotation is inconsistent with the amount and style (i.e., normal faulting) of deformation in the area. Also, removing 40° of clockwise rotation would require an original paleovalley orientation of approximately N25°E, which is strongly oblique to the more easterly trends of its western and eastern continuations (Plate 1).

**Primary Dips**

The paleomagnetic data thus demonstrate that major differences between dips within Nine Hill Tuff are primary and require that probably all six tuffs show some component of primary dip. The following discussion assumes that the entire paleovalley was tilted ~28° toward 294° and subtracts that from measured attitudes to estimate initial attitudes.

Primary dips are most obvious for the Nine Hill Tuff, which dips steeply inward on both sides of the northeastern part of the paleovalley in the vicinity of paleomagnetic sites NH1 and NH2, which are separated by only 700 m (Figs. 3B–3D; Fig. 10). We focus on attitudes close to contacts with underlying rocks, because highly variable dips in the interior of the Nine Hill Tuff probably also reflect rheomorphism (see section Rheomorphism). Although measured dips suggest a large, relatively symmetrical syncline, correction for tilt steepens the northwest wall to nearly vertical in many locations and flattens the southeast wall to approximately horizontal. Small, open anticlines are locally developed at the base of the Nine Hill Tuff, for example, where it overlies Jurassic metavolcanic rocks (location A, Plate 2) in the northeastern part and where it overlies granodiorite west of site NH8 (location B, Plate 2).

These primary dips must result from compaction of the tuff against the paleovalley wall, which further implies that at least the northwestern wall was near vertical in places. The small anticlines probably reflect small, local topographic highs in the underlying Mesozoic rocks, particularly over the more resistant metavolcanic rocks. Tors of granodiorite are common today and may have been present during deposition of the tuffs. Some other anticlines and synclines are probably rheomorphic folds.

Primary dips are also apparent in the Eureka Canyon and Santiago Canyon Tuffs. The Eureka Canyon Tuff at the west end of the paleovalley dips 30°–35° northward close to the southeastern wall but shallows to near horizontal a few hundred meters to the north (Fig. 3E). Subtracting tectonic tilt indicates that the gently dipping interior probably dipped moderately to the southeast before tilt, whereas the tuff near the southeast wall was more nearly horizontal. The thalweg of the paleovalley when Eureka Canyon Tuff was deposited was probably near the present southeast wall. Eureka Canyon Tuff also shows a small “drape” anticline over Nine Hill Tuff (location C, Plate 2).

The Santiago Canyon Tuff mostly dips 35°–45° northward. Subtracting this dip but still requires a small, 10°–15° primary northwest dip. Also, the Santiago Canyon Tuff forms a small syncline (location D, Plate 2) with a steep southeastern limb and shallow northwestern limb. Subtracting tilt makes this syncline nearly symmetrical with 40°–50° dipping limbs, and the nearly flat basal contact with underlying granodiorite would dip ~28° to the southeast. This pattern suggests that the syncline was near the bottom of the paleovalley at the time of Santiago Canyon deposition.

Primary dips are less prominent in other tuffs. The tuff of Chimney Spring mostly dips 10°–30° to the northwest in its two northwestern outcrops. Untilting would make these approximately flat-lying, although the close-spaced variability in attitude suggests deposition on an irregular surface. Also, the tuff of Chimney Spring is nearly flat-lying in the middle of the paleovalley, and untilting would indicate a primary dip of 25°–30° to the southeast.

The two Mickey Pass Tuffs are exposed only along the southeast flank where present-day dips are mostly 25°–35° to the north but locally as much as 45°. Untilting would return most outcrops to approximately flat-lying but leave some with small (~10°–15°) primary northward dips. Additionally, both units locally dip ~30° to the northeast. Untilting these would change the dip direction to more southeasterly but not reduce the amount. A small, isolated area of the lower unit, including a basal vitrophyre, dips 25° to the east and would dip more steeply eastward if untilted (location E, Plate 2). This outcrop appears to be in place but could be slumped.

**RHEOMORPHISM**

The Nine Hill Tuff, which underwent rheomorphic flow throughout much of its distribution (Bingler, 1978a; Deino, 1985; Henry et al., 2004), is the only tuff in the Nine Hill paleovalley to show rheomorphism. Rheomorphism is expressed by stretching lineations, stretched pumice, boudins, rotated lithic fragments, probable lenticules, flow folds, tension cracks, and autobrecciation of the upper part of the tuff. We do not try to resolve when all of these features developed during flow, aggradation, and/or postdepositional secondary flow (Chapin and Lowell, 1979; Kobbergen and Schmincke, 1999).

The Nine Hill Tuff is densely welded and devitrified to within ~20 cm of the base. Stretching lineations near the base are primarily stretched pumice up to 1 m long and no more than 5 mm thick (Fig. 11A). Internal layers are locally stretched and boudinaged (Fig. 11B). Lithic fragments are rotated, top to the southeast. All of these features indicate minor downvalley movement.

Pumice that is highly stretched parallel to the paleovalley axis is also abundant in the upper part (Fig. 11E). However, fractures perpendicular to the flow direction show that these commonly have opened into ovoid, secondary gas cavities. The cavities may be similar to the lenticules of Chapin and Lowell (1979) but seem to have developed primarily from stretched pumice. Tension cracks are abundantly developed along near vertical partings (Fig. 11F) and show flow parallel to the paleovalley axis, commonly with tuff closer to the axis flowing past tuff away from the axis.

Three types of flow folds have been observed. Crinkle folds showing no apparent preferred orientation are most abundant (Fig. 11C). A few isoclinal folds are present in the thickest parts of the Nine Hill Tuff but may be more common because they are difficult to recognize except where the hinge is well exposed (Fig. 11D). A few more open folds have axes that parallel the paleovalley axis and suggest a small component of contraction perpendicular to the axis.

Rheomorphic breccia of Nine Hill Tuff is best exposed in the central part of the map (Figs. 11G and 11H), probably because minor silicification in this area preserves intact breccia. The breccia consists of angular clasts of tuff from a few centimeters to ~2 m in diameter in a matrix of finer grained, brecciated tuff. Many tuff clasts are themselves rheomorphic, with stretched pumice and lineations, but densely welded, non-rheomorphic clasts are also common. Breccia overlies and is commonly interleaved with lenses of steeply foliated, rheomorphic tuff (Fig. 11H). Foliation and lenses generally dip steeply southeast, and removal of the 28° of west-northwest dip would restore these to approximately vertical. Areas of Nine Hill Tuff with no measured attitudes on the geologic map generally consist of a lag of abundant, small, angular pieces of rheomorphic Nine Hill Tuff and probably mark similar breccia where it was not indurated. We interpret this breccia to have formed during secondary flow of densely welded tuff, where
Deposition of oldest ash-flow tuff—preserved river gravel in bottom of paleovalley. Welding of ash-flow tuff created a low in the middle of the valley, so river flow remained there. Compaction foliation (thin dashed lines) slightly draped topography, creating minor primary dips.

Tuff and basal conglomerate were eroded by river.

The paleoriver deposited additional gravel, and a second ash-flow tuff was deposited. Welding of the tuff again created a low in the middle of the valley.

Subsequent erosion of second cycle deposits.

The Nine Hill Tuff was deposited with the greatest primary dips. Extensive secondary (rheomorphic) flow created abundant flow folds and upper breccia.

Subsequent erosion was focused away from the densest, most resistant parts of the Nine Hill Tuff.

Late ash-flow tuff filled the paleovalley with local primary dips developed on the steep topography eroded into the Nine Hill Tuff.

Figure 10. Diagrammatic evolution of repetitive partial filling of paleovalley by gravel and ash-flow tuff and subsequent erosion. Each erosion cycle reached approximately to the bottom of the original channel. The paleovalley and river probably lasted long after deposition of the 27–23 Ma ash-flow tuffs. Small boxes show conceptual sites of selected photographs.
Figure 11 (Continued on following page). Photographs of rheomorphic features in Nine Hill Tuff. (A) Stretched pumice ~50 cm above base; same location as Figure 3B. Pumice has undergone spherulitic devitrification. (B) Stretched and slightly boudinaged and rotated layer ~1.5 m above base; same location as Figure 3B. (C) Crinkle folds in middle of tuff. (D) Isoclinal fold in middle of tuff. Note that hinge line is unrecognizable except along an ~30 cm segment. Pen ~15 cm long.
Figure 11 (Continued). (E) Stretching lineation in middle of Nine Hill Tuff showing pumice opening into elongate lenticules (?) (Chapin and Lowell, 1979). (F) Tension cracks developed perpendicular to stretching lineations in E. (G) Breccia of densely welded, commonly lineated Nine Hill Tuff clasts up to 1 m in diameter in fine, granular matrix. (H) Steeply dipping lenses of coherent, rheomorphic tuff (dark rock on left and right) and breccia (lighter-colored rock in middle).
Ash-flow tuffs in the Nine Hill, Nevada, paleovalley

hotter, interior parts of the tuff continued to flow ductilely while overlying tuff had cooled sufficiently to become brittle and brecciate.

Rheomorphism probably was concentrated in the Nine Hill Tuff for several reasons. The most important is probably high eruption and emplacement temperature, which means both pyroclasts and the welded deposit had low viscosities (Chapin and Lowell, 1979). Based on combined data from Fe-Ti oxide, pyroxene, feldspar, and biotite geothermometers, Deino (1985) estimated magmatic temperatures of 850 ± 60 °C for the lower phase and 930 ± 40 °C for the upper phase. Deino also pointed out that common dense welding of the Nine Hill Tuff to its base (e.g., Fig. 3D) and extensive rheomorphism support high emplacement temperatures. Paleomagnetic data from this study indicate that the tuff was emplaced at temperatures greater than 530–590 °C, the range of blocking temperatures for fine-grained titanomagnetite observed in the samples of Nine Hill Tuff. Some rheomorphic flow may have continued below that temperature. The Nine Hill Tuff is also moderately alkaline, although not peralkaline, which also makes for low viscosity (Deino, 1985). Confinement of flow to a paleovalley would reduce heat loss compared to more radial dispersion of the tuff and interaction with atmosphere (Bursik and Woods, 1996). Deposition in a paleovalley also means that the Nine Hill Tuff was thicker than if it had been deposited on an open plain, which also allows better heat retention.

No other tuffs in the Nine Hill paleovalley show evidence of rheomorphism, and none of these tuffs is known to be rheomorphic elsewhere in Nevada. Magmatic temperatures are known only for the upper Mickey Pass Tuff, for which Boden (1994) estimated a range of 700–730 °C from plagioclase and sanidine compositions. All tuffs except the Nine Hill Tuff are typical calc-alkaline rhyolites for which temperatures were probably no more than ~750 °C.

IMPLICATIONS FOR TECTONIC AND VOLCANIC PROCESSES

Nontectonic Angular Unconformities between Ash-Flow Tuffs

Ash-flow tuffs in the Nine Hill paleovalley generally overlie older tuffs in angular unconformity. We attribute these unconformities to the younger tuffs overlying eroded tuffs that have primary dips or dips related to rheomorphism of the Nine Hill Tuff. Angular unconformities are most common and most easily explained where the Eureka Canyon Tuff or tuff of Chimney Spring overlies Nine Hill Tuff, which has the steepest primary dips and the only certain rheomorphism. Examples include the entire tuff of Chimney Spring–Nine Hill Tuff contact and most of the Eureka Canyon–Nine Hill Tuff contact in the west-central part of Plate 2. The contact between conglomerate and underlying Nine Hill Tuff is also almost certainly an angular unconformity, based on the assumption that conglomerate is tilted 28° toward 294°. The entire top of the Nine Hill Tuff probably was marked by an angular unconformity, but all younger rocks have been eroded above most of the resistant Nine Hill Tuff.

Many other tuff/tuff contacts appear angular. The most obvious examples are near the southeastern paleovalley wall where primary dips are most common. Examples include where breccia separates Eureka Canyon Tuff that dips 20°–25° (present-day attitudes) from 27.1 Ma Mickey Pass Tuff that dips 35°. An example away from the southwestern wall occurs west of the 9 Ma basaltic andesite, where Santiago Canyon Tuff dips 20° north-northeast, and underlying Eureka Canyon Tuff dips more steeply, 35°–40°, or to the northwest.

An “inverted” angular unconformity occurs where overlying tuff develops primary dip in channels cut into flat-lying ash-flow tuffs. This relationship is best shown in paleovalleys north of Reno and in the Sierra Nevada (Figs. 3G and 10) but may be a particularly common type of unconformity. Primary dips of as much as 35° are common where ash-flow tuffs compacted against paleotopography in the negligibly tilted Sierra Nevada and can reach as much as 80° for the Nine Hill Tuff (Brooks et al., 2003; this paper).

We argue that these angular contacts are not faults, either postdating or contemporaneous with the period of ash-flow tuff deposition, and do not indicate deformation during the period of ash-flow deposition. Mapped post-tuff faults in the Nine Hill paleovalley consist only of several, north-striking, small-displacement normal faults and the northeast-striking fault that bounds the paleovalley on the northwest. Contacts between tuffs have highly irregular and diverse attitudes, compaction foliation and vitrophyres in the overlying tuff generally parallel the contact, and conglomerates generally separate tuffs. These relations are inconsistent with the contacts being faults.

The angular unconformities probably do not indicate faulting during the period of ash-flow tuff deposition. The same ash-flow tuffs or tuffs spanning the same age range as in the Nine Hill paleovalley are conformable north of Reno (Fig. 3H; Henry et al., 2004, 2009; Faulds et al., 2005a, 2005b) and in the Singatse Range (Proffett and Proffett, 1976, their fig. 5; Proffett and Dilles, 1984). In these locations, tuffs are in the middle of wide paleovalleys, so primary dips near paleovalley walls are insignificant. However, angular unconformities from primary dips could exist near paleovalley walls in both locations. Similar angular unconformities are developed between ash-flow tuffs in paleovalleys in the Sierra Nevada (Fig. 3G; Brooks et al., 2003, 2008). Although the uplift and paleoelevation history of the Sierra Nevada remain controversial, the range has undergone at most 2° of westward tilting in the mid- to late Cenozoic (Wakabayashi and Sawyer, 2001; Jones et al., 2004; Mulch et al., 2006; Cassel et al., 2009b).

In contrast, Dilles and Gans (1995) interpreted features in the northern Wassuk Range (Fig. 1) similar to those seen in the Nine Hill paleovalley, including angular unconformities, paleosurfaces with major topography, and deposition of tuffs of different ages on basement, to indicate major faulting and uplift beginning ca. 26–25 Ma. In part using similar features, Ekren and Byers (1984), Hardyman and Oldow (1991), and Hardyman et al. (1993) also interpreted syn–ash-flow tuff strike-slip, extensional, and/or detachment faulting in a zone from the Terrill Mountains southeast through the Gillis Range to Dicatalite Summit (Fig. 1). However, Eckberg et al. (2005) reinterpreted relations in the Gillis Range to result from deposition and erosion of tuffs in a paleovalley, similar to our interpretations about the Nine Hill paleovalley. Also, the ability of 27.3–23.1 Ma ash-flow tuffs to flow from source calderas in the Toiyabe and Toquima Ranges at least to the Nine Hill paleovalley indicates that a through-going paleovalley system existed throughout that time and that any deformation was insufficient to disrupt the drainage system. We suggest that tuffs in the Wassuk, Gillis, and Gabbs Valley Ranges also occupy paleovalleys, and relations in these areas should be reexamined. Regardless of relations in these eastern areas, Dilles and Gans (1995) recognized that no faulting occurred before 15 Ma in or southwest of the Singatse Range, which includes the Nine Hill area. From thermochronologic data, Surpless et al. (2002) concluded that extension and tilting of the Carson Range occurred between 10 and 3 Ma.

Interbedded Clastic Rocks

The coarse conglomerate and breccia interbedded with ash-flow tuffs in the Nine Hill paleovalley are characteristic of sedimentary deposits found in paleovalleys throughout western Nevada and the eastern Sierra Nevada (Brooks et al., 2003, 2008; Henry et al., 2004, 2009; Garrison et al., 2008; Hinz et al., 2009). Similar deposits are also present in paleovalleys that drained eastward from central Nevada in
the Eocene (Henry, 2008) and from topographic highs associated with Sevier deformation in Idaho (Janecke et al., 2000). These deposits could be interpreted to have been derived from nearby, contemporaneous fault scarps, but the nearest interpreted extension or strike-slip faulting was 70 km away in the Wassuk Range (Dilles and Gans, 1995). Even if total extension in the intervening area were 100%, fault scarps would have been 35 km away at the time.

We interpret conglomerates to result from normal, fluvial transport and deposition of clasts in a high gradient or discharge stream. Well-rounded clasts up to 2 m in diameter (Fig. 4A) indicate significant transport in a high-energy river not derivation from nearby fault scarps. The headwaters for the Nine Hill and other paleovalleys were probably at least as far east as central Nevada (Fig. 1). Thus the rivers had large drainage areas. The elevation of the headwaters and therefore gradient are uncertain, and the uncertainty is tied to the controversy over the uplift history and paleoelevation of the Sierra Nevada and western Great Basin. Based on interpreted late Cenozoic uplift, the average Oligocene elevation of the Sierra Nevada at Lake Tahoe and of western Nevada were <1.2 km and ~0.6 km (Wakabayashi and Sawyer, 2001; Axelrod, 1992). Alternatively, the Sierra Nevada and western Nevada were at elevations between 2.2 and 3 km (Mulch et al., 2006; Wolfe et al., 1997; Cassel et al., 2009b). Coney and Harms (1984), Dilek and Moores (1999), DeCelles (2004), and Cassel et al. (2009b) interpreted central Nevada to have been at elevations of 3–4 km in the Eocene, analogous to the high plateaus of modern Tibet and the Andes. The 1.2 km depth of the paleo-valley in the Singate Range (Proffett and Proffett, 1976) is possible with either set of elevation estimates but implies either a very low or moderately high overall gradient to the Pacific Ocean. Although the climate was drier, and discharge probably much less, in the Oligocene than in the Eocene (Kelly et al., 2005), the large drainage area suggests discharge was probably large and the gradient could have been high.

Sedimentary breccia probably resulted either from transport and deposition from “dam-burst”-type floods, where the river was temporarily blocked to create a lake that eventually overtopped its dam to generate a catastrophic flood (Henry, 2008), or from landslides where erosion undercut paleovalley deposits. Dam-burst floods are common, even in historic times, in volcanically or tectonically active regions worldwide, have far greater magnitudes than normal floods, and commonly generate extremely coarse fluvial deposits (Wilson and Walker, 1985; Costa and Schuster, 1988; Manville et al., 1999; Waythomas, 2001). A likely origin for a temporary dam in the Nine Hill paleovalley would be blockage of one of the tributaries by ash-flow tuff that flowed in only one tributary. The Mickey Pass Tuffs probably flowed only in the southeastern tributary and deposited as much as 300 m of tuff near the confluence; upper parts of the tuff would have been poorly or non-welded. Water would have backed up in the northeastern tributary until it overtopped and eroded rapidly through the dam. Alternatively, erosion within the paleovalley could have produced unstable slopes that failed as landslides or rock avalanches, especially where more resistant rocks overlaid less resistant rocks. An obvious example is where densely welded tuff overlay lower, poorly or non-welded tuff. For either dam-burst floods or landslides, clasts would be dominantly of the tuff itself, as is the case for the sedimentary breccia in the Nine Hill paleovalley. Basement clasts would be sparse or absent, because neither process would significantly expose or erode basement. Similar breccias could form from dam-burst floods related to extension or strike-slip faulting, but the lack of nearby, contemporaneous faulting precludes this origin for breccia in the Nine Hill paleovalley. Garrison et al. (2008) interpreted similar “ignimbrite-clast megabreccia” as a landslide deposit in an unfaulted part of the northern Sierra Nevada.

Discontinuity of Tuffs and Sedimentary Deposits

The ash-flow tuffs and interbedded sedimentary rocks are discontinuous, not only between different paleovalleys (Fig. 1), which is obvious, but also along paleovalleys. In the Nine Hill paleovalley (Plate 2), the Nine Hill Tuff is most continuous, presumably because it is the thickest, most densely welded, and therefore most resistant paleovalley deposit. It is more resistant than most paleovalley wall rocks. However, even Nine Hill Tuff is missing in the appropriate stratigraphic interval along the southwestern part of the paleovalley and along the northwestern wall where Santiago Canyon Tuff rests directly on granodiorite. All other tuffs are highly discontinuous.

Discontinuity of tuffs and sediments probably results from several factors. All tuffs were probably deposited as relatively continuous paleovalley fills (Fig. 10). However, the paleovalley was a major drainage and would have remained so after deposition of each tuff. Even if a tuff filled the valley, compaction and welding would have generated a low area in the middle of the former paleovalley, and this topographic low would have focused stream flow and subsequent erosion. Soft, upper, poorly welded parts of each tuff would erode most rapidly. However, the abundance of densely welded tuff clasts in conglomerates and the complete removal of tuffs demonstrate that even densely welded parts were severely eroded. Moreover, vagaries of erosion probably would have led to irregular paleovalley topography, with irregular knobs of tuff remaining between low eroded areas. Subsequent tuffs would have filled around these knobs to form deposits with highly varied thickness and degree of welding. Where paleovalley deposits such as the Nine Hill Tuff were more resistant to erosion than wall rocks, erosion probably would cut into wall rocks. Deposition of Santiago Canyon Tuff on granodiorite may indicate erosion cut into the granodiorite rather than into resistant Nine Hill Tuff. A further factor is whether an ash flow flowed in one or both of the tributaries that join near Nine Hill. Tuff that flowed down only one tributary would not be deposited in the other tributary other than to the extent it flowed back into the lower part of that tributary. The degree to which backflow occurred would vary depending on density and flow rate of the ash flow and on the depth and angle of intersection of the tributaries (Woods et al., 1998). Distribution of younger tuffs toward the northwest in the paleovalley may only reflect late Miocene to recent tilting of the section in that direction and subsequent erosion of upthrown parts of the fault block, although the paleovalley may have also migrated northwestward in the late Oligocene away from the resistant Nine Hill Tuff. The complex pattern of well-mapped paleovalleys in the Sierra Nevada indicates that channel migration and even complete channel switching were probably common (Fig. 1; Lindgren, 1911; Jenkins, 1932). However, channels in the Sierra Nevada were shallower than channels to the east because absolute elevation and relief relative to sea level were less. All these depositional and erosional processes would contribute to the very irregular distribution of tuffs and sedimentary deposits in the paleovalley.

Flow Lengths of Tuffs

All tuffs in the Nine Hill paleovalley flowed considerable distances from their sources as pyroclastic flows (Table 3; Figs. 5–7). All locations marked on the figures consist of massive pyroclastic-flow deposits, generally welded and showing welding zonation, and commonly having basalt vitrophyres (e.g., Fig. 3G); none are reworked deposits. Because most of the region that the tuffs traversed has been extended, it is necessary to correct for this extension to determine actual distances traveled. We have done this for the two Mickey Pass Tuffs, the Lemhi Canyon Tuff, the Santiago Canyon Tuff, and the

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Geosphere, August 2010
Caldera source Distance (km)* from caldera 
To Nine Hill paleovalleys To most distal known outcrop 
Santiago Canyon Tuff—tuff of Toiyabe 23.1 Unnamed caldera, Toiyabe Range (Brem et al., 1991) 
Eureka Canyon Tuff 25.0 Unknown unknown 
Lenihan Canyon Tuff and upper tuff of (John, 1995) 
26.8 Upper Mount Jefferson caldera of Toquima Mount Jefferson 
27.1 Lower Mount Jefferson caldera of Toquima Mount Jefferson (Boden, 1992) 
29.0 Upper Mount Jefferson caldera (Boden, 1992) 
29.0 Unnamed tuff, Soda Springs? Desatoya Mountains? 175? (to Soda Springs) Same 
29.0? (to west of Lake Tahoe) Same 
Tuff of Sutcliffe 30.1 Job Canyon caldera, Stillwater Range? 

*Present-day distance; value in parentheses is distance after correcting for extension.

Ash-flow tuffs in the Nine Hill, Nevada, paleovalley

We interpret the great flow distances of all these tuffs to their flow within paleovalleys. Topography commonly controls flow and distribution of ash-flow tuffs, which are pyroclastic density currents (Ross and Smith, 1961; Wilson and Walker, 1985; Baer et al., 1997; Ort et al., 2003). Tuffs flowing in paleovalleys can travel farther than can unconfined tuffs because they are channeled and therefore disperse less and because they interact less with air and do not cool as rapidly (Bursik and Woods, 1996). Moreover, for the Nine Hill paleovalley tuffs, flow to the west was down the gradient of the paleovalley. In contrast, the tuff of Chimney Spring flowed eastward, or upstream, less than half the distance it did to the west (Figs. 1 and 7). Total north-south extents of the tuffs, no more than ~100 km for both the 27.1 Ma Mickey Pass Tuff and tuff of Chimney Spring, indicate flow distances in those directions of no more than 50 km. Flow to the north and south would have been severely hindered by the need to cross a series of paleovalleys and interfluves, and tuff flowing in a paleovalley would tend to stay in the valley. Thus primary distributions are asymmetric, elongate west-east and shifted to the west, because of preferential flow and deposition in west-draining paleovalleys. Extension accentuated but did not produce this asymmetry.

**Thicknesses and Volumes of Ash-Flow Tuffs**

We use the 27.1 Ma Mickey Pass Tuff and the tuff of Chimney Spring to illustrate both thickness variations and possible volumes of erupted tuffs in a paleovalley setting. Although both tuffs are thinnest in their most distal deposits, neither tuff decreases regularly in thickness away from source. Instead, thicknesses are highly irregular, and both tuffs are very thick far from source (Figs. 6 and 7). The Mickey Pass Tuff is more than 100 m thick, commonly several hundred
Figure 12. Estimated percent extension between the central Nevada caldera belt and Sierra Nevada (see text for discussion). The 27.1 Ma Mickey Pass Tuff crops out as much as 295 km (present day) west of its source caldera. Correcting for estimated extension here, it flowed ~160 km to the Nine Hill paleovalley and ~200 km to its most distal outcrop.
Ash-flow tuffs in the Nine Hill, Nevada, paleovalley

Volumes of ash-flow tuff are commonly estimated for outflow deposits based on measured and contoured thicknesses and under the assumption that the tuffs spread approximately radially from source (Byers et al., 1976; Ekren et al., 1980; Henry and Price, 1986; Cas and Wright, 1987; Best and Christiansen, 1991; John, 1992b; Best et al., 1995). Radial distribution is probably generally true for proximal tuff but is definitely not true for tuffs that flowed extensively in paleovalleys. Moreover, as just shown, thicknesses of tuffs are extremely irregular. Numerous uncertainties, including discontinuous and nonsymmetrical distribution, extensive cover in basins, abrupt variations in thickness due to both depositional environment and subsequent erosion, and variations in degree of welding and therefore dense rock equivalent greatly complicate volume estimates of outflow tuff, but relative volumes can be determined for different types of distribution. We ignore dispersed ash, which may be a significant proportion of the tuffs, but is impossible to estimate for mid-Cenozoic tuffs.

Figure 13 diagrammatically shows three possible distributions of ash-flow tuff around a 20-km-diameter caldera and lists approximate areas for the different types. For all three, ash-flow tuff is assumed to blanket an approximately circular area extending 20 km from the caldera. The dashed circle centered on the caldera, with a diameter of 250 km that approximates the total east-west extent of the tuffs, is the most unrealistic distribution. Based on this study, the most realistic distribution is for distal tuff to be confined to paleovalleys within a roughly elliptical area that is shifted in the western, downstream direction (Figs. 6 and 7). The long and short axes of the ellipse in Figure 13 are 250 and 100 km, respectively, similar to the extents of the tuffs. We assume the tuffs flowed long distances downstream (the amoeba’s pseudopods of Matumoto, 1943), much shorter distances upstream, and backflowed only a few kilometers into tributaries. For calculation purposes, paleovalleys are assumed to be 10 km wide and spaced every 20 km. With these assumptions, the “modeled” initial outcrop area of the tuff in paleovalleys plus the proximal blanket is ~11,000 km², the ellipse has an area of 19,600 km², and the circle has an area of ~49,000 km². Volumes calculated either from average or contoured thickness would be proportional to these areas. Thus the most realistic distribution would likely indicate a volume no more than ~22% of the volume for a circle. Although highly simplified, these calculations demonstrate the need for thorough understanding of the distribution of outflow tuff to estimate volume.

A volume calculation based on the distribution and thickness of the 27.1 Ma Mickey Pass Tuff illustrates the implausibility of radial distribution. The tuff is as much as 300 m thick 150 km from source corrected for extension (Fig. 6). Assuming a radial distribution and that 300 m is an average thickness between source and 150 km, i.e., that the tuff did not thin away from source, would imply an incredible 21,000 km³ of outflow tuff. Even using an elliptical distribution where tuff covers the entire area to an average depth of 300 m gives an outflow volume of ~8000 km³. For comparison, the most voluminous known tuff, the Fish Canyon Tuff of the San Juan caldera complex of Colorado, has an estimated total volume of ~5000 km³, including both outflow and intracaldera deposits (Lipman, 2007).

Under the assumption that the total volume of caldera collapse accompanies the volume of magma erupted, we suggest that the volume of subsidence in the source caldera where the ring-fracture system (not topographic wall) and amount of subsidence are reasonably known best approximates the volume of erupted tuff. This seems reasonable because collapse would almost certainly not allow any voids to form, and magma replenishment is unlikely to be rapid enough to replace magma during nearly instantaneous eruption and collapse. The Mount Jefferson caldera has an area of ~400 km² within its ring fracture. The maximum exposed thickness of intracaldera tuff is ~1300 m, and the base is not exposed (Boden, 1992). The tuff did not fill the caldera, presumably because a significant volume was lost as outflow tuff or dispersed ash. Although now deeply eroded, the topographic rim probably rose ≥1000 m above the top of intracaldera tuff. These values indicate a minimum volume of erupted tuff ~900 km³. Total collapse of 3–4 km, typical of calderas in the western United States (Best et al., 1989; Lipman, 2007), would indicate a volume of ~1200–1600 km³.

Calculations for both a mid-Cenozoic and Quaternary caldera also give reasonable results. Faulting and tilting have provided exceptional exposure, including the caldera floor, of the 33.8 Ma Caetano caldera, which lies ~140 km north of the Mount Jefferson caldera (Fig. 1; John et al., 2008a). Intracaldera tuff is as much as 4 km thick and averages ~3 km, and collapse generally

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**Figure 13.** Diagram illustrating possible areas covered by outflow ash-flow tuff based on different assumptions of distribution. Estimated volumes, which would be directly proportional to areas, could vary by a factor of 4 based on different interpretations of distribution.
exceeded fill by ~1 km. Using the caldera area of 280 km², John et al. (2008a) estimated the volume of intracaldera tuff to be ~840 km³. The additional 1 km of collapse suggests an additional 280 km³ of erupted tuff, presumably outflow or fine ash, for an estimated total volume of 1120 km³. As with the Mickey Pass Tuff, direct estimation of the volume of outflow tuff is hampered by its irregular distribution and preservation, mostly in west-draining paleovalleys, around the caldera (John et al., 2008a; Gonsior and Dilles, 2008). The Long Valley caldera, ~200 km southwest of Mount Jefferson, has an area within its ring fracture (not topographic wall) of ~280 km², and total subsidence was between 2 and 3 km (Bailey et al., 1976; Bailey, 1989), to yield a subsidence volume of ~700 km³. The best current estimate of total erupted volume of Bishop Tuff is ~750 km³, consisting of 50 km³ of pyroclastic fall, 200 km³ of outflow tuff, and 500 km³ of intracaldera tuff (Hildreth and Mahood, 1986). For both calderas, intracaldera tuff is 67% to 75% of the total, consistent with other conclusions that erupted tuff dominantly ponds within source calderas (Lipman, 2007). Difficulty in direct estimation of outflow volumes may not be critical to estimating total tuff volumes in cases where the caldera is exposed.

CONCLUSIONS

As exemplified by the Nine Hill paleovalley, ash-flow tuffs in western Nevada and the Sierra Nevada are distal deposits from source calderas in central Nevada. The tuffs dominantly flowed and were deposited in paleovalleys (Fig. 10), which led to what we suggest are common but little appreciated characteristics that have major implications for the volcanic and tectonic evolution of the region. Deposition and rapid erosion in major river valleys meant that the tuffs never smoothed the topography. Western Nevada was probably a broad plateau cut by deep (up to 1.2 km) but relatively wide (up to ~10 km) paleovalleys.

Considerable variation in dip value and direction among the same ash-flow tuffs separated by distances of as little as a few hundred meters in the Nine Hill paleovalley indicate that all tuffs had primary dips, commonly up to ~20°–~30°. These primary dips resulted from compaction against moderate to steep slopes in the paleovalley. Paleomagnetic data on the Nine Hill Tuff, which shows the greatest variation in dip, confirm the primary dips and show that they reached nearly vertical in extreme cases. Although most attitudes of ash-flow tuffs undoubtedly record paleohorizontal, this should not be assumed without confirming evidence.

Angular unconformities are common where younger tuffs overlie tuffs that have primary dips and have been eroded into the dipping parts or where the younger tuff has a primary dip against an eroded wall of flat-lying tuff. Such angular unconformities are a result of volcanic and erosional, not tectonic, processes, and are not evidence for tectonism.

Coarse clastic deposits interbedded with the tuffs in the paleovalley resulted from a mix of normal fluvial processes in major rivers and dam-burst type floods resulting from catastrophic failure of natural dams where ash-flow tuffs blocked rivers. These coarse deposits are a result of common fluvial, volcanic, and erosional processes and also do not require tectonism.

Ash-flow tuffs are laterally discontinuous, both between and along paleovalleys, because they were preferentially deposited in the paleovalleys (not on interfluves) and because they were rapidly eroded in what were major rivers. Tuffs flowed as much as 200 km from their source calderas in central Nevada because they were channelized in the west-draining paleorivers. They flowed much lesser distances eastward because that was up gradient of the paleodrainage. Preferential westward flow in paleovalleys generated highly elliptical distributions shifted westward from tuff sources.

The complexity of distribution and great thicknesses even in distal parts of paleovalleys greatly hinders calculation of tuff volumes. The best way to calculate tuff volumes, in situations where the source caldera is well known, is probably from the area contained within the ring-fracture system and amount of collapse of the caldera.

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Ash-flow tuffs in the Nine Hill, Nevada, paleovalley


Trexler, D.T., 1977, Carson City geologic map: Nevada Bureau of Mines and Geology Map 1Ag, scale 1:24,000.


