

Yellowstone hotspot volcanism in California? A paleomagnetic test of the Lovejoy flood basalt hypothesis

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ABSTRACT

In 2000, D.L. Wagner and colleagues hypothesized that the middle Miocene Yellowstone hotspot volcanism thought to have produced the great expanses of Columbia River and Oregon Plateau Basalts also gave rise to the Lovejoy Basalt of California. Paleomagnetic directions of lava flows of the Lovejoy Basalt in isolated localities scattered more than 200 km across northeastern and central California show that they were erupted rapidly and that some of them traveled great distances. Most of the paleomagnetic directions form a tight cluster distinct from the Miocene mean field direction for the region, indicating eruption within a relatively short time span compared to geomagnetic secular variation—that is, within a few hundred to a few thousand years. Directional correlations demonstrate that some flows traveled at least 75 km and likely as much as 200 km. These findings support the hypothesis that the Lovejoy flows are flood basalts that compose a large south-westward extension of Yellowstone hotspot volcanism.

Keywords: flood basalts, Sierra Nevada, paleomagnetism, correlation, Columbia River Basalt.

INTRODUCTION

Turner (1895) described and mapped a patchwork of distinctive Tertiary basalt outcrops in the northern Sierra Nevada Mountains that extends 100 km from northeast to southwest. Durrell (1959) named these basalts the Lovejoy Formation and argued that they are the remnants of a series of great flows that crossed the Sierra Nevada in an ancestral river valley, where they flooded into lowlands that are now the Sacramento Valley and spread at least 70 km farther to the northwest and 130 km to the southwest. Wagner et al. (2000) suggested that the Lovejoy basalt flows were part of the same 17–14 Ma outpouring of lava flows, attributed to the Yellowstone hotspot, that compose the voluminous Columbia River flood basalt and high plateau lavas of Washington, Oregon, and western Idaho (Fig. 1). If this hypothesis is correct, it greatly extends the southwestward extent of Yellowstone hotspot volcanism.

As recently as 10 yr ago stratigraphic interpretations regarding the Lovejoy Formation were hotly disputed and K-Ar dates were highly variable. Estimates for the age of various outcrops ranged from late Eocene to early Pliocene. Now five $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating determinations are available that cluster between 15.5 and 16.4 Ma (Page et al., 1995; Garrison, 2004). The Lovejoy flows are remarkably homogeneous geochemically and much more similar to Grande Ronde flows of the Columbia River Basalt (though significantly higher in Ba, K, and P) than to other basalt flows in the less distant Sierra Nevada, Coast Range, and Cascade Arc (Siegel, 1988; Garrison, 2004). Geochemical fingerprinting of individual units is difficult, and megascopic and microscopic properties are generally inadequate for this purpose as well (Durrell, 1959). Thus, the Lovejoy flood basalt hypothesis is still untested.

In this paper we present a strong test of this hypothesis based on paleomagnetism. Changes in geomagnetic field direction that are pa-

leomagnetically resolvable occur within one to several centuries. If the widely separated outcrops of Lovejoy Basalt were the remnants of one or more great eruptions of lava that flowed long distances, all outcrops of an individual flow would have nearly the same paleomagnetic direction. This paleomagnetic test is based on degree of simultaneity, quite different from more usual fingerprinting tests that are based on chemistry or appearance. Its temporal discrimination is on the order of several hundred years, assuming rates of geomagnetic secular variation that are similar to those of today and the past few millennia (Hagstrum and Champion, 2002), much better than any available radiometric technique for rocks this old.

SAMPLE COLLECTION AND LABORATORY MEASUREMENTS

We drilled 157 cores from 20 sites at 6 localities, spanning the range of suspected Lovejoy Basalt outcrops from Thompson Peak in the northeast to Putnam Peak in the southwest and including the type

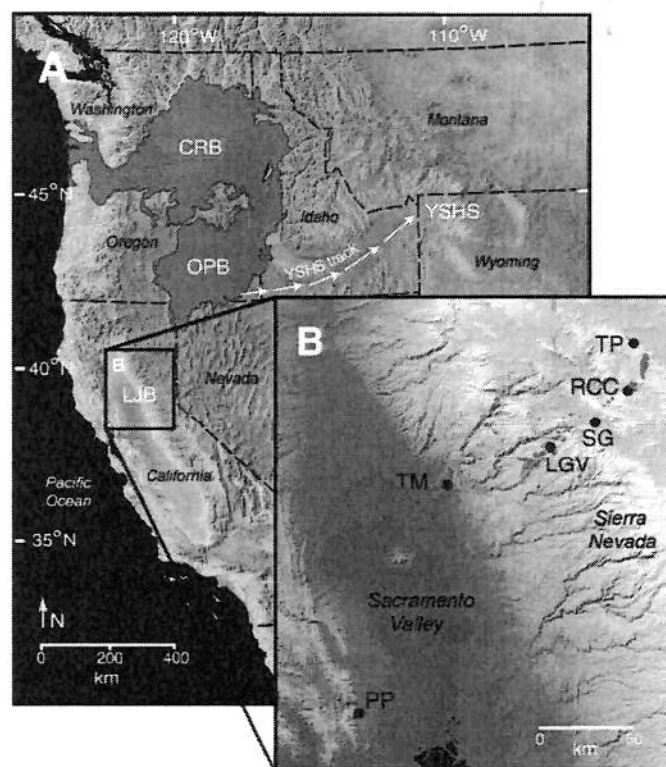


Figure 1. A: Western United States showing location of Lovejoy Basalt (LJB) relative to Columbia River Basalt (CRB), Oregon Plateau Basalt (OPB), and Yellowstone hotspot track (YSHS) track (adapted from Camp and Ross, 2004; Wagner et al., 2000). **B:** Outcrops of Lovejoy Basalt (in red) and our paleomagnetic sampling localities: TP—Thompson Peak; RCC—Red Clover Creek; SG—Spring Garden; LGV—Little Grass Valley; TM—Table Mountain; PP—Putnam Peak.

TABLE 1. SITES AND MEAN PALEOMAGNETIC DIRECTIONS

Site	Section	Elevation (m)	Declination (°)	Inclination (°)	α_{95}	k	N_f	N_{gc}
1	RCC	1606	167.0	-53.0	4.4	139.8	9	0
2	RCC	1620	164.7	-59.0	4.4	108.6	11	0
3	RCC	1654	165.9	-54.9	4.7	86.6	12	0
4	RCC	1676	169.2	-57.2	6.3	118.6	5	1
5	RCC	1733	165.5	-62.7	7.2	183.8	3	1
6	RCC	1750	277.5	-56.0	6.4	143.5	5	0
7	RCC (dike)	1607	162.9	-57.3	6.0	236.8	4	0
8	TP	1951	155.5	-56.2	3.6	243.9	7	1
9	TP	1984	156.4	-64.6	4.6	111.1	10	0
10	TP	2051	167.6	-59.4	7.0	196.2	4	0
11	TP	2182	255.0	-60.1	6.1	114.7	3	4
12	LGV1	1722	156.0	-60.0	5.1	140.6	7	0
13	LGV1	1743	257.6	-50.6	5.2	137.3	7	0
14	LGV2	1570	150.6	-29.5	7.6	47.2	9	0
15	LGV2	1699	259.0	-55.0	7.7	52.7	8	0
16	TM	360	153.7	-49.2	5.4	91.5	9	0
17	TM	402	155.0	-51.1	4.3	136.4	4	6
18	PP	253	155.8	-56.0	5.6	134.9	3	4
19	PP	299	158.2	-50.0	6.6	71.9	8	0
20	SG	1330	267.7	-24.7	11.1	37.2	6	0
Mean of sites 1-5			165.5	-57.4	3.7	440	$N = 5$	
Mean of sites 1-5, 8-10, 12, 16-19			160.6	-56.5	2.9	199	$N = 13$	
Mean 14-17 Ma (Mankinen et al., 1987)			178.6	-59.9	2.8	31	$N = 87$	

Note: Dec/Inc—paleomagnetic declination/inclination, α_{95}/k —95% confidence circle/precision parameter (Fisher, 1953), and N_f/N_{gc} —number of line fit/great-circle fit site means (Kirschvink, 1980). RCC—Red Clover Creek, TP—Thompson Peak, LGV—Little Grass Valley, TM—Table Mountain, PP—Putnam Peak, SG—Spring Garden.

section at Red Clover Creek (Fig. 1B). We oriented the cores by magnetic compass and corrected each one for magnetic anomalies by sighting the sun and known landmarks. Cores from a single site are from the same eruptive cooling unit, but the boundaries between cooling units within a locality are often not well exposed, in which case we had to infer them from talus-covered or vegetated benches that punctuate the steeply sloping sections.

Low-field thermomagnetic cycles in argon atmosphere on selected samples revealed Curie temperatures (T_c) ranging from 70 to 225 °C. With the exception of the samples with T_c of 100 °C or less, heating to 250–400 °C caused irreversible increases in both T_c and induced magnetization. Hysteresis loops saturated between 100 and 200 mT and were almost all wasp-waisted, regardless of T_c , and ratios of saturation remanence to saturation magnetization (M_{rs}/M_s) ranged systematically from ~0.17 to 0.47 as T_c varied from 100 to 250 °C. These results indicate that the main magnetic mineral is titanomagnetite with a composition around TM60–70, variably oxidized to titanomaghemite (e.g., Dunlop and Özdemir, 1997). This interpretation is corroborated by microscopic examination of polished sections and magnetic susceptibility curves for samples warmed from 77 K to room temperature.

Alternating-field demagnetization was generally superior to thermal demagnetization at reducing the scatter in directions of natural remanent magnetization for samples from the same flow. It was much better than thermal demagnetization of sister cores at removing secondary magnetization caused by lightning and almost as good at removing viscous components acquired over time at ambient temperature. The thermal demagnetization gave no indication of self-reversed partial remanence, such as has been reported in some highly oxidized submarine basalts (e.g., Doubrovine and Tarduno, 2004). We obtained excellent line-fit end points for 134 samples and great-circle fits for 17 samples. We excluded from further consideration six samples with highly discrepant directions that did not move at all during demagnetization (Table 1). For each site we calculated the mean direction from the line-fit data using Fisher (1953) statistics or the modification of McFadden and McElhinny (1988) for sites with both great-circle and

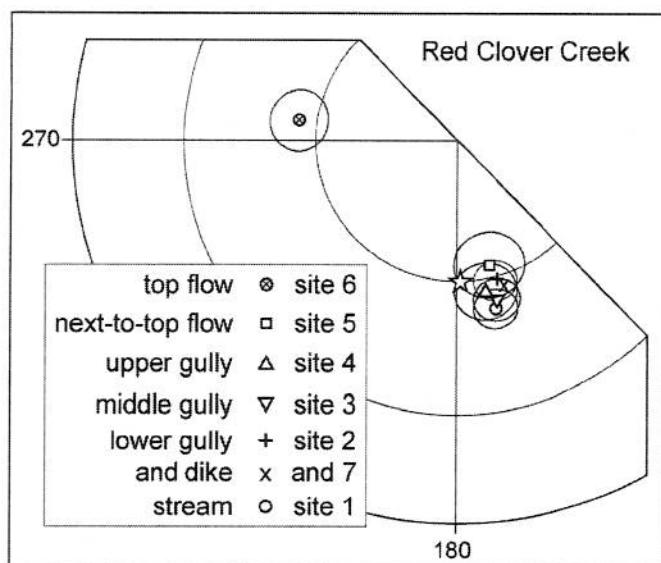


Figure 2. Site mean directions and 95% confidence circles for type section of Lovejoy Formation at Red Clover Creek. Sites are listed in stratigraphic order. Star indicates mean reversed field direction at 16 Ma (Mankinen et al., 1987). Tight clustering of site 1–5 directions distinct from 16 Ma mean shows that these flows—composing 90% of the section—were erupted quickly, probably within several centuries (see text).

line-fit data. None of the sites was corrected for dip of the flows. Except for the site at Spring Garden (Fig. 1B), discussed here, dips were small where they could be estimated and might in some cases represent the initial slopes down which the lava flowed.

PALEOMAGNETIC DIRECTIONS

All sites have upward inclinations, and most of the directions are quite similar to each other (Table 1). Even though the magnetization of most of the Lovejoy samples is carried by titanomaghemite, known to form by oxidation of titanomagnetite at relatively low temperatures, there is no correspondence between the direction of remanence and the degree of maghemitization. Moreover, the four unaltered titanomagnetite samples from a small dike (site 7 in Table 1) carry the same mean direction, within error, as that of the titanomaghemite samples of site 2 from which they emanate. Clearly the titanomaghemite either inherited the original magnetization direction of its titanomagnetite host or was magnetized as it formed during the last stages of primary cooling of the flows.

We sampled seven sites at the type locality at Red Clover Creek in the northeast Sierra Nevada range (Fig. 1B, RCC), six in superposed flows, and one in a small dike (mentioned previously). Our sites spanned 143 m in elevation, 47 m of which between sites 4 and 5 were entirely covered. Except for the top flow, the site mean directions are all SSE and up (Fig. 2; Table 1), i.e., full-polarity reversed directions that differ from the Miocene axial dipole direction by the small amount typical of ordinary secular variation of the geomagnetic field. The top flow, however, has a west and up direction. This direction is quite unusual for ordinary secular variation and could represent a rare moment during a reversal or an excursion of the field.

Figure 3 shows the site mean directions for all six localities. The directions of 18 of the 20 sites fit the pattern we found at Red Clover Creek, most of them SSE and up and a few west and up. Only 2 of the 20 sites are outliers from these 2 clusters. The similarity of directions among the various localities is striking and shows that the Lovejoy flood basalt hypothesis merits serious consideration.

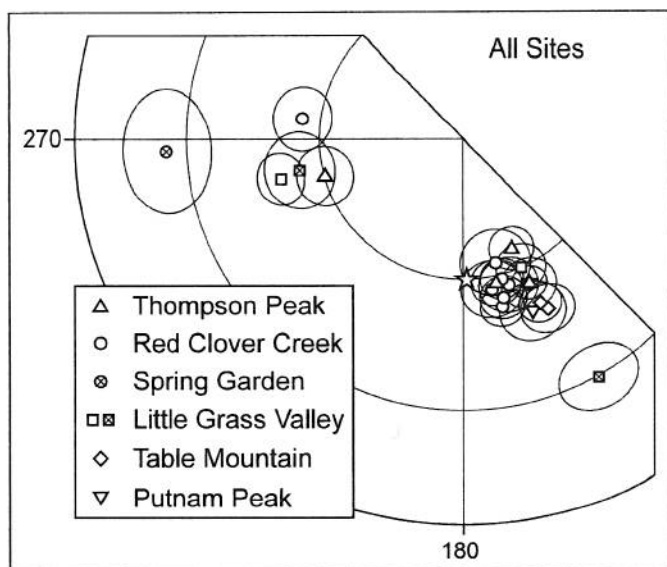


Figure 3. Site mean directions and 95% confidence circles for all 20 Lovejoy sites studied (see Table 1). Star indicates mean reversed field direction at 16 Ma (Mankinen et al., 1987). Unusual west and up directions are almost certainly from sites in a single flow. Clustered southeast and up directions suggest rapid eruption (within few hundred to few thousand years), with some individual flows represented at multiple localities 100–200 km apart.

DISCUSSION AND INTERPRETATION

Sites with West and Up Directions

We found outcrops of Lovejoy Basalt with similar west and up directions in four sections: one at Red Clover Creek, one at Thompson Peak, and two near Little Grass Valley (Figs. 1B and 3). In each case the site with this unusual direction is the uppermost Lovejoy flow of the section. Moreover, the basalt in these outcrops is visually distinctive, containing plagioclase phenocrysts. As described by Durrell (1959) and elaborated on by Page et al. (1995), Lovejoy Basalt is aphyric, with the exception of the top flow at some sections. The combined occurrence of all three characteristics—similar unusual direction, uppermost flow, and plagioclase phenocrysts—is convincing evidence that these widespread sites represent a single flow. Assuming this flow followed an ancestral river channel from Thompson Peak south to Red Clover Creek and then southwest to Little Grass Valley (Fig. 1B), it traveled a minimum of 75 km.

We sampled one other site of Lovejoy-like basalt containing plagioclase phenocrysts, a small outcrop of only part of one flow at Spring Garden (Fig. 1B) that is near the bounding faults of the Mohawk graben. It also carries an unusual west and up direction, but is $\sim 30^\circ$ shallower than the directions of the other phenocryst-bearing sites (Fig. 3). Probably this outcrop was tilted westward during the normal faulting that accommodated down-dropping of the graben. Such tilting is also suggested by the $\sim 30^\circ$ westward lean away from the vertical of crude basaltic columns.

Sites with SSE and Up Directions

The similar SSE and up directions of the five superposed sites below the top flow at Red Clover Creek (Table 1; Fig. 2) imply a rapid eruption rate. These flows span almost 90% of this 143 m Lovejoy type section. The mean direction of site 1 differs by 9.7° in inclination from that of site 5 and is statistically distinct at 99% confidence, while the directions of sites 2, 3, and 4 cluster between these two and are statistically indistinguishable from each other. Using recent rates of secular variation obtained from observatories and paleomagnetic studies of young well-dated materials (e.g., Hagstrum and Champion,

2002), these flows were probably erupted within 100–1000 yr, most likely within a time closer to the lower figure. The very different and quite unusual direction of the top flow suggests a considerable hiatus until it was emplaced, at least 1 k.y. and perhaps much more. Except for the phenocrysts, it resembles the other Lovejoy flows both in outcrop and under the microscope, and apparently signals the waning stages of eruption.

Eight other sites yielded directions that cluster with the five SSE and up site directions recorded at Red Clover Creek (Fig. 3). They occur at four localities, spread over the entire length of known Lovejoy occurrence, from Thompson Peak in the northeastern Sierra Nevada to Putnam Peak 230 km to the southwest in the Sacramento Valley (Fig. 1B). These 13 clustered sites display only 40% of the angular dispersion of directions that characterizes paleosecular variation in the northwestern United States between 17 and 14 Ma (Mankinen et al., 1987), and this figure is an overestimate because it includes the dispersion from all other causes of between-site scatter. Furthermore, the mean direction of these 13 sites is distinct from the average 17–14 Ma geomagnetic field direction for this region (Mankinen et al., 1987), mainly in declination, which is 18° less than expected (Table 1). This difference is highly significant (99.9% confidence) and almost certainly cannot be explained by tectonic rotation about a vertical axis of this large region. Thus we conclude that all these flows were erupted within a period of time much shorter than that required to record the full secular variation of the geomagnetic field, probably within a few centuries to at most a few thousand years.

Detailed inspection of the declinations of the SSE and up site mean directions in Figure 3 shows that our Red Clover Creek section may actually have undergone a small local vertical axis rotation of 9° or 10° clockwise relative to the other sections. The west and up directions of the top flows confirm the sense of this rotation but constrain the magnitude much less tightly. The consistency of declinations from the other four sites spanning the Sierra block is remarkable. Correcting for the presumed rotation would make the mean declination discrepancy discussed here even larger.

The similarity of the SSE and up directions for most of the Lovejoy sites over a very wide area suggests that some of these flows may have traveled great distances, much farther than the 75 km that is demonstrated for the top, phenocryst-rich flow with the very unusual direction. Looking closely at the directions within the SSE and up cluster, there are two intriguing long-range correlations. Sites 16 and 17 at Table Mountain, where Lovejoy outcrops reach the eastern margin of the Sacramento Valley, correlate very well with site 19, the higher flow sampled at Putnam Peak, 130 km to the southwest at the western margin of the Sacramento Valley. An even longer-range correlation is suggested between Red Clover Creek site 4 and the lower Putnam Peak site 18, 210 km away, which have very similar directions after correcting the declination of the Red Clover Creek site for the vertical axis rotation inferred here. In both cases the probability that random sampling of secular variation would yield directions so close is small, $\sim 1\%$ or 2% calculated by the method of Bogue and Coe (1981).

Source of Lovejoy Flows

No obvious feeder dikes of the Lovejoy flows have been reported. The absence led Durrell (1959) to suggest that they were erupted east of the Sierra Nevada. Roberts (1985) discovered spatter-cone material in a quarry on the shoulder of Thompson Peak associated with flows that she identified as Lovejoy, suggesting that this was a source area of Lovejoy Basalt, but Durrell did not agree with her identification (see Wagner et al., 2000, for a discussion). However, the paleomagnetic directions we found at Thompson Peak (Fig. 3; Table 1), especially those of the top, phenocryst-bearing flow and of the spatter material

(sites 11 and 10, Table 1), confirm Roberts' original—and Garrison's (2004)—interpretation.

Wagner et al. (2000) persuasively argued that Lovejoy flows were erupted at Thompson Peak during the initiation of Basin and Range faulting in the area, flowing south before turning to the southwest across the Sierra Nevada in an ancestral river valley (Fig. 1). While our paleomagnetic data say nothing about the timing of faulting, they fit that scenario nicely for the source and flow pattern. Site mean directions similar to some of those at Thompson Peak occur at locations that traverse the entire Sierra Nevada and continue into the Sacramento Valley. Whether all of the Lovejoy flows were erupted at Thompson Peak is a different question. An earlier paleomagnetic study of the Lovejoy Basalt by Grommé (1965) reported highly variable directions for 13 sites, mainly with nonoverlapping 95% confidence circles. He concluded that most of the sites represented separate lava flows. One of our site mean directions (site 14, Table 1; Fig. 3) is an unexplained outlier that could have erupted from a different vent system than that that produced the other flows that we studied. The same could be true for some of the other sites reported by Grommé (1965) with quite different directions.

FLOOD BASALT OR NOT?

A defining characteristic of flood basalts is rapid eruption of great volumes of lava, producing flows that travel long distances. The maximum thickness of the Lovejoy Basalt is 250 m and its total volume is estimated as 150 km³ (Wagner, 2000; Garrison, 2004), much smaller than an entire flood basalt province but an order of magnitude greater than the largest historic flow (Self et al., 1997). We have shown here that almost 90% of the Lovejoy type section was erupted quickly compared to geomagnetic secular variation, probably within a few centuries. The paleomagnetic evidence also demonstrates conclusively that the uppermost flow traveled a minimum of 75 km and is consistent with the hypothesis that some others traveled 200 km or more. Furthermore, it confirms that an important source area is Thompson Peak on the eastern margin of the Sierra Nevada. An alternate hypothesis to explain the similar directions that we have documented at 14 sites—eruption almost simultaneously from separate vents closer to the various far-flung paleomagnetic sampling localities—is unlikely.

Yellowstone hotspot volcanism is currently thought to have begun with the 16.6 Ma eruptions in southeast Oregon around Steens Mountain (Hooper et al., 2002; Glen and Ponce, 2002; Camp and Ross, 2004), initiating the Oregon Plateau Basalt Province that also extends into northern Nevada and western Idaho. Volcanism then migrated rapidly 200–400 km northward to the great dike systems of the even more voluminous Columbia River Basalts. We think that Wagner et al. (2000) were correct in proposing that Yellowstone hotspot magmatic activity also extended ~300 km southwest to California, generating the much less voluminous but far-traveled flows of the Lovejoy Basalt. The best radiometric ages available for Lovejoy flows, which range from 15.5 to 16.4 Ma (Page et al., 1995; Garrison, 2004), though consistent with this scenario, are not precise enough to pinpoint the temporal relation between northward and southward migration of volcanism.

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REFERENCES CITED

- Bogue, S.W., and Coe, R.S., 1981, Stratigraphic correlation in the Columbia River Basalt using secular variation of the ancient field: *Journal of Geophysical Research*, v. 86, p. 11,883–11,897.
- Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: *Journal of Geophysical Research*, v. 109, p. B08204, doi: 10.1029/2003JB002838.
- Dobrovine, P.V., and Tarduno, J.A., 2004, Self-reversed magnetization carried by titanomaghemite in oceanic basalts: *Earth and Planetary Science Letters*, v. 222, p. 959–969, doi: 10.1016/j.epsl.2004.04.009.
- Dunlop, D.J., and Özdemir, Ö., 1997, *Rock magnetism: Fundamentals and frontiers*: Cambridge, Cambridge University Press, 573 p.
- Durrell, C., 1959, The Lovejoy Formation of northern California: *California Publications in Geological Sciences*, v. 34, p. 193–220.
- Fisher, R.A., 1953, Dispersion on a sphere: *Royal Society of London Proceedings*, v. 217, ser. A, p. 295–305.
- Garrison, N.J., 2004, *Geology, geochronology and geochemistry of the mid-Miocene Lovejoy flood basalt, northern California* [M.S. thesis]: Santa Barbara, University of California, 106 p.
- Glen, J.M.G., and Ponce, D.A., 2002, Large-scale fractures related to inception of the Yellowstone hotspot: *Geology*, v. 30, p. 647–650, doi: 10.1130/0091-7613(2002)030<0647:LSFRTI>2.0.CO;2.
- Grommé, C.S., 1965, Anomalous and reversed paleomagnetic field directions from the Miocene Lovejoy Basalt, northern California: *Journal of Geomagnetism and Geoelectricity*, v. 17, p. 445–457.
- Hagstrum, J.T., and Champion, D.E., 2002, A Holocene paleosecular variation record from ¹⁴C-dated volcanic rocks in western North America: *Journal of Geophysical Research*, v. 107, p. 8–14.
- Hooper, P.R., Binger, G.B., and Lees, K.R., 2002, Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon: *Geological Society of America Bulletin*, v. 114, p. 43–50, doi: 10.1130/0016-7606(2002)114<0043:AOTSAC>2.0.CO;2.
- Kirschvink, J.L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: *Royal Astronomical Society Geophysical Journal*, v. 62, p. 699–718.
- Mankinen, E.A., Larson, E.E., Grommé, C.S., Prévot, M., and Coe, R.S., 1987, The Steens Mountain (Oregon) geomagnetic polarity transition. 3. Its regional significance: *Journal of Geophysical Research—Solid Earth and Planets*, v. 92, p. 8057–8076.
- McFadden, P.L., and McElhinny, M.W., 1988, The combined analysis of remagnetization circles and direct observations in paleomagnetism: *Earth and Planetary Science Letters*, v. 87, p. 161–172, doi: 10.1016/0012-821X(88)90072-6.
- Page, W.D., Sawyer, T.L., and Renne, P.R., 1995, Tectonic deformation of the Lovejoy Basalt, a late Cenozoic strain gage across the northern Sierra Nevada and Diamond Mountains, in Page, W.D., ed., *Quaternary geology along the boundary between the Modoc Plateau, southern Cascades and northern Sierra Nevada*: San Francisco, Friends of the Pleistocene Pacific Cell Field Trip, 368 p.
- Roberts, C.T., 1985, Cenozoic evolution of northwestern Honey Lake basin, Lassen County, California: *Colorado School of Mines Quarterly*, v. 80, p. 73 p.
- Self, S., Thordarson, T., and Keszthelyi, L., 1997, Emplacement of continental flood basalt lava flows, in Mahoney, J.J., and Coffin, M.F., eds., *Large igneous provinces: American Geophysical Union Geophysical Monograph* 100, p. 381–410.
- Siegel, J.H., 1988, *Stratigraphy of the Putnam Peak Basalt and correlation to the Lovejoy Formation, California* [M.S. thesis]: Hayward, California State University, 119 p.
- Turner, H.W., 1895, The rocks of the Sierra Nevada: *U.S. Geological Survey 14th Annual Report*, p. 435–495.
- Wagner, D.L., Saucedo, G.J., and Grose, T.L.T., 2000, Tertiary volcanic rocks of the Blairsden area, northern Sierra Nevada, California, in Brooks, E.R., and Dida, L.T., eds., *Field Guide to the geology and tectonics of the northern Sierra Nevada*, National Association of Geoscience Teachers, Far West Section Fall Conference: California Division of Mines and Geology Special Publication 122, p. 155–172.

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