Paleomagnetic Investigation of Lake Lahontan Sediments and Its Application for Dating Pluvial Events in the Northwestern Great Basin

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A comparison of paleomagnetic secular variation in sediment of Pleistocene Lake Lahontan in the northwestern Great Basin with secular variation in lake sediment in the Mono Basin, California, indicates that Lake Lahontan was in the valley of the Truckee River between Pyramid Lake and Wadsworth, Nevada, from about 19,000 to 13,000 yr B.P. The secular variation in older Lake Lahontan sediment in the Truckee River valley has the general features of secular variation in middle Pleistocene lacustrine sediments near Rye Patch Dam, Nevada, 125 km to the east. On the basis of field mapping and tephrachronology, the sections of older lacustrine sediments are not coeval. The apparent, but erroneous, correlation of those sediments emphasizes the need for multiple dating methods when paleomagnetic secular variation is used to date stratigraphy.

INTRODUCTION

The interpretation of paleoclimate in western North America for the latest Pleistocene depends in part on an accurate chronology for pluvial lakes in the Great Basin. Lakes Bonneville and Lahontan were among the largest of those lakes (Morrison, 1991), and more than 30 years ago Broecker and Kaufman (1965) attempted to establish their chronology on the basis of radiocarbon and u-series dates. More recently, tephrachronology (Davis, 1977; Sarna-Wojcicki et al., 1991), palynology (Adam, 1988), aminostratigraphy (Oviatt et al., 1994), magnetostratigraphy (Liddicoat et al., 1980; Rieck et al., 1992; Glen and Coe, 1997), and radiometric dates (Benson et al., 1995, and references therein) for those and other lakes have been used to refine the chronology.

The data we report provide an additional opportunity to date a stand of Lake Lahontan in the northwestern Great Basin. The data document long-term change (secular variation) of the paleomagnetic field in lake sediment exposed along the Truckee River near Wadsworth, Nevada, and are compared with secular variation in lake sediment in the Mono Basin, California (Lund et al., 1988), 250 km to the south. Included also is a comparison of the secular variation in older Lake Lahontan sediment in the Truckee River valley with a record of secular variation in middle Pleistocene lake sediments exposed near Rye Patch Dam, Nevada (Negrini et al., 1987), 125 km east of Wadsworth.

HISTORICAL BACKGROUND

Records of paleomagnetic secular variation that span all or part of 36,000 to 12,000 yr B.P. are reported for sediment from Lake Russell, California (Lund et al., 1988), and Lake Lahontan, Nevada (Verosub et al., 1980; Liddicoat, 1992). In addition, the behavior of the paleomagnetic field during portions of the Pleistocene is recorded in older Lake Lahontan sediment (Negrini et al., 1987) and in sediment from Tulelake (Rieck et al., 1992) and Owens Lake, California (Glen and Coe, 1997), and Lake Chewaucan, Oregon (Negrini et al., 1988; Negrini and Davis, 1992). The Lake Russell paleomagnetic record (known in the literature as the Mono Lake record, the name we use hereafter) is for duplicate records of multiple subsamples in back-to-back horizons that each are 2-cm thick in an exposed, 3-m section on the southeast side of the Mono Basin. Radiometric dates and interpolation place an age of about 13,000 yr B.P. on the top of the section and about 22,000 yr B.P. on the base. On the northwest side of the basin 20 km away, the section is continued and reaches an estimated maximum age of about 36,000 yr B.P. (Lund et al., 1988). The section on the northwest side of the basin is about 4-m thick and the measured horizons are separated by 10 cm or less (Liddicoat and Coe, 1979).

The initial reason for studying the Lake Lahontan sediments was to search for an anomalous feature of the paleomagnetic field called the Mono Lake Excursion (Denham...
posed in a 7.5-m section in the former riverbank. The section consists of six units of siltstone and two ca. 20-cm-thick beds of fine-grained sand. Diatom-rich layers are found at several horizons, and dendritic tufa occurs within the upper half meter of the section. The base of the section is a disconformable contact with non-lacustrine sediments (Fig. 2).

That individual sedimentary units can be recognized in the section on the west side of the Truckee River provides evidence for irregular rates of deposition, and fluctuations of water depth are certainly reflected in the lithologies of the deposits. However, because the non-sand units are lacustrine silt, the rate of deposition in those units may have been fairly uniform. Still, the lithology is different between units, as seen in polished thin sections (Liddicoat, 1976). In the lowermost unit (Fig. 2, Unit 1) non-opaque grains represent a variety of clastic minerals in a matrix of silica. Opaque grains make up about 5% of the volume and range in size from 1 to 60 μm. Thermomagnetic measurements (J - T) (Fig. 3) and X-ray diffraction analysis of a magnetic separate (Liddicoat, 1976) identify only magnetite, which is consistent with an unblocking temperature of about 590°C during thermal demagnetization of subsamples throughout the section (Fig. 4). Midway in the section at Unit 3, by comparison, the sediment is rich in diatoms, and contains about 30% authigenic and detrital grains. The non-opaque minerals are quartz and feldspar in the 40-μm-size range and grains of authigenic gypsum that have a diameter of up to 100 μm. Opaque grains represent about 1% of the volume and are widely distributed. Most opaque grains are rounded and have a diameter of about 5 μm; the largest opaque grain has a diameter of 40 μm.

and Cox, 1971; Denham, 1974; Liddicoat and Coe, 1979; Liddicoat, 1992, 1996; Coe and Liddicoat, 1994; Liddicoat and Coe, 1996). The Lake Lahontan sediments were used because the radiometric dates and tephrochronology cited above show that the commencement of the last major lake stand predates the excursion, which spans the interval 29,000–27,000 yr B.P. (Lund et al., 1988).

STRATIGRAPHY AND AGE

In parts of the Pleistocene, lacustrine sediments were deposited in Lake Lahontan in a large, internally drained area of northeastern Nevada. A history of the lake prior to 12,000 yr B.P. is well documented (King, 1878; Russell, 1885; Morrison, 1991; Benson et al., 1995 and references therein), and Morrison et al. (1965) describe the stratigraphy in a large, crescent-shaped exposure (Wadsworth Amphitheater) on the east side of the Truckee River north of Wadsworth (Fig. 1).

Due west of the amphitheater and on the opposite side of the Truckee River, Lake Lahontan sediments also are exp-

FIG. 1. Map of Truckee River area north of Wadsworth, Nevada. Filled circle identifies the locality where the younger Lake Lahontan sediments were sampled for paleomagnetic investigation. The locality is in the west erosional bank of the Truckee River about 1 km north of the University of Nevada Agricultural Station (S-S) and 20 km south of Pyramid Lake. Unfilled circle 3.5 km to the east-southeast is the locality in Wadsworth Amphitheater where the older lake sediments were sampled.

FIG. 2. Stratigraphic section of the younger Lake Lahontan sediments sampled for paleomagnetic investigation. Numbers adjacent to the column identify the sedimentary units. Tufa at the top of the section was dated by the 14C method and has an age of 12,910 ± 110 (carbonate fraction) and 13,110 ± 140 (organic fraction) yr B.P. Layers of cross-bedded, fine-grained sand bracket Unit 3 near the middle of the section.
carbon method. The ages are $12,910 \pm 110$ (SMU-116; carbonate fraction) and $13,110 \pm 140$ yr B.P. (SMU-137; organic fraction). Broecker and Kaufman (1965) dated tufa from other parts of the lake and also reported dates of about 13,000 yr B.P., as did Davis (1977) and Benson et al. (1995).

There are no radiometric dates for the base of the section on the west side of the Truckee River but the base must be younger than 27,000 yr B.P. The age is based on the absence of the Mono Lake Excursion and on its presence lower in the section on the shore of Pyramid Lake at Pelican Point and near Pyramid Island, and along the Carson River in the Carson Sink, 60 km to the east (Liddicoat, 1992, 1996). As well, a comparison of the curves of secular variation in the Mono Basin (Lund et al., 1988) with those for the section on the west side of the Truckee River indicates that the contact between the lacustrine and underlying subaerial deposits is younger than about 19,000 yr B.P., as described in our analysis of the paleomagnetic data.

FIELD AND LABORATORY PROCEDURES

Oriented hand samples were collected from the wall of an active gully that exposes the lake sediments on the west side of the Truckee River, or were collected from the cliffs in Wadsworth Amphitheater on the east side of the river. Before orienting a sample, up to 0.5 m of the exposed surface was removed to reach unweathered sediment. In the laboratory, using a band saw, up to six, and never less than four, subsamples (cubes 1.5 cm on a side) were prepared for each measured horizon. The error in sample orientation and laboratory preparation of subsamples is estimated to be $\pm 3^\circ$ in the horizontal and vertical planes.

The subsamples were encased in polythylene boxes for

FIG. 3. Strong field magnetization versus temperature ($H_{110}$) heating and cooling curves for a magnetic separate from Unit 1. Upper diagram, heating in air; lower diagram, heating in vacuum. Experiments were done in the Rock Magnetic Laboratory, U.S. Geological Survey, Menlo Park, CA.

FIG. 4. Vector component diagrams and plot of normalized intensity for paired subsamples from Unit 4 treated by a.f. demagnetization to (a) 100 mT or (b) thermal demagnetization to 590°C. In (a) and (b), solid circles are projections on the NS–EW plane and open circles are projections on the NS–vertical plane. Divisions on the axes are $5.00 \times 10^{-5}$ Am$^{-1}$. 
measurement in a slow-spin magnetometer at Stanford University and the Lamont-Doherty Earth Observatory of Columbia University, and alternating field (a.f.) demagnetization was done in a 4-axis tumbler. Following demagnetization to 60 milliTesla (mT) of representative subsamples from both localities, a peak field of 15 mT was used when demagnetizing the remaining subsamples. For most of the subsamples, the difference between the undemagnetized and demagnetized directions is less than 10° of a great circle arc, and the grouping of directions (alpha-95) within a horizon averages about 3°. In addition, from each unit on the west side of the Truckee River there are paired subsamples that were fully demagnetized to 590°C or in an alternating field to 100 mT, showing that the stable direction of magnetization is obtained by either treatment (Fig. 4).

ANALYSIS OF THE PALEOMAGNETIC DATA

As explained above, we compare paleomagnetic secular variation in Lake Lahontan sediment exposed in the valley of the Truckee River with secular variation in lake sediment in the Mono Basin (Lund et al., 1988) and near Rye Patch Dam (Negrini et al., 1987).

West Side of the Truckee River

At this locality the declination swings as much as 30° east or west of geographic north as the inclination fluctuates by 30° and averages about 10° shallower than the inclination of an axial dipole field (59°) (Fig. 5). The larger swings in the paleomagnetic directions persist across most unit boundaries, which is an indication that there probably are not major discontinuities in the depositional record.

The shallow average inclination raises the possibility of an inclination error [the difference between the recorded inclination and the inclination of an axial dipole field (King, 1955)], which we attempted to check experimentally. To do that, we redeposited sediment from each unit (Liddicoat, 1976; Liddicoat and Coe, 1979), discovering that the inclination in the experimental samples is at least 13° less (in Unit 5) than the inclination in the laboratory, and in one set of samples (from Unit 3) the inclination difference is about twice that amount. Several factors inherent to the redeposition experiment could account for some of the difference: the rapid drying of laboratory samples (when compared to drying in nature), allowing less time for post-depositional alignment of magnetic grains; shallowing of the orientation of grains that touched the bottom of the container (the samples of redeposited sediment, when dry, averaged about 1 cm thick, so we used the entire sample for measurement); and the rotation of grains in the vertical plane during shrinkage that accompanied drying. For the last, there is a correlation between the percentage of shrinkage and the inclination before and after redeposition (Fig. 6).

FIG. 5. Paleomagnetic curves for the younger Lake Lahontan sediment exposed along the Truckee River north of Wadsworth, Nevada. The data are for a.f. demagnetization at 15 mT. The data for Unit 6 are not plotted because the paleomagnetic directions are very scattered (Liddicoat, 1976). The scatter in Unit 6 is attributed to fracturing and weathering of the siltstone during continuous exposure in the gully cutting the desert surface. Vertical line in the plot of inclination is the inclination of an axial dipole field (59°). Intensity is Am^-1.

The sediment redeposition experiment admittedly was crude, so we are hesitant to place much significance on the findings. Still, an error in the inclination did occur, and the average difference for the experimental samples is about 20°, or twice the average error for the entire data set. The lesser error in the natural sediment might stem from the activity of burrowing benthic organisms or chemical overprinting, although there is no evidence for the latter, as explained below.

If an inclination error exists in the natural sediments, then one of the magnetizing processes is detrital remanent magnetization (DRM) (Irving, 1964). A basaltic cone that borders the east side of the Truckee River valley could be a source for detrital magnetite; the fine-grained opaque minerals seen in thin section are sufficiently small to be aligned by the paleomagnetic field (Keen, 1963; King and Rees, 1966).

The amount of chemical overprinting appears to be small because the deposits do not contain a large secondary component of magnetization (Fig. 4), nor one of high coercivity as would be expected if the main magnetic carrier were fine-grained hematite. Furthermore, the petrographic, thermomagnetic, and X-ray diffraction analyses do not indicate that hematite is present in the sediment. Thus, it seems that DRM was the dominant magnetizing process, which implies that the paleomagnetic directions (allowing for a systematic incli-
nation error) and periodicities correspond to fluctuations of the geomagnetic field at the time the sediment was deposited.

As noted, one of our interests in the paleomagnetic record at the locality on the west side of the Truckee River was the presence or absence of the Mono Lake Excursion. As part of that search in the lowermost m of the section (Unit 1), we attempted to determine the uniformity of magnetization and, correspondingly, the fidelity of the record. We did this by comparing paleomagnetic data for two suites of subsamples separated laterally by half a meter (Fig. 7). Generally, the declination in both sets of data is compatible, having the same west-to-east trend when traced from old to young. The inclination in the upper (younger) half of the curve shows about a 5° difference, but the horizons in the upper two-thirds of the smaller data set (open circles) came from two large hand samples, so at least part of this discrepancy may be due to orientation differences. Overall, though, the agreement in inclination is quite good. Furthermore, both data sets indicate that the magnetic field was behaving in a smooth fashion, in contrast to the more unsettled behavior in some of the overlying (younger) units.

Almost certainly the changes in the paleomagnetic field in the Mono Basin (Fig. 8) would be similar to those recorded in the Truckee River valley, about 250 km away. We would, therefore, expect the paleomagnetic record for the two localities to match at least in their general features. Examination of Figure 9, in which the paleomagnetic curves are compared, shows, however, that there are differences. The differences raise questions such as: (1) What effects do conditions of sedimentation and subsequent drying and diagenesis have on the recording process? (2) What is the reliability of the dating on the stratigraphy? (3) Do fluctuations and other changes in the records reflect details of the composition and physical state of magnetic minerals carrying the remanence? (4) Which, if either, data set accurately represents behavior of the paleomagnetic field? A brief exploration of these questions and possible answers follows.

Sedimentation and diagenesis. Our assumption that the sedimentation rate in Mono Lake was constant or nearly so has some justification. The section is uniformly silt, with no obvious lithologic differences other than volcanic ash layers; the source of the layers is the Mono Craters on the southern
end of the Mono Basin and a volcano that erupted within the lake on its northwestern side. For the Lake Lahontan section, by comparison, it is easy to imagine variable rates of deposition because of the sediment types described earlier. Shrinkage of the sediments during drying in the redeposition experiment was also variable in the Lake Lahontan silt, but it was minimal in the one redeposited sample from the Mono Basin (Fig. 6). The presumed provenance of the sediment in the Truckee River valley is the surrounding landscape, whereas the silt in the Mono Basin is glacial silt from the Sierra Nevada (Lajoie, 1968, 1993). The lacustrine sediment in both basins appears to be unaltered when examined in polished thin sections (Liddicoat, 1976).

**Dating.** Accurate radiometric dating of the sampled sediment is a constant concern. The age of the tufa from the top of the section on the west side of the Truckee River might be in error by several thousand years if there was isotopic contamination by young carbon, which seems a definite possibility for so porous a material. Nevertheless, the assigned age of about 13,000 yr B.P. seems reasonable in light of the age placed on the termination of Lake Lahontan by Benson et al. (1995); Figure 10. The approximate age of 13,000 yr B.P. for the youngest Mono Lake sediments is based on five radiocarbon dates (Lund et al., 1988) from the Mono Basin and correlation of volcanic ash layers (Lajoie, 1968).

**Magnetic minerals.** Petrographic and laboratory studies of magnetic minerals separated from the silt in the Mono Basin and on the west side of the Truckee River indicate that magnetite is the primary carrier of the magnetization (Liddicoat, 1976). The size fraction is appropriate for DRM, and the apparent inclination error in each set of paleomag-

![Diagram](image-url)
netic curves is evidence against post-depositional remanent magnetization (PDRM) or chemical remanent magnetization (CRM) as biasing factors.

Reliability of the paleomagnetic records. Because the paleomagnetic record in the Lahontan and Mono basins was not confirmed at a second locality, we are unable to claim that one record is more accurate than the other. It is reasonable, however, to put more faith in the Mono Basin record on the basis of the extensive work on the Mono Lake Excursion at three far-removed localities that record the nearly identical behavior of the paleomagnetic field (Liddicoat, 1992; Liddicoat and Coe, 1996). (As noted, our only check of the record in the Lahontan Basin on the west side of the Truckee River was in Unit 1 when we were searching for the excursion.) On the assumption that the major east–west swings in declination and steepening or shallowing of inclination over time would be recorded simultaneously in the sediment in the Lahontan and Mono basins, the following observations are made about a comparison of the paleomagnetic records.

Examining first the curves of inclination (Fig. 9), there is not a one-to-one correlation with all of the larger fluctuations. However, some of the more obvious fluctuations can be matched reasonably well. An example is at about 14,500 yr B.P. where a relative steepness in the inclination was preceded by shallowing that followed an earlier inclination high at about 16,000 yr B.P. That high, in turn, was preceded by steepening that began about 17,000 yr B.P., and 2000 yr of shallowing inclination at the base of the records.

Major features in the declination record for each locality stand out in several places. At the top of the records and ending at about 16,000 yr B.P., declination moves gradually from east to west. From 16,000 to 18,000 yr B.P., declination is entirely easterly, and at about 18,000 yr B.P. the declination is again westerly. However, the large west–east declination swing 1 m from the base of Unit 1 in the Lahontan Basin, and the overall easterly declination beginning at the bottom of that record, are not present in the Mono Basin. This part of the Lahontan Basin record was duplicated in our search for the Mono Lake Excursion (Fig. 7), so the difference in the curves cannot be discounted as an error in sample orientation. There is no apparent correlation between the curves of relative intensity other than that in the lower 3 m of both records the relative intensity does not contain large fluctuations.

The sedimentation rate is variable but similar in both sections if the ages in Figures 8 and 9 are accurate. The lower two-thirds of the sections show twofold increases in the sedimentation rate compared to the upper thirds, and the overall rate is about 10 yr/cm, or three times higher than the total rate in Mono Lake (Lund et al., 1988) and in Searles Lake (Liddicoat et al., 1980), another pluvial lake in the western Great Basin for which a chronology is based on radiocarbon dates and paleomagnetic polarity (Liddicoat et al., 1980; Smith et al., 1983). The higher rate in the lower two-thirds of the section along the west side of the Truckee River might be attributed to an increased sediment influx when a large volume of water entered the Lahontan Basin to raise Lake Lahontan to one of its high stands (Fig. 10). Although impossible to prove, the beds of fine-grained sand that bracket Unit 3 might represent brief times when the lake surface fell below an altitude of 1250 m about 16,000 yr ago (Benson et al., 1995) (Fig. 10).

Wadsworth Amphitheater

Several km east of the Truckee River, where we sampled the Lake Lahontan sediments, older lake sediment crops out in the Wadsworth Amphitheater. Measured from the present floodplain, the section consists of about 30 m of interbedded siltstone and unconsolidated medium- and fine-grained sand (Morrison et al., 1965; Smoot, 1993). The age of the section is not known, but deposition of the sediment is estimated to have occurred between approximately 380,000 and 120,000 yr B.P. (Morrison, 1991).

We sampled the siltstone exposed in the amphitheater at vertical intervals of about 10 cm. The mean paleomagnetic directions have an overall inclination that is about 20° shallower than the inclination of an axial dipole field (Fig. 11). Examining the curve of declination, starting at the base of the section, the lower 4 m show a gradual change toward the west (to 330°) that is followed by a return to north. The overlying ca. 10 m record a more fluctuating field behavior with numerous east–west swings if the data are not smoothed. Superimposed on this record is a long-period cycle that moves first to the west, then to the east, and ends about 8 m below the top of the section. The upper fifth of the record has nearly unchanging declination that remains about 10° east of north.

Negrini et al. (1987) report a paleomagnetic record for localities of middle Pleistocene Lake Lahontan deposits exposed near Rye Patch Dam along the Humboldt River. Although the deposits are believed to be older than those we sampled [tephrochronologic correlations by Davis (1978) assign an age of about 500,000 yr B.P. to the youngest deposits; Negrini et al. (1987)], the paleomagnetic data for the oldest deposits sampled (at locality HR-3) are remarkably similar to the younger ca. 4 m of the record at the Wadsworth Amphitheater. When the data for HR-3 are smoothed and traced from old to young, the overall declination is easterly by about 10° during a gradual steepening of inclination (Fig. 12). Nowhere else in the paleomagnetic records for Lake Lahontan sediments of any age does such behavior stand out. Thus, an erroneous correlation of the records would be made in the absence of stratigraphic and tephrochronologic information of the kind that exists for the two localities.
CONCLUSIONS

1. The pattern of paleomagnetic secular variation in Lake Lahontan sediment exposed on the west side of the Truckee River can be correlated quite well with secular variation in the Mono Basin to show that Lake Lahontan was at a high stand from about 19,000 to 13,000 yr B.P. The mean declination in the sediment averages close to geographic north for those 6000 yr, but inclination is shallow by about 10° when compared to the inclination of an axial dipole field.

2. The upper ca. 4 m of a 30-m section of older Lake Lahontan sediments in the Wadsworth Amphitheater contain paleomagnetic directions that are similar to the directions in middle Pleistocene lacustrine sediments exposed along the Humboldt River about 125 km to the northeast. Those sediments are at least 500,000 yr old, so they are not correlative with the sediments at the amphitheater. The age discrepancy emphasizes the necessity of multiple dating methods when correlations using paleomagnetic secular variation are attempted.

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FIG. 11. Paleomagnetic curves for the older Lake Lahontan sediment in the amphitheater on the east side of the Truckee River 5 km north-northeast of Wadsworth, Nevada (Fig. 1). Data are for six subsamples for each horizon, demagnetized in an alternating field of 15 mT. Horizontal lines about 5 m from the base of the section represent breaks in sampling where there was unconsolidated sand. Vertical line in the plot of inclination is the inclination of an axial dipole field (59°). Intensity is Am⁻¹.

FIG. 12. Inclination and declination recorded in middle Pleistocene lacustrine sediments exposed along the Humboldt River 400 m south of Rye Patch Dam, Nevada. The section contains the Rye Patch Dam Tephra, which is stratigraphically beneath the Lava Creek Tephra that has an assigned age of 610,000 yr B.P. Plot (b) is a smoothed plot of (a). Data are from Negrini et al. (1987, Figs. 7 and 8). Note the easterly bias in the smoothed plot of declination.


