Reports

An Episode of Steep Geomagnetic Inclination 120,000 Years Ago

Abstract. *The mean inclinations of three sections of 120,000-year-old fine-grained sediments from northern California range from 62° to 66°. These inclinations are significantly steeper than the inclination of the geocentric axial dipole at this site. Because these sediments have probably recorded an actual episode of steep inclination lasting several thousand years, they provide new insights into the significance of mean inclinations shallower than the geocentric axial dipole. Such inclinations are characteristic of fine-grained sediments younger than 35,000 years. The results raise questions about the time-averaged geomagnetic field and about the determination of plate motions from paleomagnetic data.*

Much of our knowledge of geomagnetic secular variation has been derived from paleomagnetic studies of sequences of rapidly deposited, fine-grained sediments. For the most part, such investigations have focused on lacustrine sediments of late Glacial or Holocene age, that is, sediments less than about 35,000 years old. One finding of virtually all the studies at northern mid-latitudes is that the mean inclinations are 0° to 12° shallower than the inclination of the geocentric axial dipole at the latitude of the sampling site (*1*). In many cases all the individual inclinations are shallower than the geocentric axial dipole value.

It has been argued that the shallow inclinations arise from an inclination error acquired as the sediments became magnetized with a depositional detrital remanent magnetization (*2*). The existence of an inclination error in certain types of natural sediments, particularly glacial varves, is well documented; however, its occurrence in normal lacustrine sediments has not been established (*1*). Consequently, an alternative explanation for the consistently shallow inclinations has been proposed, namely, that the paleomagnetic results reflect actual geomagnetic field behavior and that mean inclinations in northern mid-latitudes were shallow during the late Glacial and Holocene epochs (*3*). Two observations support this idea. First, many lacustrine sequences probably possess a postdepositional rather than a depositional detrital remanent magnetism, and thus are not susceptible to an inclination error (*1*). Second, at present the mean inclination of the geomagnetic field at mid-latitudes is less than that of the geocentric axial dipole (*4*).

As part of a detailed study of secular variation during the past 500,000 years, I studied the paleomagnetism of three sections of the Riverbank Formation of northern California. The Riverbank Formation is a sequence of silts, sands, and gravels deposited by rivers that drained the Sierra Nevada and flowed into the Sacramento and San Joaquin valleys (*5*). These fluvial deposits are believed to represent outwash associated with a major episode of glaciation in the Sierra Nevada. Uranium-trend dating of a soil developed in the Riverbank Formation above the studied section yielded an age of 120,000 ± 40,000 years (*6*). This date is consistent with a minimum age for the site of 103,000 ± 6,000 years determined earlier from uranium dating of bone samples (*7*).

The study site is a large gravel quarry in eastern Sacramento County, California, in the drainage of the American River. The three sampled sections are all in the walls of the quarry in a 10-m-thick overburden of sand and silt removed to expose river gravels. Two of the sections, A and B, consist of coarse silt and fine sand and probably represent overbank and levee deposits. The third section, C, is composed of finer-grained silt and probably represents a back-swamp or slack-water deposit. All the sections were sampled with small plastic boxes (2.5 by 2.5 by 1.8 cm). Sections A and B were continuously sampled over intervals of 2.00 and 1.20 m, respectively, for a total of 137 samples at section A and 81 samples at B. At section C only 12 samples were collected, at an average interval of about 10 cm.

Complete demagnetization studies were done on 15 pilot samples from sections A and B and on all the samples from section C (*8*). The pilot samples from A and B showed virtually no directional change on demagnetization. The mean angular change between the direction of the natural remanent magnetization and the direction at the median destructive field was 3°. Furthermore, the small changes in direction between each demagnetization level showed no systematic trend. Examination of individual samples showed that the relatively friable material was beginning to abrade as the sample rotated in the magnetometer. This abrasion caused the samples to jostle slightly in their boxes. In view of this effect and the extreme stability of the magnetic directions, I concluded that the natural remanent magnetization directions were the most reliable.

The magnetic directions of samples from section C did show small, systematic changes on the order of 5° to 10°. These samples were considerably less friable than those from sections A and B, and abrasion did not occur. Consequently, the directional changes in samples from section C were interpreted as representing a small viscous component. The primary direction of magnetization of each of these samples was determined from the behavior of each sample on demagnetization.

The paleomagnetic directions of the samples from sections A and B are shown in Fig. 1. The most significant feature of these data is that almost all the inclinations are steeper than that of the geocentric axial dipole at this site. The mean direction of all samples from section A is I (mean inclination) = 66.3°, D (mean declination) = 0.9°, and α_{95} (the cone of 95 percent confidence) = 0.9°, while for section B, I = 61.6°, D = 0.3°, and α_{95} = 1.3°. These mean inclinations are 8.4° and 3.7° steeper than the inclination of the geocentric axial dipole, 57.9°. For the 12 samples from site C the mean inclination is 61.9°. These results cannot be explained in terms of effects involved in the acquisition of the detrital remanent magnetization. The inclination error, if present, can only make the inclination more shallow. In certain geometries a current rotation effect can steepen the inclination (*9*). However, because the paleocurrent direction is known in this case, that possibility can be excluded. From the sedimentary structures abundantly exposed in the quarry, any significant tilting of the sediments can be eliminated as a cause of the steepened inclinations.

Another possibility is that the remanent magnetization of the sediments reflects an overprint of the present geomagnetic inclination of 63°. However, the present geomagnetic declination is 16°E, and there is no evidence for a bias in the declination. Furthermore, recent work on the history of the earth's field in the western United States (*10*) indicates that during the past 500 years the mean declination was the same as the present declination while the mean inclination was equal to or even less than the geocentric axial dipole. Thus a viscous overprint acquired over the past 500 years would have an anomalous declination rather than an anomalous inclination. In addition, consistent results are obtained from the three sites even though two very different sedimentary environments are represented, involving particles of two very different grain size distributions. These circumstances make it unlikely that the magnetic directions are controlled by sedimentologic or rock magnetic factors. I therefore conclude that these sediments record an interval of time during which the geomagnetic field had a relatively steep inclination.

This result is significant if it can be shown that the mean inclinations for each site represent average values of the geomagnetic field over a geologically significant period of time. Although it is probably impossible to determine the actual duration of an episode of sedimentation that is 120,000 years old, evidence indicates that at least 20,000 years of sedimentation are involved here. In the first place, the results from all three sections are consistent, even though they are from different stratigraphic levels in the quarry. Furthermore, the magnetic records of sections A and B each contain features that are characteristic of a secular variation record. At both sites the inclination values are not uniformly scattered about the mean value, but change systematically so that the mean inclinations over portions of each section are steeper or shallower than the mean inclinations of the entire section. Such behavior is what would be expected if the sediments had recorded the passage of several nondipole features of the geomagnetic field. Similar, correlated features are seen in the declination records. Furthermore, the angular standard deviations of sections A, B, and C are 5.7°, 6.6°, and 8.4°, respectively. These values are comparable to the 8.1° angular standard deviation of the present field at the site's latitude, and they are substantially greater than would be expected if the sediments had recorded only a spot reading of the magnetic field. If the variations in the inclination record do represent nondipole features and if the rate of occurrence of such features was comparable to that of the present field, then comparison of the records from sections A and B with those of the Holocene field (*11*) indicates that sections A and B represent intervals of about 12,000 and 9,000 years, respectively. The sedimentation rate corresponding to these times is about 0.15 mm per year, which is quite reasonable for this type of sedimentary environment.

While these arguments cannot prove that each section records several thousand years of geomagnetic secular variation, they do demonstrate that such an

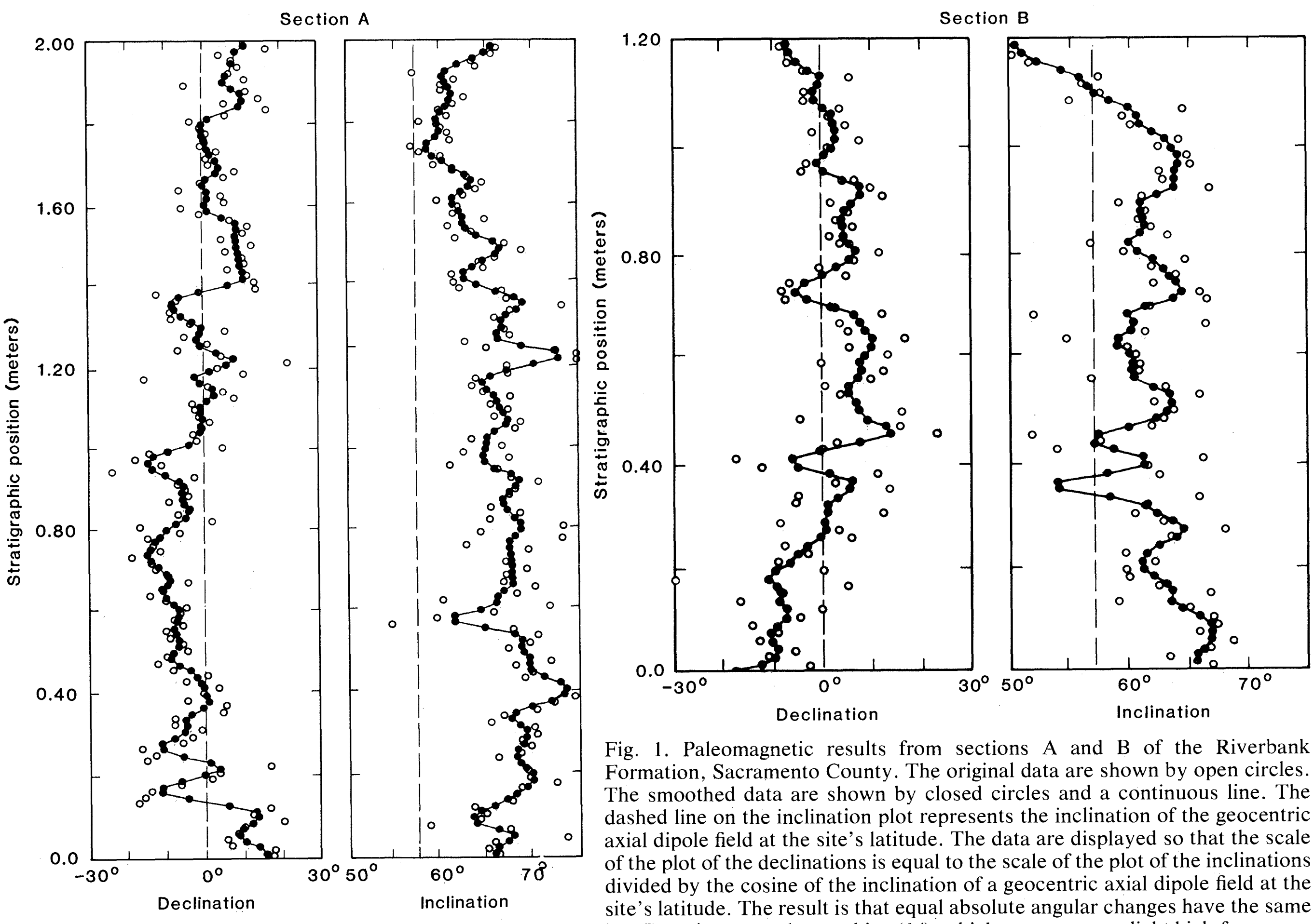

Fig. 1. Paleomagnetic results from sections A and B of the Riverbank Formation, Sacramento County. The original data are shown by open circles. The smoothed data are shown by closed circles and a continuous line. The dashed line on the inclination plot represents the inclination of the geocentric axial dipole field at the site's latitude. The data are displayed so that the scale of the plot of the declinations is equal to the scale of the plot of the inclinations divided by the cosine of the inclination of a geocentric axial dipole field at the site's latitude. The result is that equal absolute angular changes have the same amplitude in each plot. The data were smoothed by using seven-point, Gaussian-normal smoothing (*14*), which suppresses a slight high-frequency scatter between successive data points while preserving the detail of the lower frequency trends. Weighting factors of 0.035, 0.231, 0.693, 1.000, 0.693, 0.231, and 0.035 were used in determining the weighted mean of each vector direction. The degree of smoothing is almost equivalent to that of a three-point running mean, but the method used avoids the statistical pitfalls inherent in a simple running mean. Furthermore, it does not involve any of the assumptions required for more sophisticated smoothing methods, such as the use of splines. The average properties of the data were computed on the smoothed data.

assumption is consistent with all the available information. Taken together, the three sections provide evidence that about 120,000 years ago the mean inclination of the geomagnetic field was, for perhaps 20,000 years, steeper than that of the geocentric axial dipole (*12*).

This conclusion has important implications for our understanding of the geomagnetic field. If the field can sustain a steep inclination for tens of thousands of years, it is likely that it can sustain shallow inclinations for long periods as well. Such a conclusion supports the view that the shallow inclinations seen in late Glacial and Holocene sediments represent actual behavior of the geomagnetic field. It also suggests that it may be feasible to subdivide the Brunhes normal polarity epoch on the basis of whether the mean inclinations are steeper or shallower than the geocentric axial dipole value.

Equally important, if, over the past 35,000 years, the mean inclination of the geomagnetic field has been shallower than that of the geocentric axial dipole, then the time required for the field to average to such a dipole may be substantially greater than the 10,000- to 25,000-year interval now assumed to be required. Nongeocentric, axial components of the field may persist for 50,000 to 100,000 years, and the time required to average to a geocentric axial dipole field may be several hundred thousand years. In fact, paleomagnetic data from sequences of lava flows have been interpreted as showing that the geomagnetic field averages to an offset axial dipole rather than a geocentric dipole (*13*). All paleomagnetic determinations of the apparent motion of plates and microplates depend on the assumption that the paleomagnetic samples represent enough time for the field to have averaged to a geocentric axial dipole. If this time is significantly longer than has been assumed, or if it does not exist at all, then the results of some of these determinations will require reevaluation.

KENNETH L. VEROSUB
Department of Geology,
University of California,
Davis 95616

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16 November 1982; revised 14 March 1983

Entwined and Parallel Bundled Orbits as Alternative Models for Narrow Planetary Ringlets

Abstract. *Particle orbits can be bundled in two different ways to produce narrow, Uranus-type ringlets. The usual assumption is that they are packed in a parallel manner in a structure that is essentially only two-dimensional, but it is then difficult to explain the large numbers of particles per unit area of the ring plane that are inferred from the observations. The alternative of a bundle of entwined orbits produces a three-dimensional structure of potentially large projected areal density. A start has been made in identifying possible mechanisms for stabilizing these structures, but much remains to be done, particularly for the less-studied model of entwined orbits. The two models might be discriminated observationally by differences in the motion of the line of intersection of the orbital and equatorial planes, and by the predicted radial reversal (entwined) or nonreversal (parallel) of features in occultation signatures taken at certain longitudes.*

The individual rings of Uranus are very narrow in their radial extent (*1*), and similar ringlets are embedded in the ring system of Saturn (*2*). There are two fundamentally different ways of bundling a large number of elliptical orbits to produce narrow, dense, and collisionless planetary ringlets. In a "parallel" arrangement, the radial order of orbits is the same at all longitudes. Nearly all the literature on rings is restricted, explicitly or implicitly, to the fundamental properties of this model (*3*). However, an "entwined" arrangement of the elliptical orbits is also possible, as described by Michel (*4*) and as treated independently by Eshleman *et al.* (*5*). Here the radial order changes with longitude and can even be reversed. For example, a particle on the inner edge of the entwined ringlet at one longitude is on the outer edge at another, making one clockwise or counterclockwise twist relative to the ringlet core during each circuit of the planet.

A successful model must explain the large observed optical depths, which can range to values so high that they indicate more area of particles projected into the average ring plane than there is ring plane area. It must explain ringlets that are both eccentric and inclined, since French *et al.* (*6*) found that the ringlets of Uranus are so disposed. And it must account for the apparent long-term stability of its structure in the face of perturbing forces. In this report the two models are compared on these points to the limited degree allowed by their corresponding states of development. Some new material on their general structures is also presented.

The orbit and position of each ring particle is given by six parameters: a, e, i, ω, Ω, and f, representing, respectively, the semimajor axis and eccentricity of the elliptical orbit, its inclination relative to the planet's equatorial plane, the argument of periapsis or angle between the intersection (line of nodes) of the orbital and equatorial planes and the major axis or line of apsides (from the greatest orbital radius at apoapsis to smallest radius at periapsis) of the orbit, the longitude of the ascending node or angle between an inertial reference direction in the equatorial plane and the line of nodes, and the true anomaly or angle between the line of apsides and the radius vector of the particle. Although the possible arrays of these parameters for planetary ringlets are without limit, it appears that the two models can be characterized by just two sets.

For both models, it is assumed that particles are spread around each orbit with average separations proportional to their speeds, so that f is approximately