PRELIMINARY PALEOMAGNETIC RESULTS FROM THE COYOTE CREEK OUTDOOR CLASSROOM DRILL HOLE, SANTA CLARA VALLEY, CALIFORNIA

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Open-File Report 03-187

2003

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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ABSTRACT

Paleomagnetic samples were obtained from cores taken during the drilling of a research well along Coyote Creek in San Jose, California, in order to use the geomagnetic field behavior recorded in those samples to provide age constraints for the sediment encountered. The well reached a depth of 308 meters and material apparently was deposited largely (entirely?) during the Brunhes Normal Polarity Chron, which lasted from 780 ka to the present time. Three episodes of anomalous magnetic inclinations were recorded in parts of the sedimentary sequence; the uppermost two we correlate to the Mono Lake (~30 ka) geomagnetic excursion and 6 cm lower, tentatively to the Laschamp (~45 ka) excursion. The lowermost anomalous interval occurs at 305 m and consists of less than 10 cm of fully reversed inclinations underlain by 1.5 m of normal polarity sediment. This lower anomalous interval may represent either the Big Lost excursion (~565 ka) or the polarity transition at the end of the Matuyama Reversed Polarity Chron (780 ka). The average rates of deposition for the Pleistocene section in this well, based on these two alternatives, are approximately 52 or 37 cm/kyr, respectively.

INTRODUCTION

The drill hole described herein is the first of several research monitoring wells that are being drilled in the alluvial sediments of Santa Clara Valley over a period of three years. The work is a collaborative effort between the U.S. Geological Survey and the Santa Clara Valley Water District to provide a better basis for assessment of earthquake hazard and for the management of the groundwater system. The first well drilled under this program (figure 1) is named the Coyote Creek Outdoor Classroom (CCOC) after the intended future use of this site. This report describes the results of a paleomagnetic investigation of sediment cores taken at various intervals within the well (herein referred to as the CCOC drill hole), a total of 61.8 m of core in the 308-m well. By using the natural magnetization contained in rocks and sediment, the paleomagnetic method can often provide useful chronological information. We first review the geomagnetic framework and the geologic context of the CCOC drill hole, then describe and discuss the paleomagnetic study.

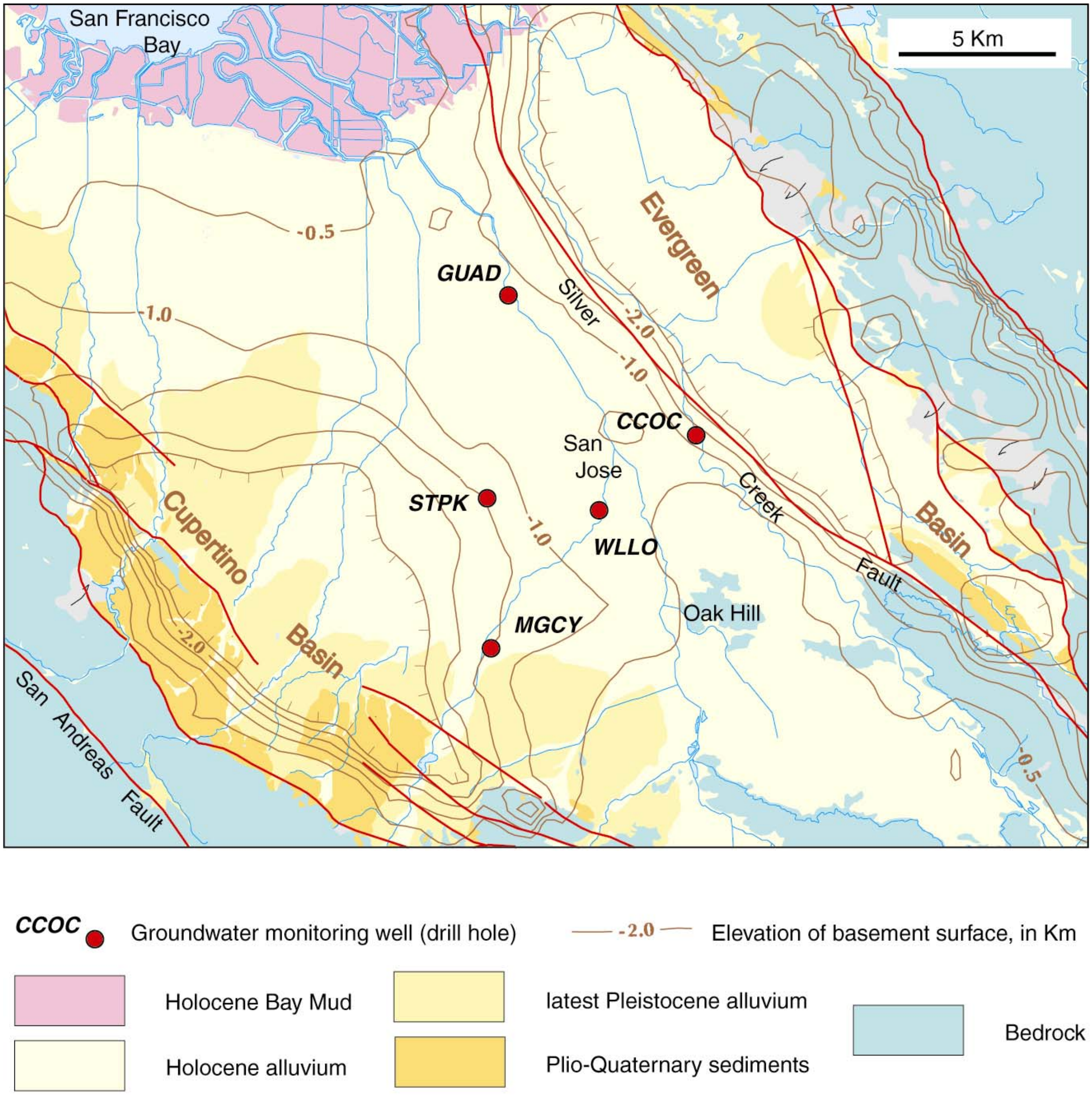


Figure 1. Map of the Santa Clara Valley showing CCOC and other new groundwater monitoring wells in their geologic context. Areal geology from Wentworth and others (1998), Brabb and others, (1998), and Knudsen and others (2000); faults modified from these and Jachens and others (2002). Basement surface from preliminary gravity inversion by R.C. Jachens (Jachens and others, 1997).

GEOMAGNETIC FRAMEWORK

Geomagnetic Polarity Reversals

The Earth's magnetic field has the peculiar ability to reverse its polarity from time to time, and the pattern of such reversals during the past 5 million years has been well established (figure 2). Ages of the reversal boundaries can thus be used to provide accurate time lines for geologic correlations. The polarity time scale shown is adapted from Mankinen and Dalrymple (1979) with ages for the boundaries revised to reflect new age information available since that earlier compilation. Most of the boundary ages shown in figure 2 were derived by Baksi (1995), who used a cubic-spline technique to fit well-determined polarity boundary ages to relative widths of the polarity intervals on the ocean floor. His revisions have substantially improved the agreement between the geomagnetic and astronomical time scales (see, for example, Hilgen, 1991). Baksi (1995) noted that one area of remaining disagreement with the astronomical time scale is in the vicinity of the Réunion Subchron, which could be explained by the presence of two separate, but closely spaced subchrons. We concur, and follow Mankinen and Dalrymple (1979) by showing two subchrons at approximately 2.08 and 2.14 Ma. The younger of these two ages is not well substantiated, and whether or not there actually are two separate events remains in doubt (Baksi and Hoffman, 2000). The age of the Cobb Mountain Subchron (Mankinen and others, 1978; Mankinen and Grommé, 1982) is currently estimated to be 1.19 Ma (Turrin and others, 1994).

Geomagnetic Secular Variation

Comparing the record of polarity reversals within a young sedimentary sequence with the geomagnetic polarity time scale shown in figure 2 can provide important time lines, especially when direct dating methods are not possible. We recognize, however, that the approximately 300-m-deep drill holes planned in the current research program may never reach even the youngest of these time lines, which occurs at 780 ka (the Matuyama/Brunhes boundary). In that eventuality, we must rely on comparisons with geomagnetic field changes that occur on time scales of 10^5 years or less, known as geomagnetic secular variation. Large changes in magnetic direction do occur over short intervals of time as evidenced by the well-known record of the past 400 years from the Greenwich, England observatory (Malin and Bullard, 1981). Accurately dated secular variation records such as this have been extended backward in time to about 4,000 radiocarbon years B.P. on Hawaii (Hagstrum and Champion, 1995) and to about 18,000 years B.P. in western North America (Hagstrum and Champion, 2002). Comparison with any such detailed record is not possible in our situation because sedimentation in this environment is not continuous and the coring is intermittent (~20% of the total section drilled). These detailed reference

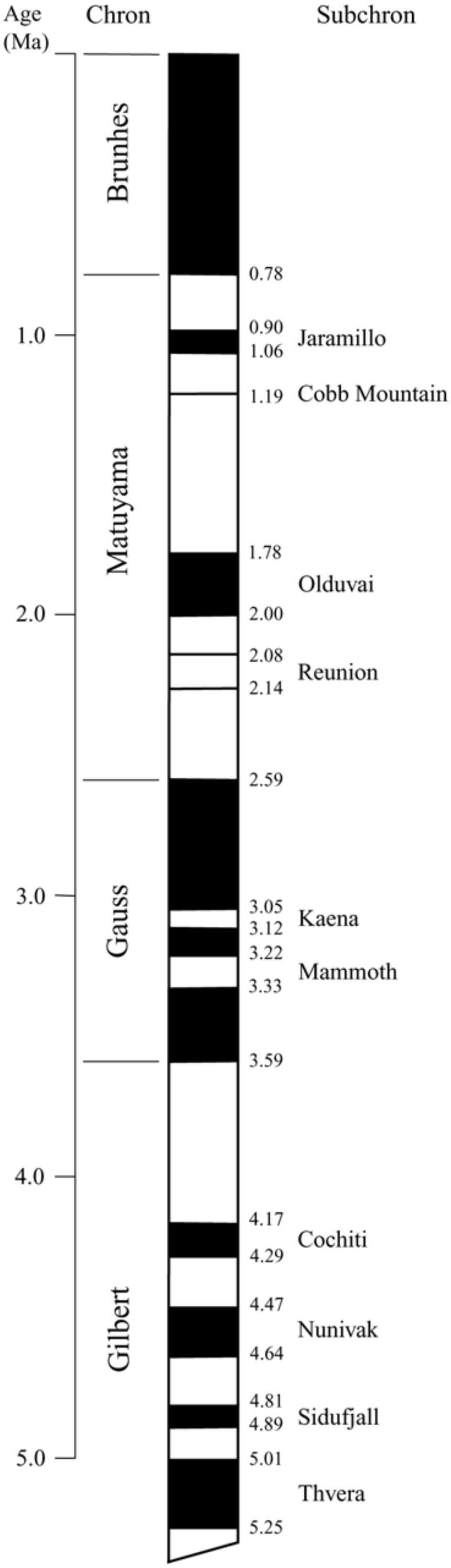


Figure 2. Late Cenozoic geomagnetic polarity time scale modified from Mankinen and Dalrymple (1979) as described in text. Dark (light) areas denote periods of normal (reversed) polarity. Polarity intervals determined mainly by radiometric ages on volcanic rocks, with auxiliary information on their duration from marine magnetic anomaly profiles and deep-sea sedimentary cores.

records also cover only a very recent period of geologic time and are exceeded at a depth of about 25 m in this hole based on radiocarbon data (see “Geologic Summary”). Thus we must rely entirely on a subset of the secular variation record where the magnetic directions extend outside of the “normal” range, intervals known as “excursions.”

Geomagnetic Excursions

Distinct geomagnetic signatures have been found in paleomagnetic records within a constant polarity interval such as the Brunhes Normal Polarity Chron, but they are much more difficult to detect and evaluate than are the polarity boundaries themselves. Magnetic directions typically remain within about 20º of the mean for a given area through time and any significant departures from this range are considered anomalous. Excursions are generally brief, ranging from about 500 years to perhaps 3-5 thousand years long (see, for example, Gubbins, 1999). Magnetization directions during an excursion may record a complete polarity reversal, but more often do not. Such excursions can be used as time markers if they can be uniquely identified, but several factors have complicated this effort. Although unusual magnetization directions have been found in paleomagnetic records from many areas, all too often each anomalous direction has been considered to be a true excursion of the geomagnetic field. Subsequent study of some supposed excursions have proven the anomalous directions to be due to physical disturbances within sedimentary sequences, chemical alteration, remagnetization effects, or perhaps some other non-geomagnetic process. Once defined, however, each named excursion has become an entrenched part of the scientific literature. Another problem arises because many of the suspected excursions occur in sedimentary sequences where the age of the event cannot be determined directly by any of the absolute dating methods and must be estimated indirectly. Thus, even a single geomagnetic excursion can appear to occur at different stratigraphic levels in separate geologic sequences where there may be hiatuses, variable sedimentation rates, or structural complications. It is easy to understand how the number of suspected excursions can proliferate and, indeed, more than twenty have been proposed for the Brunhes Epoch, causing significant problems for any attempts at correlation. Some of the most commonly reported excursions are shown in figure 3.

The major features of the non-dipolar part of the Earth’s magnetic field, which produce the short-period secular variation changes, are unevenly distributed around the world and are variable in both orientation and magnitude. Spatial drifting and/or waxing and waning of these features (Bullard and others, 1950; Yukutake and Tachinaka, 1968) can influence the magnetization being induced in geologic materials by the main field. Unusual directions resulting solely from the non-dipole features will not be global in extent but can be very important on a regional scale. When the strength of the dipole field is weak, non-dipole fields will predominate and unusual field directions can be expected over much of the

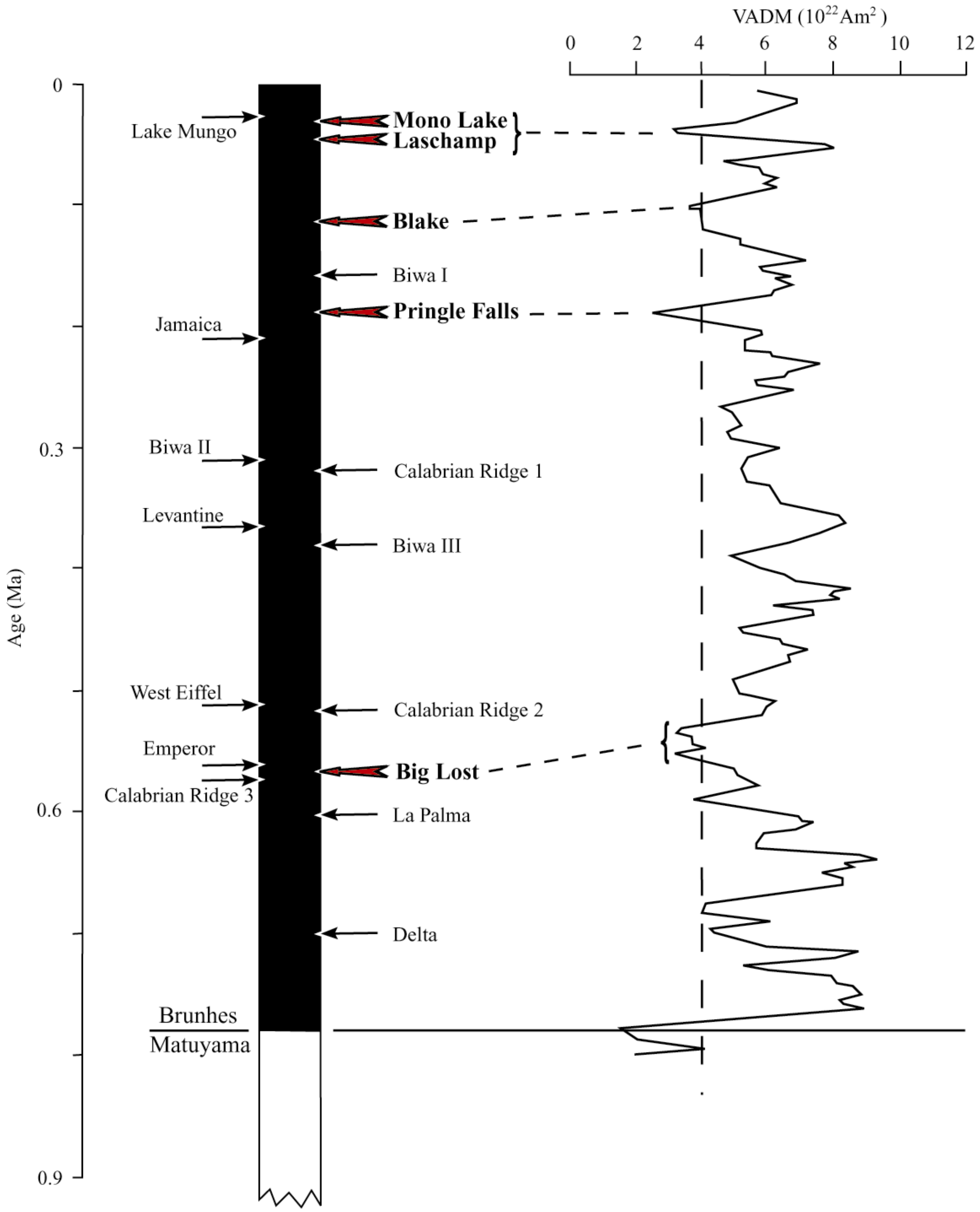


Figure 3. Approximate positions of some of the most commonly reported excursions of the Brunhes Normal Polarity Chron. Highlighted excursions are those found, or most likely to be found, in the western U.S. (see "Discussion"). Possible correlations of these to a sketch of the relative paleointensity curve of Guyodo and Valet (1999) are suggested. VADM = virtual axial dipole moment. Vertical dashed line is the critical value of intensity below which Guyodo and Valet (1999) consider several directional excursions to have occurred.

world. Although long-period secular variation due to changes in the main dipole field may produce some anomalous directions, most of the excursions reported probably will prove to have occurred during periods of very low dipole intensity. Guyodo and Valet (1999) consider many excursions to have occurred at minima in the relative paleointensity curve shown in figure 3 (see, also, Pouliquen and others, 2001). Major intervals of low dipole intensity have been documented by absolute paleointensity determinations (e.g., Mankinen and Champion, 1993), and inferred by relative paleointensity measurements (Guyodo and Valet, 1999) or by sharp increases in the production rate of ^{10}Be recorded in deep-sea sediment (Frank and others, 1997). During such intervals, however, one should not expect anomalous field directions in different places to be entirely synchronous or to have the same morphology. Thus, there can be “different” excursions from place to place occurring in a time window that might be a few tens of thousands of years long. Conversely, a weak dipole field will not necessarily produce anomalous directions in every geographic locality because of the variable distribution of non-dipole sources. The pattern of excursions observed, therefore, may differ significantly from place to place.

GEOLOGIC SUMMARY

The CCOC drill hole penetrates 308 meters of an alluvial section that fills the center of the Santa Clara Valley (figure 1). Although the general geologic setting of the drill hole can be defined, available information is not sufficient to predict with any confidence the maximum age of the CCOC section. This paleomagnetic study thus provides the principal basis for dating the deep CCOC section.

The Santa Clara Valley lies in a structural trough between the San Andreas and Hayward-Calaveras faults that consists of two deep flanking basins separating a central basement high (figure 1). The western, Cupertino basin is filled by Miocene and older (?) rocks that are truncated by an unconformity that extends across the central basement high, thus making the unconformity late Miocene or younger (Stanley and others, 2002). The very different Evergreen basin on the east is a strike-slip basin, formed between the Silver Creek and Hayward faults during activity of the San Andreas fault system (Jachens and others, 2002), in which Miocene to Quaternary fill would be expected.

West of the Silver Creek fault, the young Santa Clara basin is filled with Quaternary sediment that could be separated from the underlying basement unconformity by Pliocene-Quaternary sediments equivalent to those exposed at the Valley margins. There, the Pliocene-Quaternary deposits are semi-consolidated and typically deformed, with no stratigraphic top defined. Beneath the central Valley where the basement surface is essentially flat, however, no similar deformation would be expected.

Surface geology suggests that the Quaternary basin fill has been deposited principally as alluvial fans emanating from the flanking uplands, with a source of coarser sediment relative to the distal fan margins provided by axial drainage flowing bayward between the inward-facing fans past the CCOC drill hole. Holocene fans are inset into and overlap most of the older late Pleistocene fans with a relatively thin sheet of sediment that is typically only 10-15 m thick in the center of the Valley (Helley, 1990).

The CCOC section consists of an alternating sequence of alluvial sand, gravel, silt, and clay in various combinations (Hanson and others, 2002). Seventy-five cores ranging from 13 to 155 cm in length were taken at various locations down the hole, representing 20 percent of the depth of the hole. About one third of the cores are too coarse to yield samples useful for paleomagnetic study. Bedding is horizontal, but many erosive boundaries present at the base of sand and gravel layers and the several paleosols evident in the cores indicate that the stratigraphic record in the hole is discontinuous. Radiocarbon ages of root material constrain the base of the Holocene section located at a depth of 22.6 m to between 10,650 radiocarbon years (at a depth of 17.9 m) and 28,090 radiocarbon years (at 25.3 m), with the latter near the top of the Pleistocene section.

The basement surface beneath the hole is at a depth of about 1.25 km, based on the basement contours, although evidence from the GUAD and WLLO wells (figure 1) indicates a systematic overestimation of depth in this representation of that surface. No distinct older Pliocene-Quaternary unit or abrupt downward increase in consolidation beneath the Holocene section has yet been recognized in any of the new drill holes (figure 1). Gravel encountered in the CCOC well is composed principally of Franciscan greywacke, greenstone, and chert, as would be expected of material derived from the flanking mountains. Gravel compositions characteristic of distinctive exposed Pliocene-Quaternary units (Vanderhurst, Cummings, and Andersen, 1982; Wentworth and others, 1998) have not been recognized; there is a marked scarcity of siliceous clasts derived from Monterey or Claremont Formations, micaceous sandstone from the Great Valley sequence, and siliceous porphyries (D.W. Andersen, written communication, 2002).

CORING AND CORE DISTURBANCE

Cores from the CCOC drill hole were obtained with a Christensen 94-mm wireline core barrel operating in a drill stem rotating clockwise (looking down the hole). A total of 202.6 ft (61.8 m) of core were collected in 79 coring pushes, ranging from 2.1 to 5 ft, with recovery ranging from 0% (4 attempts) to more than 95% (14 cores). As the drill bit and coring device advanced downward, the core was pushed up into a plastic tube (liner) within the core barrel. Upon wireline recovery, this liner was cut to fit the core and capped at each end. In the laboratory, the cylindrical plastic liner and contents were split longitudinally (with mechanical knife and wire), with one half being described and sampled and the other reserved as an archive. The position of the core in the hole was recorded as depth to the top of the core (in feet), and the position of a sample within the core was recorded as depth within the core (in centimeters).

Typical disturbance (or deformation) of the core, produced largely by the drag associated with its insertion into the liner during the push, consisted of downward drag along the perimeter in contact with the liner. Other, more extreme disturbances involving injection of drilling mud and other processes were clearly evident in places. A further kind of deformation involved axial rotation of the core. Although the core barrel rides on bearings to isolate it from the rotating drill stem, torque still seems to be applied to the core. Some fine-grained sequences in the cores contain thin horizontal lamina dragged downward at the margins that separate and define apparently intact blocks of sediment typically 1-2 cm thick. Some of these laminae can be shown to truncate primary features, and thus were imposed after deposition. Structures like this are routinely recognized and called "biscuits" in the Deep Sea Drilling Program (see, for example, Shipboard Scientific Party, 1994), and are observed there only in cores taken during rotary drilling. The presumption is that individual biscuits within a liner have been rotated axially relative to one another, making their axial orientations independent of the rest of the core.

Care was taken during paleomagnetic sampling to avoid all recognizable core deformation, including the interfaces between biscuits. Deformation along core margins could deflect the magnetic inclination whereas that at biscuit boundaries or similar zones would destroy part of the magnetic signal. Noting where these biscuits occurred also was important because it determined in which cores relative declinations between samples could be used to interpret geomagnetic behavior. In the absence of biscuits, relative declinations are possible because all samples were taken from the same face of the split core.

METHODS

Seventy-two cylindrical samples, approximately 18.5 cm^3 in volume, were taken from individual core segments for paleomagnetic study after each segment had been split longitudinally into “working” and “archival” halves. An additional four samples, approximately 2.6 cm^3 in volume, were taken where a larger sample was not possible. The core segments could be oriented only with respect to stratigraphic top, thus permitting magnetic inclination and polarity but not declination/azimuth to be determined. The natural remanent magnetization (NRM) of each sample was measured using a superconducting magnetometer housed in a magnetically shielded room. Progressive alternating-field (AF) demagnetization experiments were performed using a three-axis tumbling demagnetizer (Doell and Cox, 1967) that was modified to accommodate the large 18.5-cm^3 specimens. Doell and Cox (1967) recognized that this instrument could impart a spurious component of magnetization along its innermost rotation axis. This rotational remanent magnetization (RRM, Wilson and Lomax, 1972) is particularly prevalent in sediments with low magnetic stability. To eliminate the effects of RRM, samples were demagnetized twice at each increment of alternating field above the point where unsystematic behavior was first suspected (generally 20 mT or higher). For the second of these demagnetization pairs, the long axis of the cylindrical sample was reversed 180˚ with respect to the innermost tumbler axis and the data were averaged using the method of Hillhouse (1977). The smaller samples were demagnetized using a commercial, magnetically shielded, non-tumbling demagnetizer.

DATA AND ANALYSIS

The geometric mean NRM intensity for 72 samples from the CCOC drill hole was found to be 20.8 mA/m, and values between 49.7 and 8.71 mA/m are within 1 standard deviation of the mean. Progressive alternating-field demagnetization of 15 pilot specimens revealed similar response to the experimental treatment for all grain sizes (figure 4). Anomalous components of magnetization were rare or, where present, readily removed by alternating fields of 10 mT or lower. Based on the behavior of the stepwise demagnetization experiments, all remaining specimens were demagnetized at a minimum of three alternating-field values (5, 10, 15 mT) to confirm their stability and direction. Representative magnetic inclinations were determined by fitting least squares lines (Kirschvink, 1980) to three or more vector endpoints of the magnetic component isolated during demagnetization, and these are given in Table 1. Maximum angular deviations (Kirschvink, 1980) are generally less than 5° (table 1) and indicative of well-defined inclinations.

The magnetic inclinations calculated were compared with the inclination that would be produced at the sampling site (56.7º) by a geocentric axial dipole (GAD). The GAD model is a fundamental concept in paleomagnetism wherein the best approximation of the time-averaged magnetic field is one that would be produced by a single magnetic dipole at the center of the Earth and aligned with the rotational axis. Results of this comparison are shown in figure 5. Fifty-six percent of the samples had inclinations within 5º of the expected value, and 77% are within ±10º. Inclination flattening due to compaction that is sometimes found in sedimentary sequences (see, for example, Deamer and Kodama, 1990) does not appear to be a factor in the CCOC drill hole. It also is clear from figure 5 that inclinations deviating more than 25º or 30º from the expected field are anomalous with respect to the rest of the sample population. Accordingly, we assign an intermediate polarity to the five samples in Table 1 that have a mean inclination less than 30º. Excluding those samples, we analyzed the 67 samples with normal inclinations using the inclination-only statistics of McFadden and Reid (1982) and calculated a mean inclination of 54.7º, with $\alpha_{95} = 5.6$º and a concentration factor, κ (Fisher, 1953), equal to 10.5. The relatively small value for κ is entirely consistent for a sample population that has averaged geomagnetic

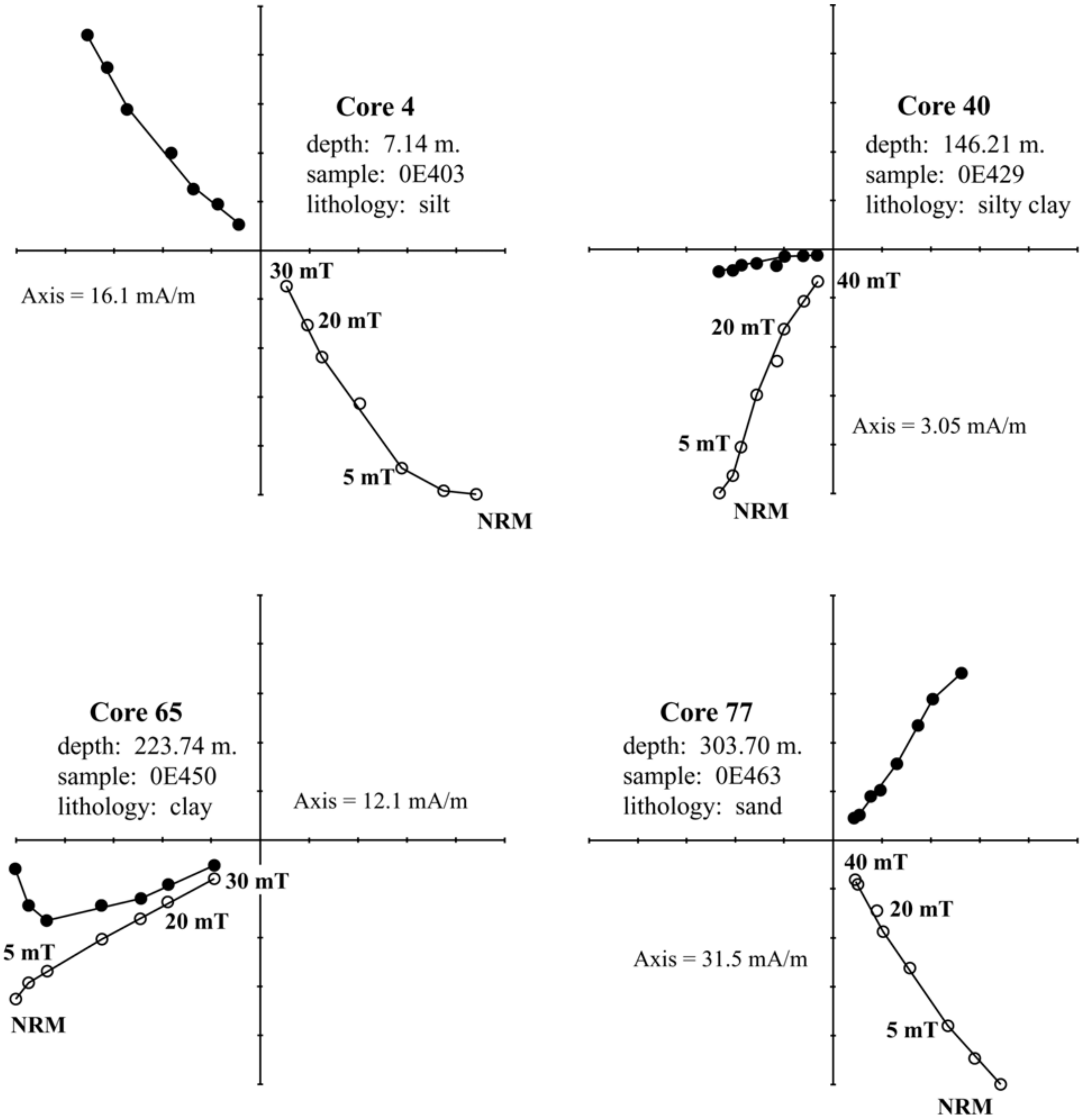


Figure 4. Orthogonal projection of remanence vector endpoints during alternating field demagnetization of representative samples from the CCOC drill hole. Open circles are projections into the vertical plane. Solid circles are projections into a horizontal plane whose axes are arbitrary because the cores were not azimuthally oriented.

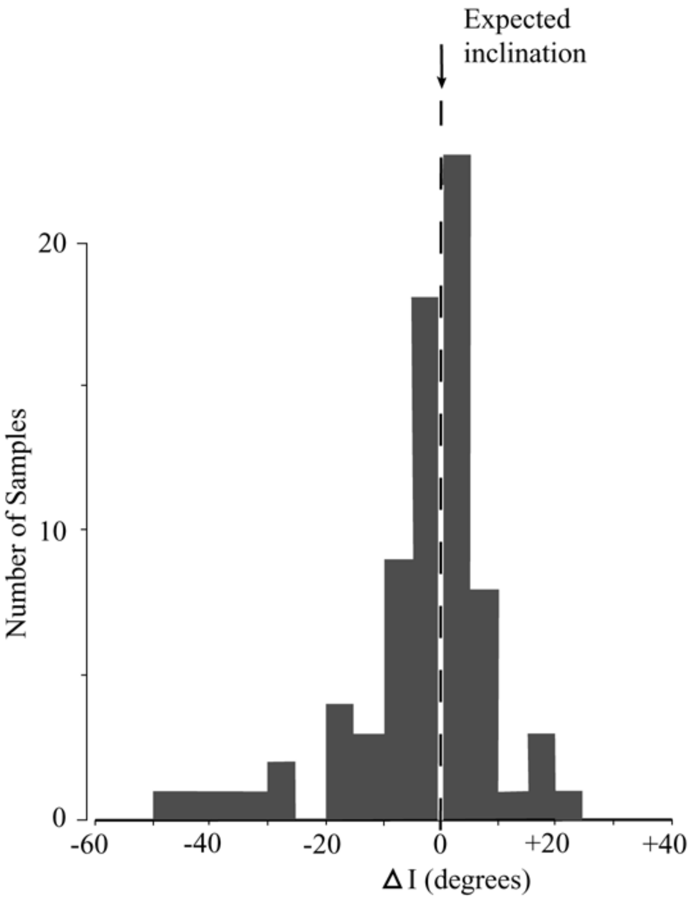


Figure 5. Histogram showing deviation of magnetic inclination (ΔI) from that expected at the latitude of the CCOC drill hole.

secular variation. Because κ increases as the distribution of sample directions becomes more concentrated, values of 100 or more could signal that remagnetization of the sediment has occurred. We conclude, from the stability of magnetization (as evidenced by the representative examples in figure 4) and the statistical parameters determined for this data set, that the sediment obtained from the CCOC drill hole provides an accurate recording of the geomagnetic field.

RESULTS

Anomalous magnetic inclinations (intermediate polarity) were encountered at two levels within the uppermost 50 m of the CCOC drill hole (table 1, figure 6). Relative declinations measured at both levels are thought to be accurate because no evidence of internal deformation is apparent. The first interval was found in core 17, which was collected from a depth of 25.57 to 24.69 meters, and consisted of 0.35 m of silt and clayey silt overlain by 0.53 m of medium-grained sand and gravel. Sample 0E433 (25.32 m.) from the lowest part of core 17 has a magnetic inclination of 38.4° (figure 7a), which is within the normal range of secular variation for the area. Eight centimeters higher, the magnetic vector swings through an angular distance of 57° to an inclination of 12.9° recorded by sample 0E410 at 25.24 m. Just 3 cm higher at 25.21 m. (sample 0E431), the magnetic vector has moved another 35.3° of arc to an inclination of 19.9°. At this point, the magnetic inclination is still in an anomalous state, however the coarser overlying sediment precludes paleomagnetic sampling to determine the total stratigraphic interval over which the shallow inclinations are expressed. Sample 0E409, taken 68 cm above 0E431 from core 16, has normal inclination. Because the changes in magnetic inclination and relative declination of three paleomagnetic samples from core 17 are large and seem to be serially correlated (figure 7a), the shallow inclinations are interpreted to record a geomagnetic excursion.

The second interval with an anomalous inclination was found in core 21, which was collected at a depth of 32.27 to 30.78 meters (table 1, figure 6) and consists of silty clay to very-fine silty sand. Sample 0E414 has a magnetic inclination that is 30° shallower than expected and is exactly at the limit that we use for defining an intermediate polarity (figure 7b). Because this inclination is at the lower limit of normal, it is possible that it may be approaching the maximum extent of normal geomagnetic secular variation rather than representing a true excursion. On the other hand, the extreme swing of the total magnetic vector, similar to that seen in core 17, strongly suggests that another excursion has been recorded.

Cores taken from the next 270 meters of the CCOC drill hole had inclinations that were well within the normal range (table 1, figure 6). The final interval where anomalous magnetization inclinations were recorded occurs near the bottom of the drill hole in core 78, which was collected between 305.7 and 305.1 meters, and consists of clay to clayey silt. Four 18.5 cm^3 and three 2.6 cm^3 samples were taken from this core. Three samples from the upper 0.1 m of core 78 (table 1, figure 8) had upward-directed inclinations (intermediate and reversed polarities) and four samples from the lower 0.5 m had downward-directed inclinations (intermediate and normal polarities). The inclination and declination changes, again, are indicative of an excursion or a polarity chron/subchron boundary, with the reversed- and intermediate-polarity directions expressed over the top 0.3 m of core 78, and only normal-polarity

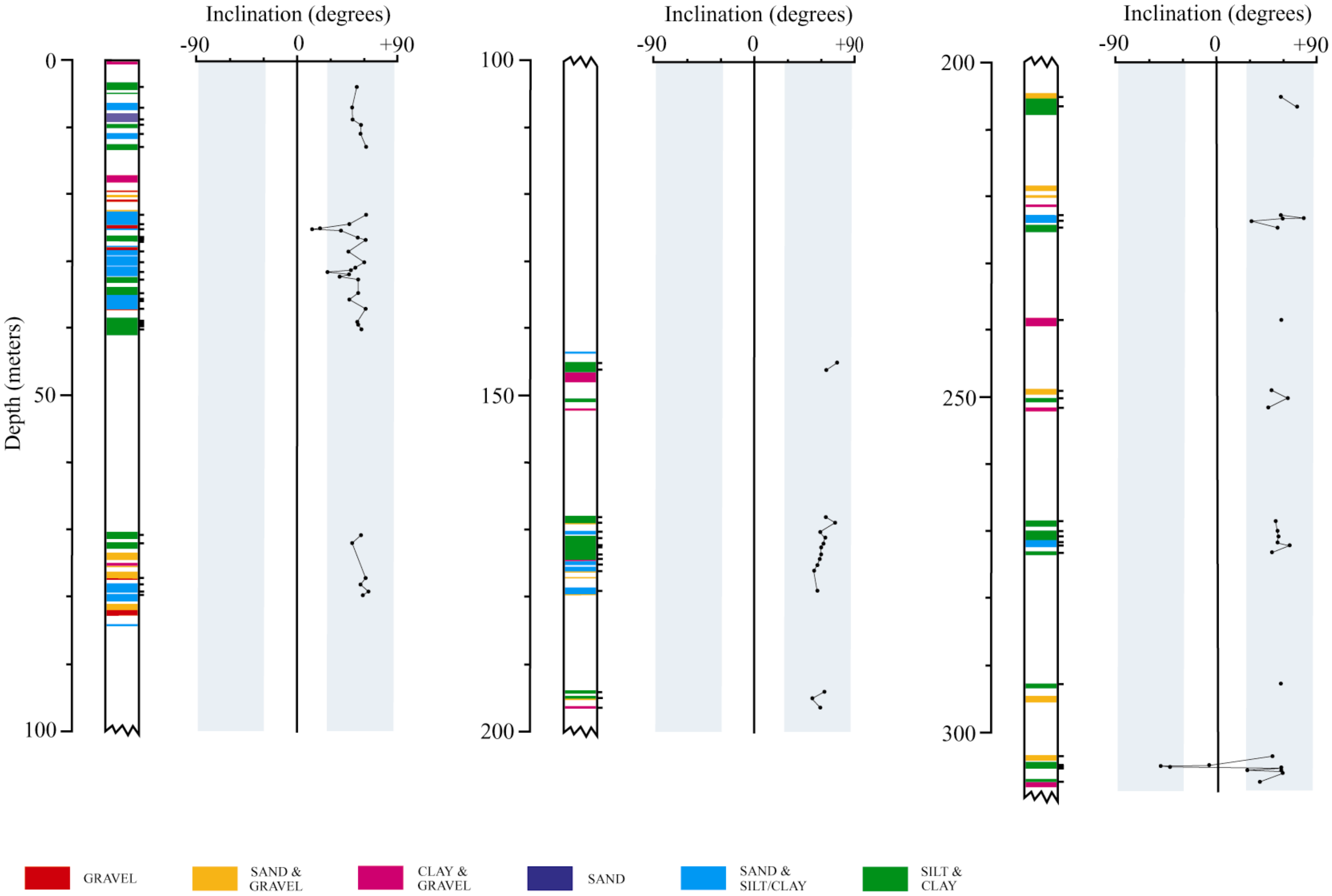
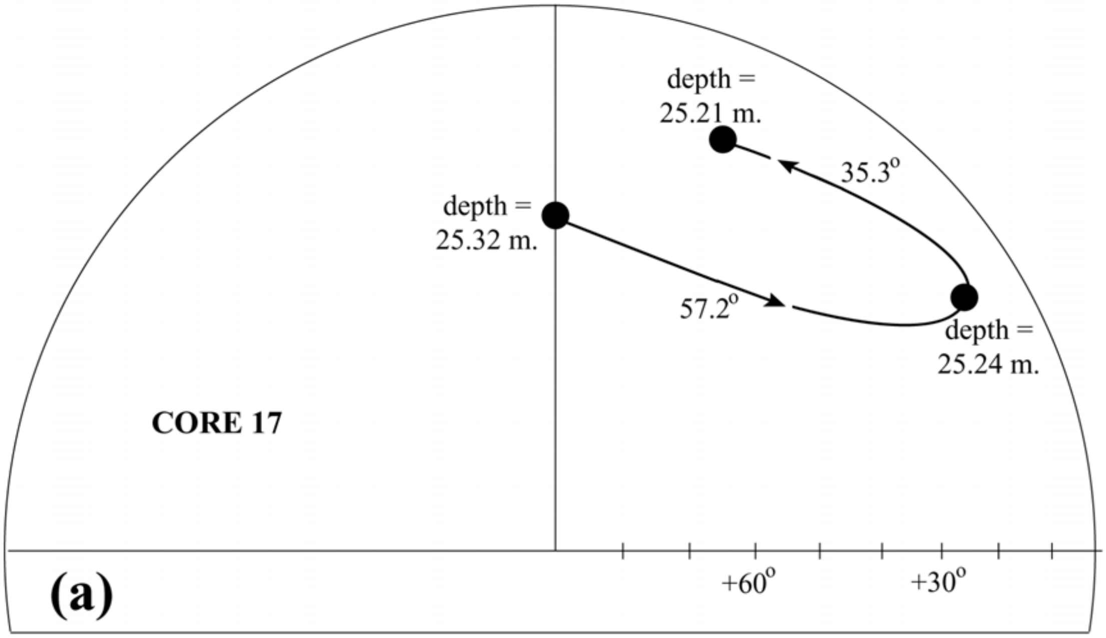


Figure 6. Inclination record for cored intervals of the CCOC drill hole. Tic marks to the right of the lithologic log indicate levels where paleomagnetic samples were taken. Shaded areas show expected normal range of inclinations (see text).



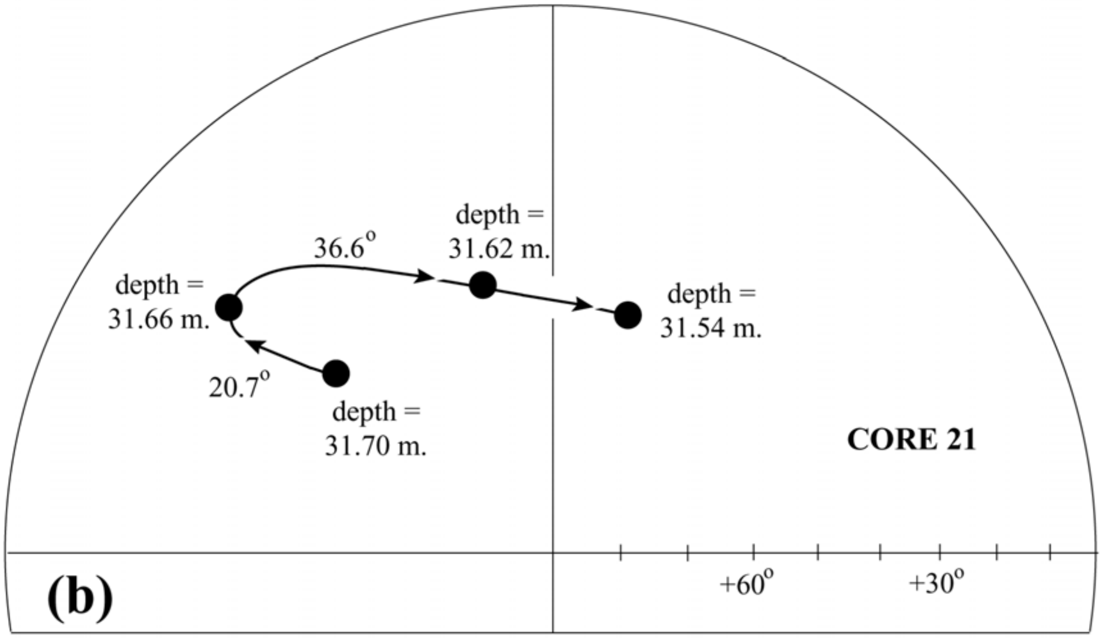


Figure 7. Magnetization directions of samples from (a) core 17 and (b) core 21. Solid circles are directions on the lower hemisphere of an equal area projection. Because cores from the CCOC drill hole were not azimuthally oriented, all declinations within each core are relative to one another, but cannot be correlated between cores. Each core was rotated about a vertical axis to produce an apparent northerly declination.

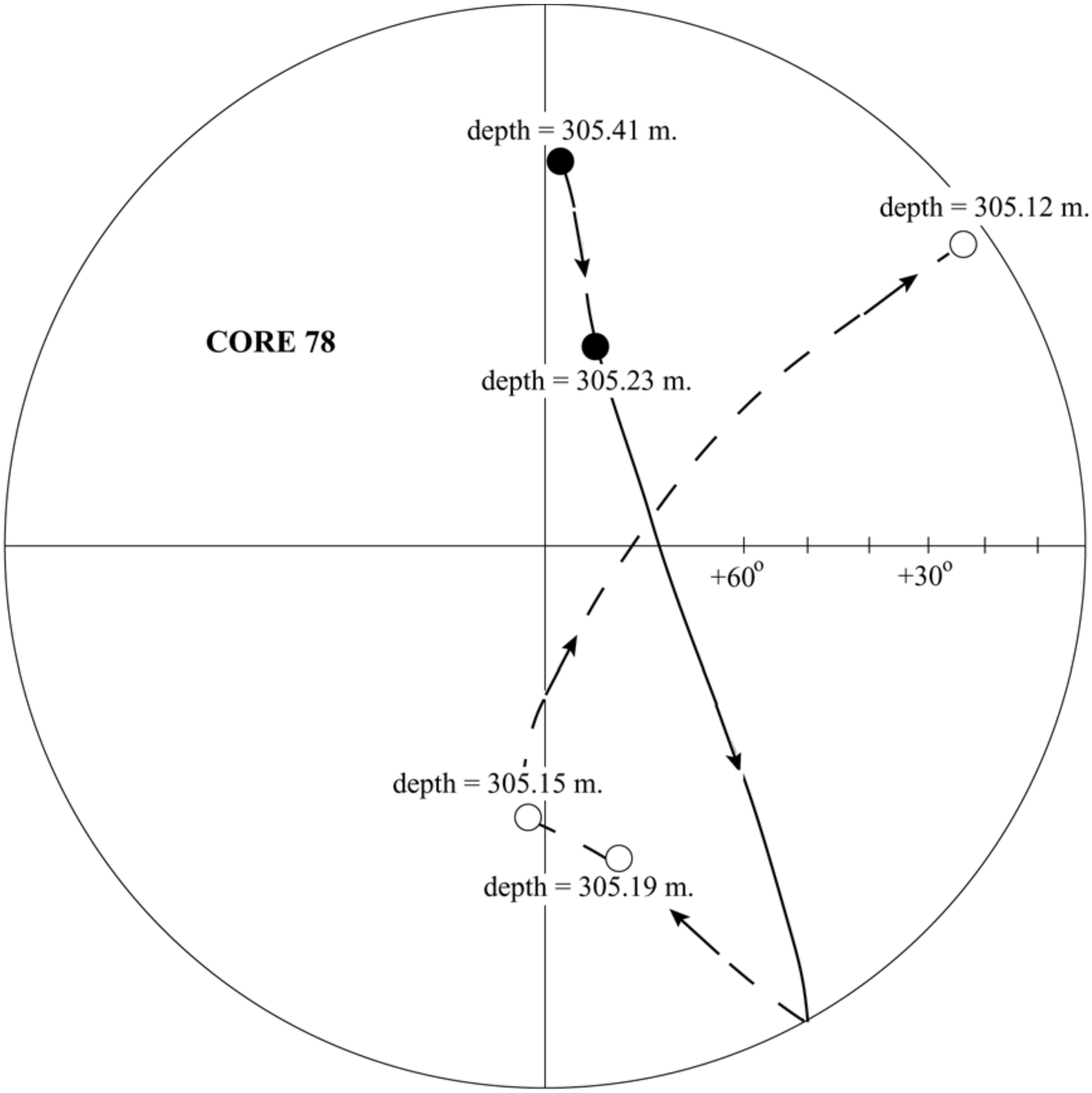


Figure 8. Magnetization directions of samples from core 78. Solid circles and lines are directions on lower hemisphere, open circles and dotted lines on upper hemisphere of equal area projection. Because cores from the CCOC drill hole were not azimuthally oriented, all declinations are relative to one another.

directions over the bottom 0.1 m sampled. Sample 0E463 taken from a thin sand layer within a gravel sequence in overlying core 77 had a normal inclination as did sample 0E468 from underlying core 79 (table 1).

DISCUSSION

Brunhes-Age Excursions

Numerous papers have reported the possibility of brief, reversed-polarity subchrons and/or excursions during the Brunhes Normal Polarity Chron. As discussed in "Geomagnetic Framework," only some of these proposed excursions are probably reflecting true geomagnetic field behavior and most of those are only significant regionally. Consequently, the total number recorded in any given area is probably limited. After a thorough review of the literature, Merrill and McFadden (1994) concluded that there was no convincing evidence for any fully reversed, global polarity events (subchrons) during the Brunhes, and they considered the Laschamp and Blake at about 40 and 100 ka, respectively, to be the only well-documented excursions represented worldwide. More recently, Gubbins (1999) considered six, including the Laschamp and Blake, to be global excursions. Whether or not this latter suggestion eventually proves correct, the Laschamp and Blake excursions still seem to be the only two that are consistently reported worldwide. While diminished dipole intensity has a global effect, anomalous directions are not always produced in every region for the reasons discussed above. Where they do occur, excursions can be much shorter than the intervals during which the intensity is low, can occur anywhere within those episodes, and have few exact correlatives in other regions. We briefly review the Laschamp, Blake, and other excursions that have been reported primarily from the western North America or eastern Pacific region in order to determine which are most likely to be found in the CCOC drill hole.

Mono Lake excursion. A paleomagnetic study of the Wilson Creek Formation near Mono Lake showed a large and rapid excursion of paleomagnetic directions in part of the sedimentary sequence that was estimated to be between about 30 and 13 ka (Denham and Cox, 1971). An additional study of the sequence by Liddicoat and Coe (1979) provided more details about the excursion and the period of time immediately preceding it. Additional records of what is considered to be the same excursion have been reported from Lake Chewaucan deposits at Summer Lake (the "Summer Lake I" excursion), southern Oregon (Negrini and others, 1984), and in deposits of Lake Lahontan in the Carson Sink and at Pyramid Lake, Nevada (Liddicoat, 1992).

Laschamp excursion. The Laschamp is one of the better-documented excursions, in part because it has been recorded in volcanic rocks. It was first discovered in lava flows of the Chaîne des Puys, France (Bonhommet and Babkine, 1967; Bonhommet and Zähringer, 1969), and later in tuffs and lava flows of the Reykjanes Peninsula, Iceland (Kristjansson and Gudmundsson, 1980). A compilation of radiometric ages (Levi and others, 1990) determined for the Icelandic lavas (42.9 ± 7.8 ka) and the Chaîne des Puys flows (46.6 ± 2.4 ka) shows that both excursions are statistically indistinguishable in age and are records of the same geomagnetic episode.

The Laschamp excursion occurred during an interval of time when the strength of the geomagnetic field, based on absolute paleointensity determinations worldwide, was only about 20% of the Holocene average (Mankinen and Champion, 1993). Importantly, Mankinen and Champion (1993) noted that the extremely low field strengths existing at the time the Laschamp flows were extruded may have lasted some tens of thousands of years, much longer than the estimated several-hundred-year duration of the excursion itself (Levi and others, 1990; Thouveny and Creer, 1992). Excursions that are not exact correlatives of the Laschamp, therefore, could easily have occurred elsewhere during this generally weak dipole interval. One such "semi-related" excursion in the western United States may be the Mono Lake excursion.

Blake excursion. Paleomagnetic results from deep-sea cores from the Greater Antilles Outer Ridge indicated a reversed polarity interval within abyssal brown clay deposited during part of the last interglacial period (Smith and Foster, 1969; Denham, 1976; Denham and others, 1977). This excursion has been reported as occurring in numerous deep-sea sediment cores from different oceans, loess deposits in China and Germany, and has been tentatively identified in a few volcanic rocks. Its existence seems to have been generally accepted by many workers even though its age remains poorly determined. Estimates of its age have been made using biostratigraphy, correlation with oxygen isotope curves, and with thermoluminescence, fission-track, and K-Ar dating methods. These estimates generally range from 100 ka to as old as 160 ka for some of the volcanic rocks. It is far from certain, however, that all of the supposed correlations to the Blake episode are correct. If sediment at the original locality is representative of marine oxygen isotope stage 5, as seems likely, the excursion probably can be no older than about 130 ka (see summary by Morrison, 1991).

Pringle Falls excursion. Paleomagnetic records from a sedimentary sequence near Pringle Falls, Oregon, reveal a magnetic excursion that Herrero-Bervera and others (1989) initially correlated with the Blake excursion. This correlation was based on the presence of two reversed intervals separated by a short normal interval similar to the pattern described for the Greater Antilles Outer Ridge cores. Herrero-Bervera and others (1994) later estimated, however, that the excursion must have occurred between about 218 and 171 ka based on ^{40}Ar/^{39}Ar ages on a tephra layer exposed at a second locality near Pringle Falls and a tephra from a correlated sequence. Using K-Ar, Ar-Ar, and thermoluminescence ages, along with correlation of tephra layers from various sites within pluvial Lake Chewaucan, Negrini and others (1994) refined the age of this excursion to about 190–180 ka.

Additional records of this excursion have been reported from Pahoa Island in Mono Lake (Liddicoat, 1990) and nearby Long Valley (Liddicoat and others, 1998), California. Although there remains some uncertainty about the ages of the Blake and Pringle Falls excursions, and both are roughly in the same time interval, they do appear to be separate events. Several lines of evidence point toward deposition of sediment containing both the Pringle Falls and the correlative Summer Lake II excursion (Negrini and others, 1994) as having occurred during oxygen isotope stage 6 (Herrero-Bervera and others, 1994; Negrini and others, 1994), whereas sediment containing the Blake excursion is generally considered to represent oxygen isotope stage 5. The Blake excursion has not been reported from the sedimentary sequences from Lake Chewaucan and is presumably missing because of the presence of a zone of unconformities correlated with stage 5e (Negrini and others, 1994).

Big Lost excursion. Shallow negative (reversed) inclinations were recorded by two of thirteen lava flows sampled in a drill hole from the Snake River Plain, Idaho (Champion and others, 1981). They determined a whole-rock K-Ar age of 465 ± 50 ka for this reversed episode. Based on similarities in age between these Snake River Plain lavas and a reversed episode in a sediment core from the Mediterranean Sea (Ryan, 1972), Champion and others (1981) concluded that both were correlative and adopted the name, Emperor, as proposed by Ryan. The Snake River Plain reversed episode was subsequently found in a second drill hole (Champion and others, 1988), and additional K-Ar determinations indicated its age to be 565 ± 14 ka. Champion and others (1988) realized, therefore, that the name Emperor should not be applied to the episode recorded by the Snake River lava flows and proposed a new name, the Big Lost Reversed Polarity Subchron.

Intermediate polarity magnetization directions were found at two sites within the informally designated basaltic andesite of Hootman Ranch (Lanphere and others, 1999) near Mount Lassen, northern California. Based on $^{40}Ar/^{39}Ar$ ages that they determined for both this unit (570 ka) and the underlying Rockland tephra (614 ka), Lanphere and others (1999) considered the andesite of Hootman Ranch to contain another record of the Big Lost excursion.

Expectations for the San Francisco Bay Region

Based on the previous discussion, we could realistically expect to find a few instances of unusual geomagnetic field behavior recorded by Brunhes-age sediment in the Santa Clara Valley drill holes. In considering these, however, we will be very specific in our use of nomenclature. There has been a tendency in recent years to attempt to correlate excursions from different parts of the world and to use some of the names interchangeably. Doing so tends to blur the distinction between truly global events, which seem to be quite rare, and those that are more regional in extent. Initial correlations of the Pringle Falls episode to the Blake excursion and the Snake River Plain lavas to the Emperor excursion are good examples of problems that can result from attempting to correlate episodes to others that are geographically distant, especially if the ages are poorly constrained. By the same token, excursions that are identified in the Santa Clara Valley should also be considered regional events unless convincing evidence indicates that they are indeed global in extent.

Levi and Karlin (1989) provided paleomagnetic results from a continuous and rapidly deposited sedimentary section in a core from the Gulf of California that has a detailed chronology based on $\delta^{18}O$ stratigraphy and counts of annual varves. A "noisy" inclination record was noted in sediment between about 50 and 20 ka, which Levi and Karlin attributed to the reduced dipole moment during this interval. During this part of the sediment record, they correlate anomalous inclinations between about 51 and 49 ka with the Laschamp excursion, between about 29 and 26 ka with the Mono Lake excursion, and perhaps about 3-5 ka later with the younger (Summer Lake I) of two excursions recorded at Summer Lake (Negrini and others, 1994). We emphasize that the presence of annual varves in this core indicates a sedimentation rate of about 1m/ka, which is probably much higher, and certainly more continuous, than is represented by the CCOC drill hole. For our more compressed and discontinuous section, we might realistically expect to see only a single excursion recorded by sediment deposited between about 50–30 ka, although with the possibility of one or more anomalous swings in inclination over a short vertical interval.

Although the Blake (or some closely related) excursion seems well represented globally, it has not been conclusively documented in the western United States whereas the Pringle Falls excursion has. A possible reason for its absence probably arises because it occurred during the last interglacial interval when the sedimentary record can be incomplete, such as evidenced by the hiatus at stage 5 in the Lake Chewaucan record. In a favorable sedimentary environment, we could realistically expect to find two instances of unusual magnetic field behavior over a rather broad interval between approximately 200 and 120 ka. If only one is found, it most likely would be the Pringle Falls excursion rather than the Blake.

Pertinent to this discussion are paleomagnetic results from volcanic rocks from central New Mexico (Champion and others, 1988; Geissman and others, 1990). The Laguna basalt flow (Champion and others, 1988) records an anomalously shallow magnetization direction and yields a whole-rock K-Ar age of 128 ± 23 ka. Geissman and others (1990) sampled 8 basalt flows in the Albuquerque–Belen Basin and all record very similar, anomalous directions that indicate eruption over a short time interval. Whole-rock K-Ar ages on three of those flows yield a mean age of 155 ± 47 ka. Determinations using the ^{238}U-^{230}Th method (Peate and others, 1996) yield an age of 156 ± 29 ka for the Albuquerque volcanic rocks. The Laguna flow and basalts from the Albuquerque cinder cones are all isolated units and no independent stratigraphic evidence is available to confirm their age. If one accepts the radiometric ages as being reasonably accurate, however, these volcanic rocks could be recording either the Blake or Pringle Falls excursion.

We can generalize the foregoing as indicating anomalous magnetization directions during periods roughly centered at about 40, 120, and 200 ka. Additional support for this comes from magnetic inclination results from lava flows encountered in a deep drill hole on the island of Hawaii (Holt and others, 1996). Within this core are lava flows spanning approximately 400 kyr, eight of which have anomalous inclinations that are either nearly horizontal or fully negative (reversed). Five shallow-inclination flows seemingly result from long-term secular variation trends (Holt and others, 1996), whereas the remaining three are considered to record true excursions of the geomagnetic field. One shallow inclination flow is younger than about 39 ka and could be related in time to the Mono Lake/Laschamp excursion(s). One with a fully reversed inclination is somewhat younger than 130 ka, possibly correlative with the Blake excursion. The third excursion in the deep drill hole, also fully reversed, is dated at about 225 ka. Holt and others (1996) suggest the Pringle Falls as one of the possible correlatives for the deeper excursion.

Little, if any, evidence exists for excursions in the western U.S. occurring between the Pringle Falls and Big Lost episodes at approximately 200 ka and 570 ka, respectively. Although Holt and others (1996) suggested the Biwa I excursion as one of the possible correlatives for the 225-ka excursion seen on Hawaii, the Pringle Falls excursion is closer in age and seems to us a more applicable choice. The Biwa I excursion is one of several reversed episodes reported from Lake Biwa, Japan (Kawai, 1984), with their ages generally considered to be approximately 160 ka (Biwa I), 310 ka (Biwa II), and 380 ka (Biwa III). The Biwa I is the best documented of these excursions (Hayashida, 1984), although a later study (Meyers and others, 1993) indicates that it may be much younger than previously thought. There have been some questions raised in recent years about the reliability of some of these excursions (see summary by Langereis and others, 1997) but these need not be reviewed here. Even if one of the Lake Biwa excursions happened to occur in the same general time interval as the Pringle Falls excursion, however, there is no reason to expect one, but not the other two, to have been recorded in Hawaii or the western U.S. Thus, we should not expect any of the Lake Biwa excursions, sensu stricto, to be represented in the CCOC drill hole. Note, also, that the relative paleointensity record of Guyodo and Valet (1999) does not indicate any interval of significantly low geomagnetic field strength between about 550 and 200 ka. If this paleointensity record is accurate, any excursion in this interval is unlikely, although not impossible.

Other possible sources of evidence for anomalous magnetic field behavior in the Santa Clara Valley are the marine magnetic profiles from the eastern Pacific Ocean. It was the presence of a small positive magnetic anomaly in the stacked profiles across the East Pacific Rise (Rea and Blakely, 1975) that provided supporting evidence for Mankinen and other's (1978) identification of the Cobb Mountain

Normal Polarity Subchron (see figure 2). A similar study by Wilson and Hey (1981) noted a consistent short-wavelength anomaly over the Galapagos spreading center that they attributed to a short reversed polarity event. They estimated its age to be approximately 490 ± 50 ka and suggested a correlation with the Emperor excursion (Ryan, 1972). This age estimate was based on the assumption of a linear spreading rate and a 730 ka age for the Matuyama/Brunhes reversal boundary. With the revised estimate for this reversal boundary (figure 2), the source of the anomaly must be considerably older and is, therefore, more likely to be correlative to the Big Lost excursion. Interestingly, Langereis and others (1997) have reevaluated the $\delta^{18}O$ record in deep-sea core V12-122 and arrive at an age of about 570 ka for the reversed interval that Ryan (1972) used to define the Emperor event. Thus, the Emperor and Big Lost excursions again seem to be approximate correlatives.

Many excursions of the geomagnetic field have been reported worldwide, often clustering in similar time intervals and where weak dipole intensities have been suggested. It is entirely possible that additional, as yet undetected anomalous magnetic field behavior was recorded by rocks of the western United States during one of these suspected periods of low intensity, or other such intervals not evident in the relative paleointensity records. It is not possible to predict with any degree of certainty where new anomalous directions are the most likely to be found, with the possible exception of around 700 ka where there is a suggestion of relatively low intensity (figure 3). Many fewer records were available in this time interval for Guyodo and Valet (1999) to evaluate than for earlier periods, however, so this part of the relative paleointensity curve is more speculative. For these reasons, we consider that excursions occurring in the intervals at about 570 ka, 200-120 ka, and 50-30 ka to be the most likely to be represented in sedimentary cores within the Santa Clara Valley.

CONCLUSIONS

The first anomalous inclinations encountered in the CCOC drill hole occur at shallow depths, at ~25 m (core 17) and ~31 m (core 21); these most likely were acquired during the Mono Lake/Laschamp time interval. An uncorrected radiocarbon age of 28.1 ± 0.1 ka from organic fragments (bark and/or woody twiglets or roots) between our two intermediate polarity paleomagnetic samples in core 17 indicates that these anomalous inclinations represent the Mono Lake excursion. Because cores 17 and 21 are stratigraphically separated by only 6 m, it seems possible that the anomalous inclination seen in core 21 represents the Laschamp excursion. If true, the expression of the Laschamp excursion in our region is subtle and could easily be missed. The feature that Holt and others (1996) correlated with the Laschamp excursion in the drill hole on Hawaii also is near the limit of normal geomagnetic secular variation at that locality. The Laschamp excursion is somewhat better expressed in the Gulf of California core (Levi and

Karlin, 1989) probably due, at least in part, to the rapid sedimentation rate and consequently minimal smoothing of the paleomagnetic signal.

Because the next, clearly identifiable excursion in the drill hole occurs at a depth of 305 m (core 78), correlation with either the Blake or Pringle Falls excursions in the 120-200 ka interval seems highly improbable, given the high sedimentation rates that would be required (~2-3 m/kyr). Two alternative correlations seem more likely. The anomalous directions in core 78 span less than 10 cm and are, in turn, underlain by 1.5 m of normal polarity sediment. This short duration is suggestive of a true excursion, and the 565-ka Big Lost seems most likely at that depth (alternative #1, figure 9). If this correlation is correct, the average rate of deposition for the Pleistocene part of the section encountered by the CCOC drill hole is approximately 52 cm/kyr. Remember, however, that this is only a very crude estimate of a long-term average because actual rates can be highly variable at any given time as evidenced by the various erosive boundaries and paleosols present.

On the other hand, core 78 occurs near the base of the drill hole and the extent of the underlying normal polarity interval cannot be determined. For this reason, it is possible that the anomalous directions in core 78 reflect the Brunhes/Matuyama boundary (alternative #2, figure 9). Mixed polarities are common near polarity transitions in sedimentary sequences because of variations in the magnetization lock-in process (e.g., Okada and Niitsuma, 1989; van Hoof and others, 1993), overprinting of weak magnetizations acquired during a polarity transition (Coe and Liddicoat, 1994), and complexities in the reversal process itself (Mankinen and others, 1985; Bogue and Merrill, 1992). Alternative #2 yields a deposition rate of approximately 37 cm/kyr for the Pleistocene section in the CCOC drill hole.

ACKNOWLEDGMENTS

This study is part of a collaborative effort with the Santa Clara Valley Water District. Primary core descriptions were made by J.C. Tinsley. Constructive reviews by J.W. Hillhouse and J.C. Tinsley are appreciated.

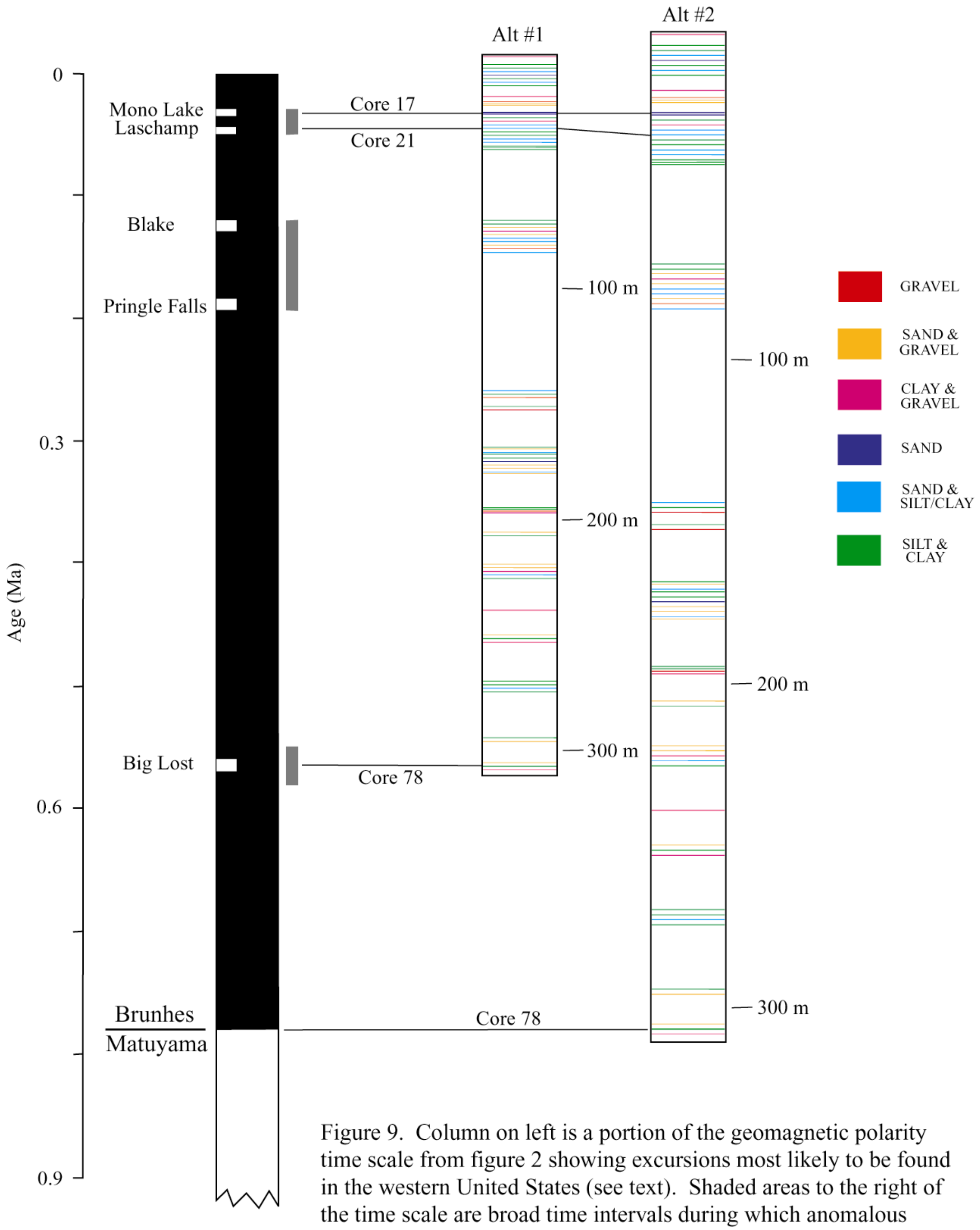


Figure 9. Column on left is a portion of the geomagnetic polarity time scale from figure 2 showing excursions most likely to be found in the western United States (see text). Shaded areas to the right of the time scale are broad time intervals during which anomalous magnetic inclinations could be expected in the CCOC drill hole. Columns to the right are two alternative correlations (see text) of the CCOC drill hole to the polarity time scale using the magnetic record in figure 6; colored lines represent cores and their principal lithologies.

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TABLE 1. Paleomagnetic data from the Coyote Creek Outdoor Classroom drill hole

Core	Sample	Depth (meters)	Inclination (degrees)	Polarity	Delta-I (degrees)	M.A.D. (degrees)	Intensity (mA/m)
2	0E402	4.03	53.7	N	-3	0.8	9.05
4	0E403	7.14	48.8	N	-7.9	2.5	28.6
5	0E404	8.7	50	N	-6.7	0.9	24.1
6	0E405	9.62	56.6	N	-0.1	1.1	91.3
7	0E406	11.06	55.5	N	-1.2	1.7	30.2
8	0E407	13.08	60.6	N	3.9	1.1	17.8
15	0E408	23.17	60.8	N	4.1	1.6	20.7
16	0E409	24.53	46.3	N	-10.4	3.2	14.2
17	0E431	25.21	19.9	I	-36.8	6.6	22.7
17	0E410	25.24	12.9	I	-43.8	4.6	102
17	0E432	25.32	38.4	N	-18.3	1.7	58.2
18	0E433	26.39	54.9	N	-1.8	1.6	17.5
18	0E411	26.64	61.1	N	4.4	1.7	9.53
19	0E412	28.65	46.4	N	-10.3	1.2	14
20	0E413	30.04	59.3	N	2.6	2.5	20
21	2E555	31.54	52.1	N	-4.6	2.8	9.11
21	0E472	31.62	47.8	N	-8.9	1.8	4.88
21	0E414	31.66	26.7	I	-30	1	12.9
21	0E473	31.7	47.3	N	-9.4	0.7	9.64
21	2E556	31.95	37.9	N	-18.8	1.7	56.5
22	0E415	32.68	54.3	N	-2.4	1.9	13.2
23	0E416	34.74	54.8	N	-1.9	1.7	37.9
24	0E417	35.74	46.4	N	-10.3	1.6	19.1
25	0E418	37.08	61.9	N	5.2	3.1	22.7
26	0E419	39.02	53.7	N	-3	1.2	10.5
27	0E420	39.49	55	N	-1.7	1.3	32.6
28	0E421	40.22	57.5	N	0.8	0.8	14.4
29	0E422	70.97	57.3	N	0.6	1.1	11.4
30	0E423	72.2	49	N	-7.7	3.7	4.56
33	0E424	77.26	60.5	N	3.8	0.7	20.4
34	0E425	78.28	56.9	N	0.2	1.9	24.5
34	0E426	79.08	64.3	N	7.6	0.9	32.6
35	0E427	79.82	58.8	N	2.1	0.9	41.1
40	0E428	145.18	74.6	N	17.9	1.5	25.3
40	0E429	146.21	64.1	N	7.4	2.4	3.36
46	0E430	168.11	64.2	N	7.5	1.4	16.8
47	0E434	168.74	72.9	N	16.2	2.6	8.55
48	0E435	170.28	59	N	2.3	0.6	59.3
49	0E436	171.2	64.7	N	8	2.1	9.96
49	0E437	172.18	62.2	N	5.5	2.4	42.5

TABLE 1. (Continued)

Core	Sample	Depth (meters)	Inclination (degrees)	Polarity	Delta-I (degrees)	M.A.D. (degrees)	Intensity (mA/m)
50	0E438	172.6	60.3	N	3.6	1.3	65.2
50	0E439	173.5	60.5	N	3.8	1.1	42.8
51	0E441	174.23	59.3	N	2.6	1.3	55.1
51	0E442	175.06	57.4	N	0.7	1.1	29.9
52	0E440	175.95	53.2	N	-3.5	0.6	25.2
54	0E443	179.01	56.7	N	0	1	43.9
56	0E444	194.06	62.4	N	5.7	3.1	7.77
57	0E445	194.9	52	N	-4.7	2	39.6
59	0E446	196.28	59.4	N	2.7	0.7	61.5
60	0E447	205.41	58.7	N	2	4	46.8
61	0E448	206.77	73.4	N	16.7	0.7	42.6
65	0E449	222.95	58.8	N	2.1	0.9	35.2
65	1E563	223.38	79	N	22.3	1.6	33.6
65	1E564	223.69	57.1	N	0.4	2	19.6
65	0E450	223.74	30.6	N	-26.1	3.6	14.7
66	0E451	224.76	56.3	N	-0.4	2.3	70.9
67	0E452	238.63	58.5	N	1.8	5	39.4
68	0E453	249.15	49.8	N	-6.9	1	68.6
69	0E454	250.27	65.1	N	8.4	2.9	54.9
70	0E455	251.9	47.6	N	-9.1	1.7	14.5
71	0E456	268.64	54.3	N	-2.4	1.5	5.72
72	0E457	270.13	56	N	-0.7	0.8	72.7
72	0E458	270.9	56.4	N	-0.3	0.8	58.6
73	0E459	271.66	55.3	N	-1.4	0.9	108
73	0E460	272.19	67	N	10.3	1.5	23.1
74	0E461	273.42	51.2	N	-5.5	4.4	12
75	0E462	293.04	59.3	N	2.6	4.9	14.2
77	0E463	303.7	51.8	N	-4.9	3.4	43.8
78	0E469	305.13	-5.5	I	-51.2	9.4	7.81
78	0E464	305.15	-48.5	R	-8.2	9.8	9.54
78	0E470	305.19	-40.5	R	-16.2	2.8	6.71
78	0E466	305.22	59.1	N	2.4	3.5	5.71
78	0E467	305.41	29.7	I	-27	3.4	7.93
78	0E471	305.46	57.9	N	1.2	1.4	9.73
78	0E465	305.49	59.7	N	3	3.5	4.19
79	0E468	306.72	39.7	N	-17	9.6	3.25

Drill hole location: 37.337°N; -121.868°W. Inclination is inclination of magnetic vector, positive downward; Polarity: N=normal, R=reversed, I=intermediate; Delta-I is deviation from expected inclination at the drill site; M.A.D.= maximum angular deviation (Kirschvink, 1980); Intensity is intensity of the natural remanent magnetization (NRM).