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A sixty thousand year paleomagnetic record from Gulf of California sediments: secular variation, late Quaternary excursions and geomagnetic implications

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A unique inclination record of geomagnetic secular variation for the past 60,000 years (60 ka) has been obtained from continuously deposited sediments in the Gulf of California, recovered during Deep Sea Drilling Project (DSDP) Leg 64 by hydraulic piston coring at Site 480. The chronology of Hole 480 was determined by $\delta^{18}O$ stratigraphy and varve counts, indicating sedimentation rates approaching 1 m/ka. The paleomagnetic results of the upper 49 m show: (1) The average inclination over this interval is identical to the geocentric axial dipole value at the sampling site. (2) Excursion directions occur between about 53 and 22 ka before present (BP). During this time, the geomagnetic field was generally "noisier" than in the overlying and underlying sections, with greater dispersion of the inclination. (3) The Laschamp excursion was apparently recorded at Hole 480 between about 51 and 49 ka BP and the Mono Lake excursion between about 29 and 26 ka BP. In addition, a narrow 0.3–0.4 m zone near 23 ka BP has a very similar paleomagnetic signature as the excursion observed at Summer Lake, Oregon [1], and we suggest that the Summer Lake is distinct from and younger than the Mono Lake excursion by 3–5 ka and of considerably shorter duration, lasting no more than a few hundred years. (4) Recurring inclination fluctuations were identified at Site 480, characterized by end points with steep inclinations and shallow intermediate value(s), as compared with the geocentric axial dipole. The inclination cycles are particularly apparent from 54 to 24 ka BP with a characteristic period of about 4.4 ka. (5) The "noisier" inclination record between 54 and 24 ka BP might be related to the generally reduced dipole moment between about 20 and 50 ka, and particularly low paleointensities for the Laschamp and Mono Lake excursions.

1. Introduction

A better understanding of the geomagnetic field and its secular variation requires longer records of the detailed vector behavior of the field in the geologic past. In this paper we present high-resolution paleomagnetic data for the last ~ 60 ka from continuously deposited sediments at DSDP Site 480 in the Guaymas Basin in the Gulf of California (Fig. 1). At this site (27°54.10′N, 111°39.34′W, 665 m water depth) the Hydraulic Piston Corer (HPC) was used for the first time to core a 152 m sedimentary section consisting of finely laminated diatomaceous ooze interstratified with mottled and homogeneous muds [2]. Because of high sedimentation rates and an anaerobic, low-energy depositional environment underlying a seasonal upwelling regime [3], the sediments at Site 480 offer an excellent opportunity for studying the paleomagnetic field during the late Pleistocene. The overall rate of sediment recovery was 80% for the 152 m section, and 92% in the top 47.5 m (i.e., cores 1–10). The sediment in the upper 49 m at Hole 480 appears to have been deposited continuously, at high sedimentation rates, and there is no evidence of hiatuses, as indicated by the absence of significant sand layers. However, between 49 m and 61.8 m subbottom, only a small amount of gray sand was recovered in the Core Catcher of core 12; thus, this interval might represent an interruption in sedimentation. We report here on the paleomagnetism of the upper 49 m (11 cores) of Hole 480, which represent approximately the last 60 ka.

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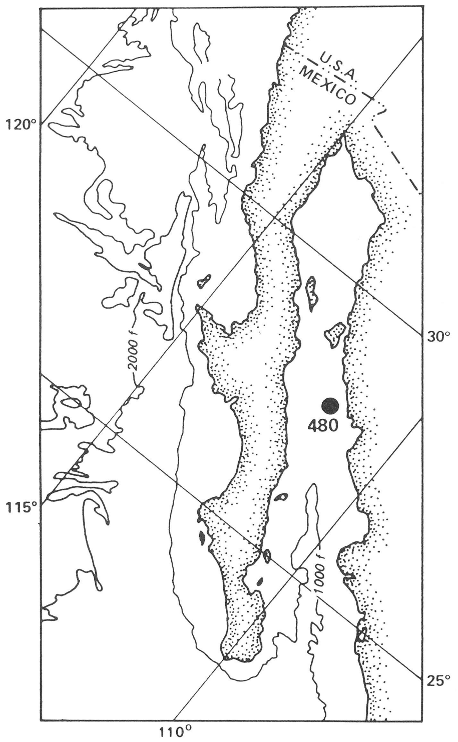

Fig. 1. Location of Site 480 in the Guaymas Basin, Gulf of California (27°54′N latitude, 111°40′W longitude, 665 m depth). Depth contours are in fathoms.

2. Experimental procedures

2.1. Coring and sampling

The 4.75 m long HPC cores were retrieved in plastic liners with 5 cm inside diameter. On the D/V "Glomar Challenger", the cores were cut to 1.5 m sections, and split lengthwise to produce the D-shaped archive and work halves of each section. Because Hole 480 was not cored primarily for paleomagnetism, only one vertical section was obtained at Site 480, precluding confirmation of the results at an adjacent site. The lack of azimuthal orientation of the cores and of the sections within cores limits the use of the declination data to within section examination of the paleomagnetic directions.

The reliability of wet sediments as recorders of the geomagnetic field depends on preserving the sedimentary fabric during coring and sampling. In sampling Hole 480, we tried to identify and avoid zones of core disturbance, and our sampling technique was designed to minimize disruption of the sediment. Samples for paleomagnetism were subcored from visually undisturbed segments of the work half sections, at approximately 10 cm intervals where possible. Sampling was done with a thin-walled, non-magnetic piston minicorer mounted in an oriented jig. The sediment was expressed from the 2 × 2 cm cross section sampling tube with a tightly fitting plastic piston. About 0.5–1 cm of sediment adjacent to the HPC core edge was trimmed, and the remaining sediment was extruded into 6.5 cm^3 plastic sample boxes with lids. In this manner 351 samples were obtained from the top 49 m of Hole 480 (cores 1–11), as near to the central axis of the HPC cores as possible. Because of the core diameter, only one specimen was obtained at each horizon, and specimens were evaluated individually for their undisturbed physical state and the reliability of their remanence. The specimens were stored and transported in magnetically shielded containers. Except during the laboratory measurements, they were kept in a moist and cold (1–4° C) environment to prevent dehydration and maximize the similarity with in-situ conditions.

2.2. Laboratory measurements and remanence stability

Remanence measurements were made on an SCT cryogenic magnetometer. Because of the high water content of the specimens, only alternating fields (AF) demagnetizations were used for magnetic "cleaning". The natural remanent magnetization (NRM) intensities were weak, with values for most of the samples from 1 to 3×10^{-7} emu/g (1 emu/g = 1 A m^2/kg), shown in the depth profile and histogram of Fig. 2a. The NRM intensities were somewhat higher for the homogeneous muds than the laminated sediments, which is consistent with a relatively higher terrigenous content of the homogeneous zones [4].

Pilot specimens were AF demagnetized to 5, 7.5, 10, 15, 20, 30 millitesla (mT), which usually reduced the magnetization to the measuring threshold of the magnetometer. Only a few specimens, usually with higher intensities and stabilities, were demagnetized beyond 30 mT. Projections of the remanence vectors onto horizontal and vertical planes usually showed linear decay to the origin for AF > 5mT. Therefore, the remaining specimens were AF demagnetized at 7.5, 10, and

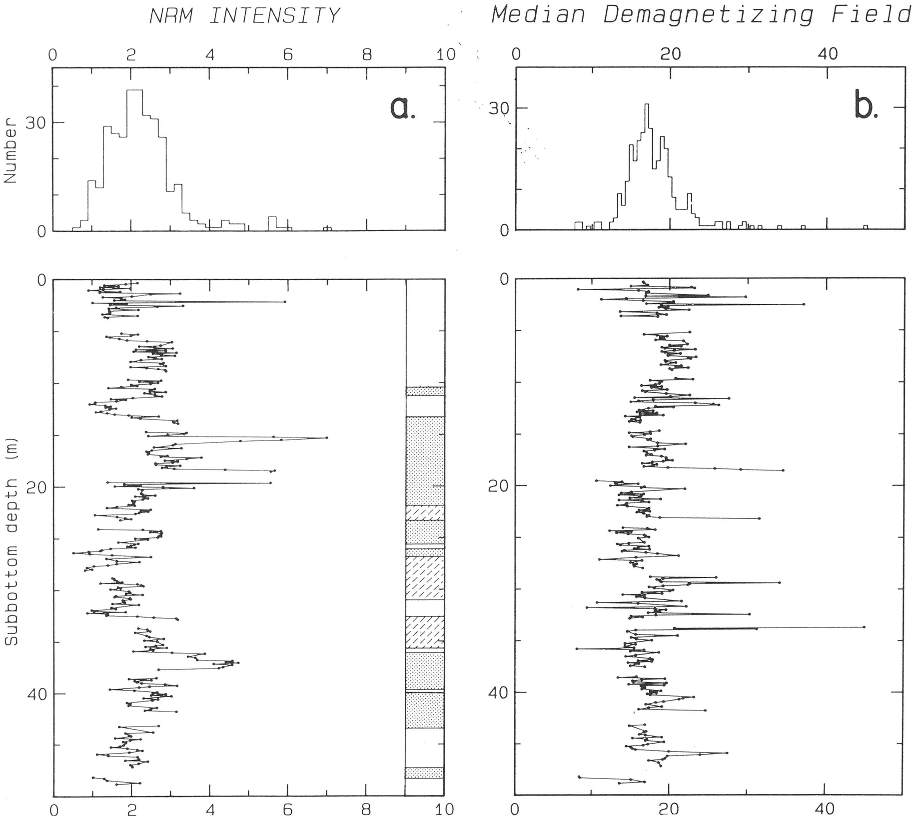

Fig. 2. Histogram and depth profiles of (a) the NRM intensities in units of 10^{-7} emu/g, and (b) the median demagnetizing fields (MDFs) in milliteslas for the upper 49 m of DSDP Hole 480. Each point represents a sample, and the gaps indicate core boundaries. The lithologic column shows core segments of laminated (unmarked), homogeneous (dotted), and rapidly alternating zones of laminated and homogeneous (diagonal hatches) sediments.

15 mT. As a measure of the remanence stability, we calculated the median demagnetizing field (MDF) for each specimen. (The MDF is the AF required to reduce the NRM to half its initial value.) The MDFs were approximated by linear interpolation between adjacent AF levels for MDFs < 15 mT and by linear extrapolation for MDFs > 15 mT. The profile and histogram of the MDFs (Fig. 2b) show that for most specimens the MDFs are between 15 and 20 mT.

The stable remanence directions were determined for each specimen as the vector average of the three demagnetization levels, each treated as an independent unit vector. For 34 specimens ($\sim 10\%$), the stable direction was determined from only two vectors of consecutive demagnetization levels. As a measure of remanence stability, we calculated the α_{95} (angular radius of the 95% cone of confidence) of the stable direction of each specimen, using the two or three demagnetization levels that were used for determining the stable directions. The histogram of Fig. 3c shows that the α_{95} of most specimens is between 2° and 6°. For 9 of the 23 specimens with $\alpha_{95} > 10°$, the stable remanence direction was determined from only two AF levels. No apparent depth trend of the remanence stability is indicated by the α_{95} or MDF profiles (Figs. 2b and 3c).

3. Sample selection

Of the 351 specimens, 21 were initially omitted. Sixteen samples were rejected because their anomalous intensities and/or directions indicated probable physical coring disturbance at or near core boundaries, especially in the top 45 cm of the cores. The upper 1–3 samples from 8 of the 11 cores were thus excluded. Three additional speci-

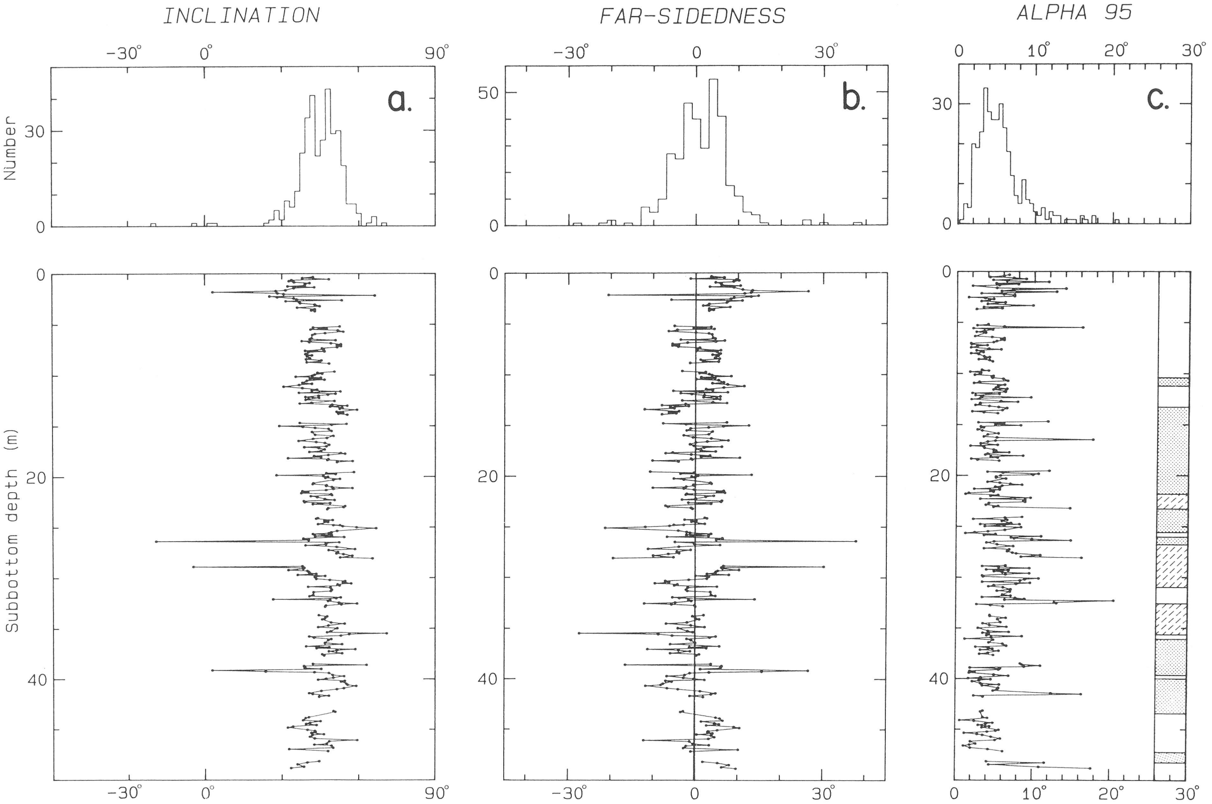

Fig. 3. Histograms and depth profiles of (a) inclination, (b) "far-sidedness", and (c) α_{95} (all in degrees) for the upper 49 m of DSDP Hole 480. Each point represent a sample, and gaps indicate core boundaries. The lithologic column is as in Fig. 1.

mens were omitted because of suspected deformation noted while sampling, although their remanence vectors were not anomalous. Two other samples were rejected because their discordant remanence directions were associated with very low MDFs (6–8 mT) and NRM intensities 5–20 times higher than the surrounding samples.

The inclination depth profile of the remaining 330 specimens is shown in Fig. 3a and as a histogram. In Fig. 3b, the sample inclinations have been transformed to "far-sidedness", defined as the difference in the colatitude of the virtual geomagnetic pole (VGP) calculated from the sample inclination and the geographic colatitude of the sampling site.

For completeness, core 1 data (0–4.5 m) are included in Fig. 3b. However, we believe that the core 1 directions are not useful for paleomagnetism due to mechanical disturbance of the wet, highly unconsolidated sediments during HPC coring. The soft diatom oozes in core 1 had water contents of 80–85% and porosities of 90–95% [2]. The very low shear strengths measured in the top several meters of the nearby rotary drilled Site 479 [5] suggest that these diatomaceous sediments can be readily deformed by coring. Visual inspections and X-radiographs indicate that many of the laminated and layered intervals in core 1 were tilted or bowed by several degrees, and some laminations were obviously disturbed. Sixteen of the 27 samples in Core 1 have laminae tilted from 3 to 12°. In contrast, only 3 additional specimens between 5 and 49 m showed evidence of tilting, and, downcore, laminated intervals were horizontally bedded. The sediments of core 1 were deposited during the last 4–6 ka, during which time the average geomagnetic field was approximately dipolar (e.g. [6,7]). However, even after tilt corrections were made for individual specimens where appropriate, the stable inclinations of core 1 (Fig. 3a) are systematically shallower than the underlying 45 m and also shallower than the expected inclination of the geocentric axial dipole (GAD) at the site latitude ($I = 46.6°$), and they indicate anomalous "far-sidedness" in Fig. 3b when transformed to VGP latitudes. For these reasons we regard the paleomagnetism of core 1 as unreliable. We attribute the inclination shallowing to stress-induced vertical compaction and lateral stretching of the micro-fabric of the varves during coring. A similar mechanism has been proposed for deformation in dry varved sequences in Sweden [8].

4. Chronology and sedimentation rates

The chronology of the sediments is obviously critical for using the paleomagnetic measurements for making inferences about temporal patterns of the geomagnetic field. Site 480 sediments are composed of thick intervals of finely laminated diatomaceous oozes and less siliceous homogeneous or mottled muds. The light diatom-rich and darker organic-terrigenous-diatom-rich laminae, which are found throughout large areas of the Gulf of California, are usually attributed to strong seasonal upwelling alternating with periods of enhanced fluvial and aeolian input. The site underlies a zone where the oceanic oxygen minimum intersects the slope [3]. At present, the anoxic bottom conditions inhibit bioturbation and favor laminae preservation. Detailed laminae counts in association with ^{210}Pb stratigraphy [9–11] have confirmed that laminae couples are indeed annual varves. The homogeneous intervals downcore are thought to represent glacial times, when bioturbation is reestablished in more oxygenated bottom waters, due to lowering of sea level, lessening of seasonal upwelling and migration of the oxygen minimum to deeper waters. Hence, varve counts provide a handle on the sedimentation rates and assist in the chronology of the upper 49 m of Site 480. Visual observations of the cores and X-radiographs (kindly provided by A. Soutar) show that in the top 49 m, 46% of the section is laminated and 54% is mottled or homogeneous. Laminae counts of 73 sample boxes from 6 cores yielded a mean sedimentation rate of 1.02 ± 0.09 m/ka when averaged by core, or 1.05 ± 0.04 m/ka by sample, with no discernable trends with depth. (The uncertainties represent one standard deviation.) These values agree favorably with the 0.96 m/ka estimated by Soutar et al. [12] for the top 71 m of Hole 480.

The very high water content near the top of Hole 480 [2] suggests that much of the top part of the section must have been recovered. However, it was concluded, from the absence of European pollen types, that the top of Hole 480 must be missing at least the uppermost 450 years [13]. Correlations of silicoflagellates between the top 3 m of Hole 480 and an adjacent Kasten core (BAM 80 E17) with a well preserved surface showed that the best agreement was achieved by matching the top of Hole 480 with the 180 cm level of E17 [14]. Based on laminae counts and ^{14}C dating of E17, the 180 cm level of E17 corresponds to ~ 1.2 ka [15]. Thus, 1.2 ka is probably the best age estimate for the top of Hole 480.

The oxygen-isotope stratigraphy of Hole 480 was determined on benthic foraminifera [16], where the samples represented averages over 10 cm core segments. Despite low concentration and poor preservation of foraminifera at the site, Shackleton and Hall [16] developed a $\delta^{18}O$ stratigraphy for the upper 35 m of the section based on 91 samples. Wang and Yeh [17] made $\delta^{18}O$ measurements in diatoms over the entire Hole 480 section with 21 data in the upper 49 m. The two oxygen-isotope stratigraphies show general agreement, but there are differences in the depths to the $\delta^{18}O$ stage boundaries: 1.5 m for the 1/2 boundary and 4.8 m for the 2/3 oxygen-isotope boundary. The latter boundary is particularly poorly determined on the diatom oxygen-isotope profile due to an apparent fresh water isotope spike in the 23–25 m range. In addition, the different $\delta^{18}O$ time scales have considerable variation of the stage boundary ages: 11–14 ka for the 1/2 boundary, 24–29 ka for the 2/3 shift, and 59–61 ka for the 3/4 boundary [18–20].

We have developed an age-depth relation for the upper 49 m of Hole 480 constrained by the following data (Table 1):

(1) The age of the top of the section is 1.2 ka.

(2) The depths of the 1/2 and 2/3 $\delta^{18}O$ stage boundaries are 12.5 and 23.8 m subbottom, respectively [16]. (These boundary depths from Shackleton and Hall [16] are preferred, because of their four-fold advantage in data density.) On the other hand, only the diatom oxygen-isotope pro-

TABLE 1

Data for time–depth relation of Hole 480, 0–49 m

$\delta^{18}O$ stage	$\delta^{18}O$ boundary	Boundary depth (m)	Depth interval (m)	Boundary age (ka)	Duration (ka)	Sedimentation rate (m/ka)
		0		1.2 [d,e]		
1			12.5		10.8	1.16
	1/2	12.5 [a]		12.0 [c]		
2			11.3		12.1	0.94
	2/3	23.8 [a]		24.1 [c]		
3			21.7		34.9	0.62
	3/4	45.5 [b]		59.0 [c]		
4			43.5–49.0		5.5	1.0 [f]

[a] Shackleton and Hall [16].
[b] Wang and Yeh [17].
[c] Martinson et al. [20].
[d] Murray [14].
[e] Karlin [15].
[f] Varve counts, this study.

file by Wang and Yeh [17] provides a good definition of the 3/4 stage boundary at 45.5 m.

(3) The age estimates of the $\delta^{18}O$ boundaries are from Martinson et al. [20], because they are the most recent and presumably the most updated analyses.

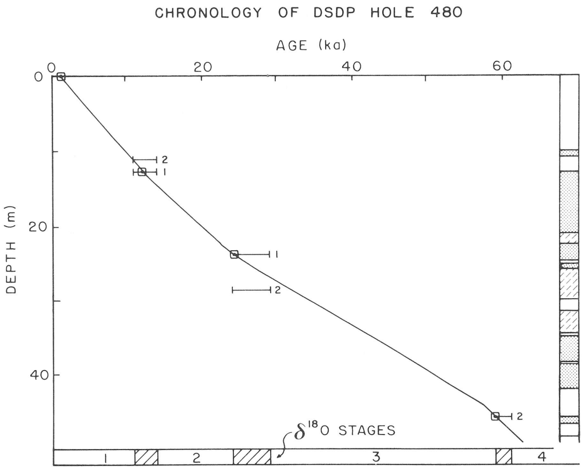

Fig. 4. Depth versus age curve for the upper 49 m of DSDP Hole 480. The squares are $\delta^{18}O$ boundary ages from Martinson et al. [20], and the age ranges are from the other $\delta^{18}O$ timescales cited in text [18,19]. *1* = boundary depths from Shackleton and Hall [16]; *2* = boundary depths from Wang and Yeh [17]. The ages of the $\delta^{18}O$ stages are plotted parallel to the abscissa; shaded zones indicate the range of boundary ages. Right-hand lithologic column is as in Fig. 1. The average sedimentation rate from 43.4 to 49 m subbottom is 1 m/ka, determined from laminae counts.

(4) Finally, the average sedimentation rate between 43.5 and 49 m subbottom is taken as 1.0 m/ka, consistent with laminae counts in this interval. The time–depth curve is shown in Fig. 4.

This age–depth curve gives a 1.16 m/ka average sedimentation rate for $\delta^{18}O$ stage 1 in the upper 12.5 m of Hole 480, similar to the 1.06 ± 0.19 m/ka from varves in the upper 13.1 m of the section. Interestingly, the average sedimentation rate in the homogeneous sediments during glacial $\delta^{18}O$ stage 2, from 12.5 to 23.8 m subbottom, is 0.94 m/ka, which is only slightly lower than the sedimentation rate in interglacial stage 1. The average sedimentation rate in oxygen-isotope stage 3, 23.8–45.5 m below the sea floor, is 0.62 m/ka. The extrapolated age at 49 m in Hole 480 is 63 ka. While we regard the chronology of Site 480 as provisional, the stratigraphy of the section shows no evidence of major hiatuses. Thus, despite the age uncertainties, the upper part of Hole 480 from cores 2–11 (5–49 m subbottom) offers an unparalleled opportunity for studying the high resolution behavior of the geomagnetic field between 63 and 5 ka BP.

5. Average paleomagnetic behavior

The paleomagnetic results of the 330 (351–21) specimens from the upper 49 m of Hole 480 are shown in Fig. 3. However, as discussed above, only data from the 298 samples from the top of core 2 at 5.2 m through core 11 at 48.8 m subbottom are considered to represent the ancient geomagnetic field. In Fig. 8 the inclinations of cores 2–11 are plotted versus time before present, obtained by linear interpolation of the $\delta^{18}O$ boundary ages and sedimentation rates discussed in the previous section and listed in Table 1. The inclinations of cores 2–11 are predominantly normal (positive) and straddle the geocentric axial dipole (GAD) value of 46.6°. Only 12 specimens have inclinations which deviate by more than 15° from the GAD value, eight with shallow and four with steep values. The three samples whose inclinations deviate from the GAD value by more than 25° all have shallow inclinations, including two with shallow negative values. Fig. 3b shows the "far-sidedness", the angle between the rotation axis and the latitude of the virtual geomagnetic pole (VGP) calculated for each specimen. Positive values indicate "far-sided" VGPs with shallower than GAD inclinations, and negative values correspond to steeper than GAD inclinations with "near-sided" VGPs. Viewed as VGP latitudes, the data are more symmetrical, and only eight specimens have VGP latitudes which deviate from the rotation axis by more than 15°, with four "near-sided" and four "far-sided" VGPs.

The average inclinations and VGP latitudes were analyzed by the Briden and Ward/Kono method for a Fisherian distribution of vectors where only the inclinations or latitudes are known [21,22]. The results are shown in Table 2, where the analyses were applied to individual cores. The data of cores 10 and 11 were combined, because for the latter there were only five specimens. The results for core 1 indicate that the average inclination is more than 9° shallower than the GAD value with $\alpha_{95} = 5°$; the corresponding VGP is "far-sided" by 7° with $\alpha_{95} = 3°$. This inclination anomaly is more than twice the 4.1° average shallowing calculated for the latitude strip from 20° to 30° N, using global paleomagnetic data for the past 5 Ma [23], and more than twice the corresponding "far-sidedness". Moreover, we note that

TABLE 2

Hole 480, 5–49 m: average paleoinclinations, paleolatitudes and associated statistical parameters.

Core	Depth (m)	n	Directions				Poles		
			I	α_{95}	θ_{63}	λ_I	λ_p	A_{95}	θ_{63}
2–11	5–49, all data	298	46.7	1.4	13.8	90.0	89.8	0.9	9.3
2–11	5–49, $\lvert\Delta p\rvert \leqslant 15°$	290	46.2	0.9	8.9	89.6	89.8	0.7	7.2
2–11	5–49, $\lvert\Delta I\rvert \leqslant 15°$	286	46.4	0.9	8.3	89.8	90.0	0.7	6.9
1	0 – 4.75	32	37.4	4.6	14.3	83.0	83.3	3.2	10.0
		30	37.1	2.9	8.8	82.8	82.9	2.1	6.3
2	4.75– 9.50	33	45.2	2.2	6.9	88.8	88.9	1.8	5.7
3	9.50–14.25	39	45.4	2.7	9.3	89.0	89.2	2.2	7.6
4	14.25–19.00	33	45.5	2.8	9.1	89.0	89.2	2.2	7.0
5	19.00–23.75	34	46.8	2.7	9.0	89.9	89.8	2.1	7.0
6	23.75–28.50	35	53.6	8.0	25.7	83.8	87.6	4.2	13.7
		32	48.9	2.4	7.7	88.1	88.0	2.1	6.6
7	28.50–33.25	36	46.3	5.5	18.3	89.7	89.0	3.2	10.9
		35	46.0	3.1	10.3	89.5	89.6	2.4	8.1
8	33.25–38.00	29	49.2	2.6	7.7	87.4	87.5	2.6	7.9
		28	48.4	2.1	6.3	88.6	88.4	1.8	5.5
9	38.00–42.75	27	48.0	6.8	19.4	88.8	89.6	4.2	12.2
		24	47.8	3.1	8.4	89.0	88.8	2.6	7.2
10+11	42.75–49.00	32	42.7	2.6	8.1	86.9	87.0	2.0	6.5

Cores under consideration and their respective depth intervals in meters below the top of the sediment; $\lvert\Delta p\rvert \leqslant 15°$, the ensemble of specimens whose VGP latitudes are within 15° from the rotation axis; $\lvert\Delta I\rvert \leqslant 15°$, the ensemble of specimens whose inclinations are within 15° of the GAD value; second line of results for cores 1, 6, 7, 8, 9 excludes specimens with $\lvert\Delta p\rvert > 15°$; n, number of specimens; I, average inclination: α_{95} (A_{95}), radius of the 95% circular cone of confidence about the mean paleoinclination, I, (paleolatitude, λ_p); θ_{63}, angular standard deviation; λ_I, paleolatitude calculated from average paleoinclination; λ_p, average paleolatitude calculated from the paleolatitudes of individual specimens.

the VGP "far-sidedness" of core 1 is nearly three times the value determined for Holocene lavas from western U.S. between 34° and 47° N [24], both for the entire data set (2.5°, $N=77$, $\alpha_{95}=$ 2.5°) or for flows younger than 2 ka (2.6°, $N=12$, $\alpha_{95}=6.5$°). These deviations of the remanence of core 1 from the average global and regional behavior of the geomagnetic field further support our previous conclusions that coring disturbances have irreversibly altered the paleomagnetic signal of core 1, the upper 4.8 m of Hole 480.

For the remaining cores five are slightly "far-sided" and four are slightly "near-sided", but for eight of the cores the deviations from the axis of rotation are not significant with respect to the α_{95} values. Only for cores 10 + 11 is the geographic pole excluded from the 2.0° α_{95} circle which surrounds the mean "far-sided" VGP of 87.0°. On considering the entire usable section from 5 to 49 m, regardless of whether one includes all data ($n=298$), or excludes specimens with VGP latitudes deviating by more than 15° from the rotation axis ($n=290$), or omits inclinations differing by more than 15° from the GAD value ($n=286$), the average inclination is essentially identical to the GAD value of 46.6°, and the average VGP is essentially coincident with the rotation axis. This is an intriguing result in terms of global analyses of average geomagnetic behavior for the past 5 Ma. On the one hand, the Gulf of California data are at variance with the average 4.1° inclination shallowing determined for the 20–30° N latitude strip, while they are most consistent with the much lower 0.9° inclination shallowing calculated for the Pacific plate [23].

The angular standard deviation (θ_{63}) of the VGPs from 5 to 49 m subbottom (Table 2) is considerably less than for lavas younger than 5 Ma in the latitude belt from 20 to 30° [25]. When the deviating inclinations are omitted, θ_{63} of the Site 480 section is about half the lava value, approximately 7° versus 14°. This may be explained by the smoothing properties of remanence acquisition in sediments, which arise from several causes, including: (1) averaging over a finite lock-in interval; (2) post-depositional processes, such as compaction and diagenesis, which affect the sediment non-uniformly; and (3) sampling of about 20–30 years per 2 cm specimen. θ_{63} values of the individual 4.8 m cores are very similar to those of the entire 5–49 m section (Table 2). This observation and the fact that individual cores, including those with the anomalous inclinations between 25 and 41 m subbottom, have average GAD inclinations suggest that in the Gulf of California the geomagnetic field retains its GAD characteristics, when averaged over core lengths representing no more than 8 ka. Finally, when the eight specimens whose VGPs deviate by more than 15° from the rotation axis are excluded, the individual cores have very similar θ_{63} values, ranging between 5.5° and 8.1°. The corresponding α_{95} values vary from 1.8° to 2.6° (Table 2).

6. Upper Pleistocene excursions

Several zones of anomalous paleomagnetic directions were identified in Hole 480. These intervals are not associated with core boundaries, and it is unlikely that they are related to coring disturbances. Moreover, these anomalous segments are characterized by samples with ordinary remanence intensities and stabilities. Therefore, we consider the anomalous directions to represent past behavior of the Earth's magnetic field. After excluding the results of core 1 because of coring disturbance, all the anomalous VGP latitudes occur between about 41 and 22 m subbottom (Fig. 3a, b), corresponding to ~ 53–22 ka BP, suggesting that the geomagnetic field during that interval was more disturbed than for the last 20 ka. It is important to emphasize that only about 3% of the specimens have anomalous directions, consistent with the predominantly normal state of the geomagnetic field during the late Pleistocene. Because each of the excursions is described by only a few samples we restrict the use of these data for correlations with previously observed geomagnetic excursions, and the following discussions must be considered preliminary and somewhat speculative. Additional samples from Hole 480 and documentation in independent parallel sections are needed to substantiate our results. However, based on the independent chronology of the Site 480 section, several of the anomalous paleomagnetic fluctuations correlate in time and morphology to previously documented excursions, and, as far as we know, this is the first time that these excursions have been observed in the same stratigraphic section.

6.1. The Mono Lake excursion

The inclination pattern between 27.2 and 25.0 m (Figs. 3a, 5, 8) is very similar to the Mono Lake geomagnetic excursion [26], first discovered by Denham and Cox [27]. In Hole 480, the estimated age span of this fluctuation is ~ 30–26 ka, as compared with the 28–26 ka age estimate reported by Liddicoat et al. [28]. In Fig. 5, the Mono Lake excursion data of Liddicoat and Coe [26] are reproduced together with the Hole 480 results, where the fluctuation occurs entirely in core 6. The declinations of core 6 were adjusted by a single rotation of section 3 about the vertical axis to match the declination of the uppermost specimen in section 3 with the lowest specimen of section 2. (No declination adjustment was needed between sections 2 and 1.) The geomagnetic fluctuation of core 6, Hole 480 is remarkably similar to that observed near Mono Lake, California. The resemblance of these two sedimentary records is especially surprising because Mono Lake is about 10° latitude north of Site 480, and different resolutions are attainable by the sediments of the two sections. The latitude difference between the two sites might account for the difference in the peak inclination, which is roughly 10° steeper at Mono Lake than in the Gulf of California; however, the excursion to negative inclinations is comparable at the two sites: −23° at Mono Lake versus −19° at Site 480. The declination patterns are also similar, with both sites undergoing large eastward swings from the beginning to the end of the excursion, and both records exhibit a sharp, high frequency spike of easterly declination associated with the negative inclination values. The cumulative eastward declination swing is about 130° at Mono Lake (38.0° N) and about 80° in the Gulf of California (28.0° N). Based on their similar ages and morphologies, we believe that the paleomagnetic fluctuation in the interval 27.2–25.0 m subbottom in Hole 480 represents the local expression of the Mono Lake geomagnetic excursion. The time span of the Mono Lake excursion is about 3 ka in the Gulf of California as compared with an estimated 1 ka near Mono Lake, California.

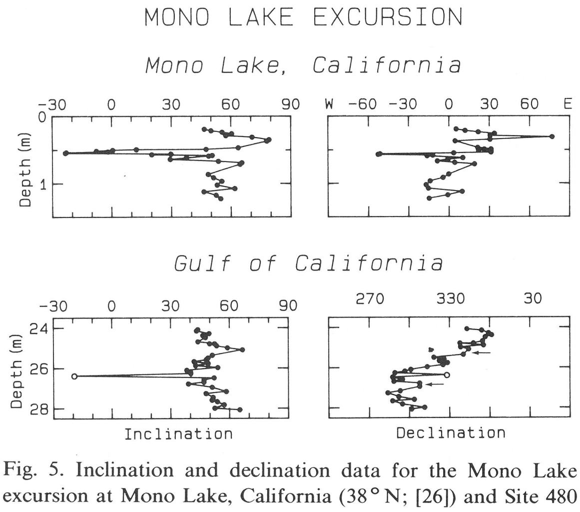

Fig. 5. Inclination and declination data for the Mono Lake excursion at Mono Lake, California (38° N; [26]) and Site 480 in the Gulf of California (28° N, this study), where the excursion occurs entirely in core 6. The arrows in the Gulf of California declination profile indicate the section boundaries. The same scales are used for the inclination and declination data, respectively; however, only relative declinations are available for the azimuthally unoriented Site 480.

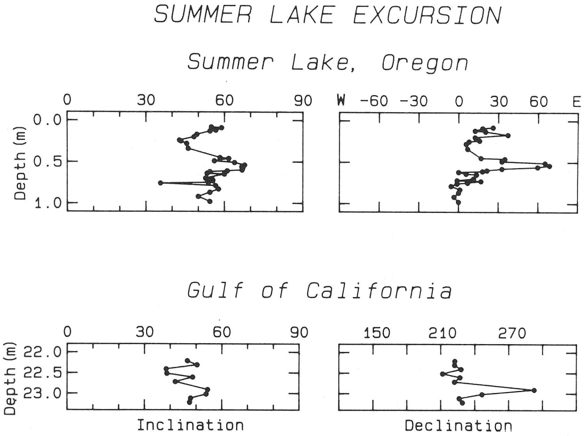

Fig. 6. Inclination and declination data for the Summer Lake excursion at Summer Lake, Oregon (43° N, [1]) and Site 480, Gulf of California (28° N, this study), where the excursion occurs entirely in core 5, section 3. The same scales are used for the inclination and declination data, respectively; however, only relative declinations are available for the azimuthally unoriented Site 480 section.

6.2. The Summer Lake excursion

Negrini et al. [1] observed a paleomagnetic feature at Summer Lake, Oregon (~ 43° N), which they correlated with the Mono Lake excursion based primarily on similar age estimates. At Summer Lake, the excursion was found in ~ 0.5 m sedimentary section, where the declination exhibits an eastward swing of about 60° associated with some (< 10°) steepening of the inclination. Although Site 480 in the Gulf of California is about 15° (> 1500 km) south of Summer Lake, it preserved a very similar paleomagnetic fluctuation (Fig. 6) as the one observed at Summer Lake, Oregon and distinct from the Mono Lake excursion. This excursion occurs in a 0.3–0.4 m segment contained entirely in core 5 section 3, centered at 23.0 m subbottom, with an estimated age of 23 ka BP. There is an easterly declination swing of ~ 70° and an inclination steepening of ~ 10°. Hence, we propose that the Summer Lake excursion is a short but distinct geomagnetic fluctuation, which lasted on the order of 0.5 ka and is about 4 ka younger than the Mono Lake excursion.

6.3. The Laschamp excursion

The oldest excursion identified in the upper 49 m of Hole 480 occurs between 40.7 and 38.6 m subbottom, from about 52.3 to 48.8 ka BP. The fluctuation begins with a steep inclination (+59°) at 40.7 m; the inclination rapidly shallows to +23° and +3° for consecutive horizons at 39.3 and 39.1 m. The fluctuation terminates at 38.6 m subbottom with a steep inclination (+63°). The major part of the fluctuation occurs in a single 1.5 m segment, core 9, section 1, shown in Fig. 7, where the inclination shallowing is accompanied by a 30–40° westward swing of the declination. The estimated 52.3 to 48.8 ka span for this geomagnetic feature is similar to the 46 ± 2 ka average K-Ar age of the Laschamp excursion in the Massif Central, France [29–31] and the 43 ± 4 ka average age of the Skalamælifell excursion in Iceland [32,33]. A geomagnetic excursion was observed in Lake Biwa, Japan [34], characterized by negative, essentially antipodal, inclinations with an interpolated age of 49 ka, which depends on the identification of a paleomagnetic excursion at 52 m in Lake Biwa as the Blake event.

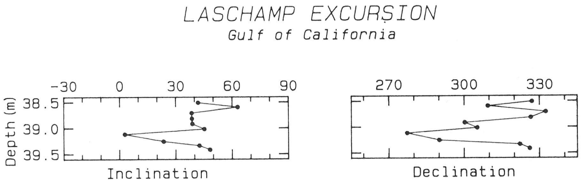

Fig. 7. Inclination and relative declination for core 9, section 1 of DSDP Site 480, which is correlated with the Laschamp excursion.

The very low paleointensity of the Laschamp and Olby flows [35] and the Skalamælifell lavas [36] are less than 15% of the field's present strength, suggesting that the Laschamp excursion might represent an aborted geomagnetic reversal during which the field at the Earth's surface was not dipolar. Hence, the age and morphology of the excursion might vary for widely separated areas. Furthermore, in the Massif Central, France and in southwestern Iceland the excursion occurs in extrusive lavas, representing geologically an instant snapshot of the geomagnetic field. In contrast, sediments record a more continuous time-averaged signal, whose amplitudes represent a lower limit of the actual geomagnetic fluctuations. Therefore, it would not be surprising to observe different geomagnetic expressions of the Laschamp excursion at different geographic locations and recorded by various remanence acquisition processes. We note, however, that the paleomagnetic direction of the Skalamælifell units in Iceland also have shallow negative inclinations and westerly declinations, similar to the expression at Site 480 in the Gulf of California.

In Hole 480, inclination changes of up to 60° occur between points separated by 0.1 m, deposited in less than 0.2 ka and corresponding to angular changes of the order of 0.5°/year. Such fluctuations are high in comparison with present-day, normal geomagnetic secular variation, but they are not unusual for times of polarity transitions, excursions and greatly diminished geomagnetic moment (e.g. [37]).

6.4. The absence of an excursion near 17 ka

A paleomagnetic excursion at circa 17 ka BP was detected in sediments from the Gulf of Mexico [38,39] and Lake Biwa, Japan [40], and the excursion is characterized by negative inclinations in these sediments. In addition, two lavas on the island of Hawaii dated by ^{14}C as > 10.4 and 17.9 ka have inclinations of 1.1° and 8.5°, respectively [41]. (However, because the VGP latitudes of these flows are 70.3° and 73.1°, respectively, they were not considered to have recorded a geomagnetic excursion.) There is no evidence for this excursion in Hole 480.

7. Recurring inclination fluctuations

The inclination versus age profile for the geomagnetically valid section of Site 480 is shown in Fig. 8, where each point is the stable inclination of one specimen between 62.3 and 5.7 ka BP. Considerably higher amplitudes of inclination fluctuations are observed from 54 to 25 ka than for the intervals from 62 to 54 ka and 25 to 5 ka. This is also reflected in the significantly higher angular standard deviations for cores 6, 7, and 9 for both inclinations and VGP latitudes (Table 2).

We were struck by the similarity of the inclination fluctuations of the Laschamp and Mono Lake excursions from 52.3 to 48.8 ka and 29.7 to 26.3 ka, respectively. Both excursions begin and end with steep inclinations, 10–20° higher than the GAD value, with corresponding "near-sided" VGPs. Between the two end points the inclination shallows to more than 40° below the GAD value, with a minimum of −19° for the Mono Lake excursion. Similar inclination fluctuations seem to recur in the section, especially between 54 and 19.5 ka BP: e.g., 52.3–48.8 ka, 38.7–35.4 ka, 35.4–31.2 ka, 29.7–26.3 ka, 21.2–19.5 ka. These inclination fluctuations account for more than half of the section between 52.3 and 19.5 ka BP. Some of the fluctuations are less well defined probably because of incomplete core recovery, smoothing of the remanence during its acquisition, and/or lower amplitudes of the inclination fluctuations.

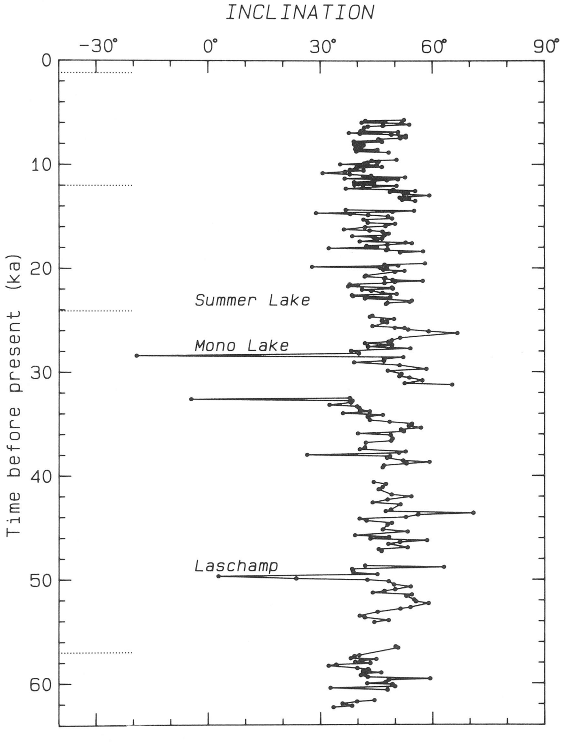

Fig. 8. Inclination versus age profile for the paleomagnetically valid section at Hole 480, from 5 to 62 ka (5–49 m subbottom). The horizontal dotted segments at the left age ordinate indicate the calibration points for the age estimates: the top of the section and the oxygen isotope stage boundaries. Note the similar inclination waveforms between 25 and 54 ka.

Yaskawa et al. [34] pointed out the similarity of the inclination patterns of the two uppermost excursions in Lake Biwa, Japan, near 13 and 26 m, whose shapes resemble those observed in Hole 480. Recurring geomagnetic waveforms were also identified from about 36 to 13 ka in sediments near Mono Lake, California [42], of which the Mono Lake excursion is the oldest feature, and it can be correlated with confidence to the Site 480 section. In addition, Hole 480 between 31.2 and 13.0 ka has been tentatively subdivided, showing recurring inclination fluctuations, whose estimated ages, duration and morphologies approximate those reported for the sediments of Mono Lake, California. Although imperfect, this correspondence was not expected in view of the > 1000 km separation of the sampling sites and the subtle expression of the inclination fluctuations at Site 480 for times younger than about 24 ka BP.

Visual inspection of Fig. 8 suggests that the inclination fluctuations may be somewhat periodic, although amplitudes and frequencies might vary through time. In particular, the spectral content of the inclination profile of cores 2–5 appears to be distinct from that of cores 6–11. For purposes of spectral analysis, we divided the inclination versus age profile into two series, from 5 to 24 ka (cores 2–5) and from 24 to 62 ka (cores 6–11). Although this subdivision limits long period resolution, we believe that the assumption of stationarity is better satisfied for the two separate segments.

In computing the spectra, the data were first demeaned and linearly interpolated to 0.2 ka intervals. The sampling density at this site was nonuniform because of core breaks and physical disturbances. Since interpolation over such sampling gaps can introduce spurious low-frequency components, data values were assigned as missing when the sampling interval exceeded 0.25 ka. The amplitude spectrum was then computed from the autocovariance function using Goertzel's algorithm [43], and missing values were not considered in the autocovariance calculation [44]. A lag window of approximately $N/2$ length was used to smooth the special estimates and a Hanning cosine taper was applied to minimize end effects [45].

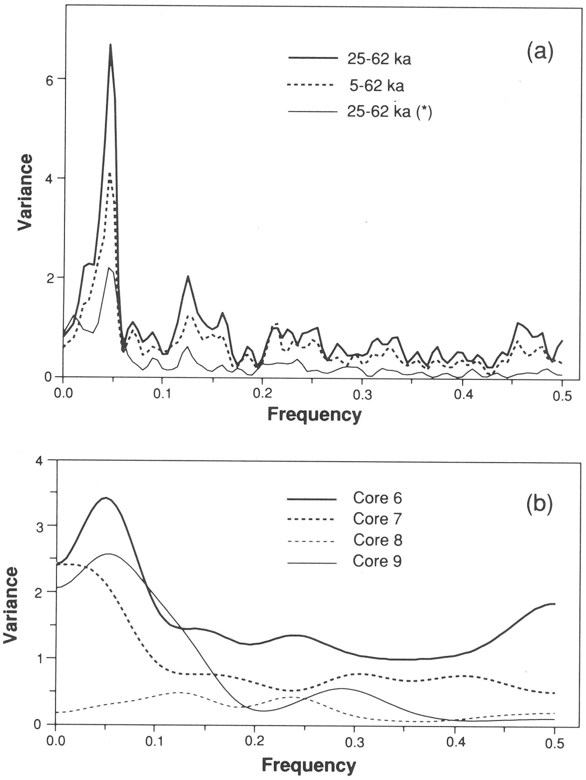

Fig. 9. Power spectra calculated from the autocovariance function for demeaned Hole 480 inclination data interpolated at 0.2 ka intervals, using a Hanning cosine taper and a lag window of 100 points in (a) and 50 points in (b). The frequency is given in cycles per 0.2 ka data interval. (a) Dashed curve, 5–62 ka (cores 2–11); bold continuous curve, 25–62 ka (cores 6–11); continuous curve, also 25–62 ka but excluding the nine specimens with inclinations deviating by more than 15° from the mean. Note that the most significant peak at 4.4 ka occurs for all three analyses. (b) Power spectra of individual cores; bold continuous curve, core 6 (24.6–31.2 ka); bold dashed curve, core 7 (32.6–39.2 ka); dashed curve, core 8 (40.6–47.2 ka); continuous curve, core 9 (48.8–55.4 ka).

In Fig. 9a, the amplitude spectrum of the 24–62 ka time series shows a strong peak with a maximum at period of 4.4 ka. Relatively minor secondary peaks occur at 1.25, 1.6, and 6.7–8 ka. Interestingly, these maxima do not appear to be caused by outliers, since removal of nine points whose inclinations deviate by more than 15° from the mean causes no change in the periodicities or relative peak amplitudes, although the total variance is reduced by a factor of three.

The spectrum of the time series from 5 to 24 ka has considerably less variance, consistent with the much lower amplitudes of the inclination fluctuations. A relatively broad maximum occurs from 4 to 8 ka and lesser peaks are seen at 1.4 and 2.0 ka. However, the amplitudes of these peaks are about an order of magnitude less than for the dominant 4.4 ka period in the older time series. Because of the higher variance in the 24–62 ka interval, the combined series from 5 to 62 ka is controlled by the strong periodicities in the older interval.

To further examine the stationarity of the spectra and the effects of the coring gaps, the 24–62 ka time series was divided into four subsets of equal length ($N = 34$) and comparable sampling density. Each subset corresponds to a single core. Despite the poorer resolution due to fewer points in each analysis, as seen in Fig. 9b, three of the four intervals show broad peaks at frequencies corresponding to periods of 4 to >6 ka. The intervals from 24.6 to 31.2 ka and from 48.8 and 55.4 ka have maxima centered at about 4 ka, whereas the peak is shifted to >6 ka in the 32.6–39.2 ka series. The interval from 40.6 to 47.2 ka is the only span whose spectra is ill-defined and has low total variance. Thus, it appears that the waveform causing the inclination fluctuations is not of equal importance at different intervals, yet it seems to retain the same periodicity through time.

We suggest that the higher variance in the time series from 24 to 62 ka is related to a general instability of the geomagnetic field and diminished dipole moment in the time interval from about 20 to 50 ka [46–48]. In particular, during the Laschamp excursion at about 45 ka BP the geomagnetic field intensity was less than 15% of its average value for the last 10 ka [35,36], and low relative paleointensity was obtained for the sediments which recorded the Mono Lake excursion

[26]. (Unfortunately, the Site 480 sediments are not suitable for relative paleointensity studies, because of intense diagenesis [49].)

The Earth's present magnetic field can be modelled as originating from several (< 10) large-scale eddies in the electrically conducting liquid outer core (e.g. [50]). Considering this kind of a model, we speculate that the increased variance in the power spectrum of the inclinations between 24 and 62 ka BP might result from energy redistribution in the core leading to fewer coherent large scale eddies and more numerous smaller and less coherent eddies, whose magnetic fields are more effectively attenuated by the intervening mantle. This would cause a reduction in the geomagnetic intensity at the Earth's surface. Such a rearrangement of the flow regime in the outer core might also occur during field reversals. As the field is regenerated, the number of large scale coherent eddies increases at the expense of smaller ones, with a corresponding increase in the dipole moment measured at the Earth's surface. Because the reverse and normal fields are equivalent solutions to the magnetic induction equation [51], the regenerated field might be parallel or opposite to the preceding field depending on conditions prevailing in the core.

8. Conclusions

In the Gulf of California, hydraulic piston coring by DSDP Leg 64 recovered a largely undisturbed sedimentary section at Hole 480, whose upper 49 m were deposited continuously with rates approaching 1 m/ka. In the upper 49 m, $\delta^{18}O$ stratigraphy was used to establish a time–depth relation, which suggests that these sediments represent the last 62 ka. The paleomagnetism of 298 specimens from the undisturbed segment from 5 to 49 m subbottom show:

1: (a) The average inclination in the interval 5-62 ka BP (5–49 m subbottom) is 46–47°, using all samples. This value is identical to that expected for the geocentric axial dipole (GAD) at the sampling site.

(b) The similarity of the angular standard deviation (θ_{63}) of individual cores to that for the entire section (5–49 m subbottom and using all samples) and the correspondence of the average inclination for each core to the GAD value indicate that in the Gulf of California individual 4.8 m cores, which represent no more than 7 ka, are sufficient to reproduce the geomagnetic field's average geocentric axial dipole behavior.

(c) The θ_{63} values of the virtual geomagnetic poles (VGPs) for each core, using all samples, are considerably less than dispersion due to paleosecular variation measured in lavas younger than 5 Ma at the latitude of Site 480, testimony to the intrinsic averaging of remanence acquisition in sediments.

(d) Only 8 of the 298 specimens have VGP latitudes which deviate from the rotation axis by more than 15°, and the angular dispersions of the magnetic directions and VGPs of individual cores are very similar, when these eight specimens are excluded.

2: (a) All the anomalous paleomagnetic inclinations occur between 24 and 54 ka BP (about 24–42 m subbottom). The geomagnetic inclinations were much "noisier" in that interval than in the zones from 5 to 24 ka (5– 24 m) and from 54 to 62 ka BP (42–49 m).

(b) The Laschamp excursion was apparently recorded at Hole 480 from 51 to 49 ka BP (39.6–38.6 m subbottom) and the Mono Lake excursion from 29 to 26 ka BP (27.0–25.0 m subbottom).

(c) A narrow 0.3–0.4 m zone centered at 23 ka BP has a very similar paleomagnetic signature as the excursion observed at Summer Lake, Oregon [1], and it is expressed primarily as an eastward swing of the declination. We suggest that the Summer Lake is distinct from the Mono Lake excursion, about 4–5 ka younger, and of considerably shorter duration, lasting no more than a few hundred years.

3: (a) Recurring inclination fluctuations were identified at Site 480, delineated by end points with steep inclinations and intermediate shallow values. The inclination cycles are particularly apparent from 24 to 54 ka BP (24–41 m subbottom). Spectral analysis of the time series from 24 to 62 ka BP shows a characteristic period at 4.4 ka, which is retained, though at lower power, when the anomalous inclination data are excluded from analysis.

(b) The "noisier" (higher variance) geomagnetic field between 24 and 53 ka BP, associated with the anomalous inclinations, is probably related to the generally diminished dipole moment between 20 and 50 ka, which might reflect a modified flow pattern in the outer core.

Further detailed studies of the geomagnetic field in this time interval are clearly warranted.

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References

1 R.M. Negrini, J.O. Davis and K.L. Verosub, Mono Lake geomagnetic excursion found at Summer Lake, Oregon, Geology 12, 643–646, 1984.

2 J.R. Curray, D.G. Moore et al., Guaymas basin slope: Sites 479 and 480, Init. Rep. DSDP 65, 417–477, 1982.

3 H. Schrader, K. Kelts, J. Curray, D. Moore, E. Aguayo, M.P. Aubrey, G. Einsele, D. Fornari, J. Geiskes, J. Guerrero, M. Kastner, M. Lyle, Y. Matoba, A. Molina-Cruz, J. Niemitz, J. Rueda, A. Saunders, B. Simoneit and V. Vaquier, Laminated diatomaceous sediments from the Guaymas Basin slope (central Gulf of California): 250,000-year climate record, Science 207, 1207–1209, 1980.

4 R. Karlin and S. Levi, Preliminary paleomagnetic results of laminated sediments from Deep Sea Drilling Project hydraulic piston core Site 480, Guaymas Basin, Gulf of California, Init. Rep. DSDP 64 Part 2, 1255–1258, 1982.

5 G. Einsele, Mass physical properties of Pliocene to Quaternary Sediments in the Gulf of California, DSDP Leg 64, Init. Rep. DSDP 64, 529–542, 1982.

6 S.P. Lund and S.K. Banerjee, Late Quaternary paleomagnetic field secular variation from two Minnesota lakes, J. Geophys. Res. 90, 803–825, 1985.

7 K.L. Verosub, P.J. Mehringer, Jr. and P. Waterstraat, Holocene secular variation in western North America: paleomagnetic record from Fish Lake, Harney County, Oregon, J. Geophys. Res. 91, 3609–3623, 1986.

8 B. Schmitz, Stress-induced variations of remanent magnetism in Late Quaternary varved clay, Earth Planet. Sci. Lett. 69, 422–426, 1984.

9 K.W. Bruland, ^{210}Pb geochronology in the coastal marine environment, Ph.D. Dissertation, 106 pp., University of California, San Diego, 1974.

10 D.J. DeMaster, The marine budgets of silica and ^{32}Si, 308 pp., Ph.D. Thesis, Yale University, New Haven, Conn., 1979.

11 T.R. Baumgartner, V. Ferreira-Bartrina, H. Schrader and A. Soutar, A 20-year varve record of siliceous phytoplankton variability in the central Gulf of California, Mar. Geol. 64, 113–129, 1985.

12 A. Soutar, S.R. Johnson, E. Taylor and T.R. Baumgartner, X-radiography of Hole 480: Procedures and results, Init. Rep. DSDP 64, 1183–1190, 1982.

13 R. Byrne, Preliminary pollen analysis of Deep Sea Drilling Project Leg 64 Hole 480 (cores 1–11), Init. Rep. DSDP 64, 1225–1237, 1982.

14 D.W. Murray, Paleo-oceanography of the gulf of California based on silicoflagellates from marine varved sediments, 129 pp., M.S. Thesis, Oregon State University, Corvallis, Ore., 1982.

15 R. Karlin, Paleomagnetism, rock magnetism, and diagenesis in hemipelagic sediments from the northeast Pacific Ocean and the Gulf of California, 246 pp., Ph.D. Thesis, Oregon State University, Corvallis, Ore., 1984.

16 N.J. Shackleton and M.A. Hall, Oxygen isotope study of continuous scrape samples from Site 480, Init. Rep. DSDP 64, 1251–1253, 1982.

17 C.-H. Wang and H.-W. Yeh, Oxygen isotopic compositions of DSDP Site 480 diatoms: implications and applications, Geochim. Cosmochim. Acta 49, 1469–1478, 1985.

18 L. Pastouret, H. Chamley, G. Delibrias, J.C. Duplessy and J. Thiede, Late Quaternary climatic changes in western tropical Africa deduced from deep-sea sedimentation off the Niger delta, Oceanol. Acta 1, 217–232, 1978.

19 M.A. Kominz, G.R. Heath, T.L. Ku and N.G. Pisias, Brunhes time scales and the interpretation of climatic changes, Earth Planet. Sci. Lett. 45, 394–410, 1979.

20 D.G. Martinson, N.G. Pisias, J.D. Hays, J. Imbrie, T.C. Moore, Jr. and N.J. Shackleton, Age dating and orbital theory of Ice Ages: development of a high-resolution 0–3,000,000-year chronostratigraphy, Quat. Res. 27, 1–29, 1987.

21 J.C. Briden and M.A. Ward, Analysis of magnetic inclination in borecores, Pure Appl. Geophys. 63, 133–152, 1966.

22 M. Kono, Statistics of paleomagnetic inclination data, J. Geophys. Res. 85, 3878–3882, 1980.

23 R.T. Merrill and M.W. McElhinny, Anomalies in the time-averaged paleomagnetic field and their implications for the lower mantle, Rev. Geophys. Space Phys. 15, 309–323, 1977.

24 D.E. Champion, Holocene geomagnetic secular variation in the western United States: implications for the global geomagnetic field, 314 pp., Ph.D. Thesis, California Institute of Technology, Pasadena, Calif., 1980.

25 P.L. McFadden and M.W. McElhinny, A physical model for paleosecular variation, Geophys. J.R. Astron. Soc. 78, 809–830, 1984.

26 J.C. Liddicoat and R.S. Coe, Mono Lake geomagnetic excursion, J. Geophys. Res. 84, 261–271, 1979.

27 C.R. Denham and A. Cox, Evidence that the Laschamp polarity event did not occur 13300-30400 years ago, Earth Planet. Sci. Lett. 13, 181–190, 1971.

28 J.C. Liddicoat, K.R. Lajoie and A.M. Sarna-Wojcicki, Detection and dating of the Mono Lake excursion in the Lake Lahontan Sehoo Formation, Carson Sink, Nevada, EOS, Trans. Am. Geophys. Union 63, 920, 1982.

29 N. Bonhommet and J. Babkine, Sur la présence d'aimantation inversées dans la Chaîne des Puys, C.R. Acad. Sci. Paris 264, 92–94, 1967.

30 C.M. Hall and D. York, K-Ar and ^{40}Ar/^{39}Ar age of the Laschamp geomagnetic polarity reversal, Nature 274, 462–464, 1978.

31 P.Y. Gillot, J. Labeyrie, C. Laj, G. Valladas, G. Guérin, G. Poupean and G. Delibrias, Age of the Laschamp paleomagnetic excursion revisited, Earth Planet. Sci. Lett. 42, 444–450, 1979.

32 L. Kristjansson and A. Gudmundsson, Geomagnetic excursion in late-glacial basalt outcrops in south-western Iceland, Geophys. Res. Lett. 7, 337–340, 1980.

33 S. Levi, H. Audunsson, R.A. Duncan, L. Kristjansson and P.-Y. Gillot, The Laschamp excursion confirmed in Icelandic lavas (in preparation).

34 K. Yaskawa, T. Nakajima, N. Kawai, M. Torii, N. Natsuhara and S. Horie, Paleomagnetism of a core from Lake Biwa (I), J. Geomagn. Geoelectr. 25, 447–474, 1973.

35 P. Roperch, N. Bonhommet and S. Levi, Paleointensity of the Earth's magnetic field during the Laschamp excursion and its geomagnetic implications, Earth Planet. Sci. Lett. 88, 209–218, 1988.

36 S. Levi, H. Audunsson, R.A. Duncan and L. Kristjansson, Unstable geomagnetic behavior circa 50 ka BP: Evidence from south-western Iceland (abstract), EOS, Trans. Am. Geophys. Union 68, 1249, 1987.

37 E.A. Mankinen, M. Prévot, C.S. Grommé and R.S. Coe, The Steens Mountain (Oregon) geomagnetic polarity transition, 1. Directional history, duration of episodes, and rock magnetism, J. Geophys. Res. 90, 10393–10416, 1985.

38 H.C. Clark and J.P. Kennett, Paleomagnetic excursion recorded in latest Pleistocene deep-sea sediments, Gulf of Mexico, Earth Planet. Sci. Lett. 19, 267–274, 1973.

39 W.K. Freed and N. Healy, Excursions in the Pleistocene geomagnetic field recorded in Gulf of Mexico sediments, Earth Planet. Sci. Lett. 24, 99–104, 1974.

40 T. Nakajima, K. Yaskawa, N. Natsuhara and N. Kawai, Very short period geomagnetic excursion 18,000 yr BP, Nature 244, 8–10, 1973.

41 R.S. Coe, S. Grommé and E.A. Mankinen, Geomagnetic Paleointensities from Radiocarbon-dated lava flows on Hawaii and the question of the Pacific nondipole low, J. Geophys. Res. 83, 1740–1756, 1978.

42 S.P. Lund, J.C. Liddicoat, K.L. Lajoie, T.L. Henyey and S. Robinson, Paleomagnetic evidence for long-term (10^4 year) memory and periodic behavior in the Earth's core dynamo process, Geophys. Res. Lett. 15, 1101–1104, 1987.

43 A.V. Oppenheim and R.W. Schafer, Digital Signal Processing, 585 pp., Prentice-Hall, Englewood Cliffs, N.J., 1975.

44 M.B. Priestley, Spectral Analysis and Time Series, 890 pp., Academic Press New York, N.Y., 1981.

45 M. Båth, Spectral Analysis in Geophysics, 563 pp., Elsevier, Amsterdam, 1974.

46 M.G. Barbetti and K. Flude, Paleomagnetic field strengths from sediments baked by lava flows of the Chaîne des Puys, France, Nature 278, 153–156, 1979.

47 M.W. McElhinny and W.E. Senanayake, Variations in the geomagnetic dipole I: the past 50,000 years, J. Geomagn. Geoelectr. 34, 39–51, 1982.

48 J.-S. Salis, Variation séculaire du champ magnétique terrestre. Direction et paléointensité sur la periode 7,000–70,000 Ans BP, dans la Chaîne des Puys, 190 pp., Ph.D. Thesis, Université de Rennes I, Rennes, 1987.

49 R. Karlin and S. Levi, Geochemical and sedimentological control of the magnetic properties of hemipelagic sediments, J. Geophys. Res. 90, 10373–10392, 1985.

50 N.W. Peddie, Current loop models of the Earth's magnetic field, J. Geophys. Res. 84, 4517–4524, 1979.

51 R.T. Merrill, M.W. McElhinny, and D.J. Stevenson, Evidence for longterm asymmetries in the Earth's magnetic field and possible implications for dynamo theories, Phys. Earth Planet. Inter. 20, 75–82, 1979.