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Earth and Planetary Science Letters 161 (1998) 145–160

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High-resolution record of geomagnetic secular variation from Late Pleistocene Lake Lisan sediments (paleo Dead Sea)

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Received 3 March 1998; revised version received 20 June 1998; accepted 30 June 1998

Abstract

We measured geomagnetic secular variation in Lake Lisan sediments (paleo Dead Sea). More than 1500 oriented samples were collected from a 27.3-m section of alternating aragonite and detritus laminae in the Dead Sea basin ranging in age from 67 to 32 ka. The natural remanent magnetization (NRM) is carried by titanomagnetite in the detrital laminae whereas the aragonite is diamagnetic. The NRM is very stable and was acquired several hundred years after deposition. The mean direction of 878 horizons is $D = 005°$, $I = 45°$ ($\alpha_{95} = 1°$; $\kappa = 22$). We observed three modes of directional geomagnetic variation as a function of (and by inference, time): very rapid inter-sample changes, slow variation in mean direction, and inclination shallowing of about 1°/m. The overall rate of change in direction is 0.57 ± 0.57°/year, not significantly different from zero. For about 83% of the record the rate of change is less than 1°/year and comparable to historical values. High rates of change are observed more frequently in the Lisan than in historical records, and peak rates are up to ten times faster. A smoothed curve resulting in a maximum rate of change of 0.66°/year and a mean 0.10 ± 0.10°/year may be a more realistic representation of the field behavior. No reverse NRMs were observed, but geomagnetic field excursions may be present where the VGPs deviate by more than 40° from the geographic north at about 52 and 41 ka; the latter may represent the Laschamp event.

Keywords: paleomagnetism; secular variations; magnetic inclination; Pleistocene

1. Introduction

Time variations of the Earth's magnetic field have a wide spectrum of about 20 orders of magnitude, from over 10^3 Hz to more than 100 million years [1]. The frequencies less than 1/year are termed *geomagnetic secular variation* (SV). SV is reflected in the field intensity and directional changes. SV is the combined effect of variation in the axial dipole field component and variation in the strength and location of the non-dipole field components. Changes in the dipole field are synchronous on a global scale, whereas the non-dipole component of the geomagnetic SV varies over smaller geographical distance. The record of geomagnetic SV is punctuated by geomagnetic *polarity transitions* which take perhaps 10^3–10^4 years to complete and by even shorter ge-

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0012-821X/98/$19.00
PII S0012-821X(98)00146-0

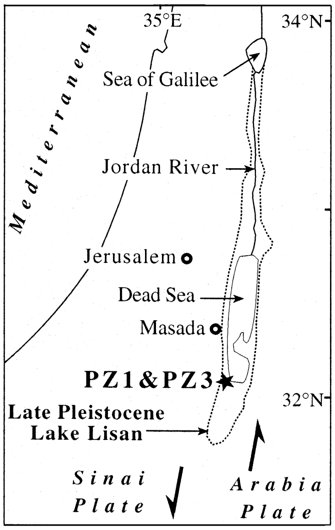

Fig. 1. Map showing the maximum extent of Lake Lisan at 180 m below mean sea level, and sampling sites PZ1 and PZ3 in the Peratzim Valley.

omagnetic *excursions* or *events* which may represent aborted polarity transitions or more localized non-dipole effects and take 10^2–10^3 years to complete. When coupled with precise age measurements, paleomagnetic variations recorded in sedimentary sequences are an important source of information about the geomagnetic field, the timing and duration of polarity transitions and excursions [1]. The temporal resolution of paleomagnetic studies is generally higher where sedimentation rates are higher. In this paper we demonstrate that the remanent magnetization of the Late Pleistocene Lisan Formation sediments can provide a high-resolution paleomagnetic record. We examine the rock-magnetic properties of the Lisan sediments, in particular lock-in depth, inclination shallowing, and the effects of soft-sediment deformation. We next show that the Lisan is a faithful recorder of the geomagnetic secular variation and conclude with discussion of the observed directional changes.

1.1. The Lisan Formation

The Lisan Formation is exposed along 220 km of the Dead Sea Transform (Fig. 1). In the study area in the south Dead Sea graben it is comprised mainly of alternating laminae of white aragonite and dark detritus, and a few thick clastic layers and gypsum. In addition, the section contains 'mixed layers' of disturbed laminae which were interpreted as seismites [2,3]. The aragonite was precipitated chemically from the upper surface of Lake Lisan whereas the detritus which contains calcite, dolomite, aragonite, quartz and clay, was carried by annual floods [4]. The chemical preservation of aragonite in the Lisan is superb due to extreme dry conditions in the Dead Sea region and the retention within the aragonite of abundant interstitial chloride salt of a high Mg/Ca ratio, inherited from the original lake, which prevented its transformation to calcite [5,6]. Lake Lisan was too saline to support bottom burrowers, leaving the sediment structure intact down to its finest details.

The Lisan aragonite was dated by ^{14}C and U-series. U–Th dating was done by the α counting technique [7,8], and more recently the studied section was dated by thermal ionization mass spectrometry (TIMS) [9]. The average sedimentation rate is 0.86 ± 0.02 mm/year [9]. Each 2-cm-thick paleomagnetic sample therefore provides, on average, a 23-year time-slice of the paleofield.

1.2. Sampling and measurements

We sampled 27.3 m out of the 43-m PZ section of Lisan sediments in the least disturbed and best exposed outcrop found at Peratzim Valley, southwest of the Dead Sea (Fig. 1). The lower part of the section, 0–1400 cm, was sampled at site PZ3 where it is best accessible. The upper part, 1445–2730 cm was sampled about 500 m west, at site PZ1. Continuous exposure along the steep canyon walls enables a direct correlation. This section was selected for detailed geochronological, paleoseismic, geochemical and paleomagnetic studies [3,6,9–11].

Sampling was done by carving a 2 cm cube pedestal with a sharp knife, placing a clear plastic box over the pedestal, measuring its orientation, removing and sealing the box. A total of 878 horizons were sampled almost contiguously, on average every 3 cm. A few parts, e.g., the bottom of PZ1, were sampled more sparsely because of gypsum layers that obstruct sampling. At several horizons we collected as many as 36 samples to test reproducibility and scatter at a single stratigraphic position.

Sample numbers indicate their elevation in the section.

Measurements of the magnetization vectors were done with a 2G cryogenic magnetometer at the Geophysical Institute of Israel. All the samples were treated by alternating field (AF) demagnetization in 5 to 10 mT steps up to 60 mT. Several samples were subjected to thermal demagnetization in quartz tubes in 50ºC steps up to 650ºC.

The characteristic direction of magnetization was defined by principal component analysis. The reference direction (the 'expected direction') is the geocentric axial dipole field (GAD) direction in the study area, $I = 51^{\circ}$ and $D = 0^{\circ}$.

2. Magnetic carriers in the Lisan sediments

2.1. Rock-magnetic tests

Natural remanent magnetization (NRM) intensities are commonly of the order of 10^{-2} A/m. Between 80% and 95% of the NRM is typically removed by AF demagnetization of 50 mT or 70 mT. The mean destructive field is between 15 and 30 mT (Fig. 2).

2.1.1. Electron microscope analyses

Electron microprobe and scanning electron microscope (SEM) analyses show that the composition of the magnetic extract is best described by almost a complete spectrum of Fe–Ti oxides with widely varying grain size. These range from several μm up to several tens of μm. Composition of grains smaller than 1 μm could not be determined.

2.1.2. Hysteresis properties

Hysteresis behavior and rock-magnetic properties were measured on a MicroMag™ apparatus at the Institute for Rock Magnetism, Minnesota. Measurements were done on twelve samples of detrital laminae, one sample of the magnetic fraction extracted from a detrital lamina, and five samples of residual material after extracting magnetic material. Hysteresis parameters of material from aragonite lamina were measured also. Fig. 3 shows a comparison of the Lisan hysteresis with the results reported by Day et al. [12]. Hysteresis parameters from detrital material are ferromagnetic while the aragonite is almost purely diamagnetic. This suggests that the NRM of the Lisan resides entirely in the detrital laminae. The H_c, H_{cr} and M_{rs}/M_s values of the magnetic extract and the bulk detrital material from which they were derived are indistinguishable (mean $M_{rs}/M_s =$ 0.14 and 0.13, respectively). The residue that contains less magnetic material and of smaller grain size has a mean M_{rs}/M_s of 0.22. We interpret the hysteresis parameters to indicate that the grain size of the Lisan magnetic grains are pseudo-single-domain (PSD) while some multidomain (MD) and probably some superparamagnetic (SPM) grains are also present (Fig. 3). Saturation of isothermal remanent magnetization (SIRM) of the residue is reached at about 300 mT.

2.1.3. Anisotropy of anhysteretic remanent magnetization (ARM)

Nine samples were subjected to ARM using a DC bias field of 0.1 mT and peak AF of 50 mT. ARM for a test sample was imparted over three different AF windows: 0–10 mT, 10–20 mT and 20–30 mT; the results were identical for each of these windows, and thus the remaining experiments were done on the 10–20 mT window only.

The results show clear evidence of ARM anisotropy, with minimum ARM perpendicular to layering, i.e., along the vertical (Z) axis. In most cases the ARM along the horizontal directions (X, Y) were quite similar and significantly larger than that along the Z direction. The degree of anisotropy ranges from a minimum of 3% to a maximum of 18%. These results suggest that ARM anisotropy is real and may be due to a depositional fabric and/or possibly compaction.

In conclusion, the AF experiments and the SEM and microprobe data confirm that the magnetic material in the Lisan is a magnetic phase of the titanomagnetite series. The AF coercivity, the unblocking temperature spectra, and the saturation of IRM at 300 mT also suggest titanomagnetite composition predominantly of PSD grain size with some MD and SPM grains. The magnetic material is detrital in origin and thus the NRM is most likely a depositional or post-depositional. No evidence for chemical remanent magnetization was found. The sources of the magnetic particles are probably Precambrian igneous

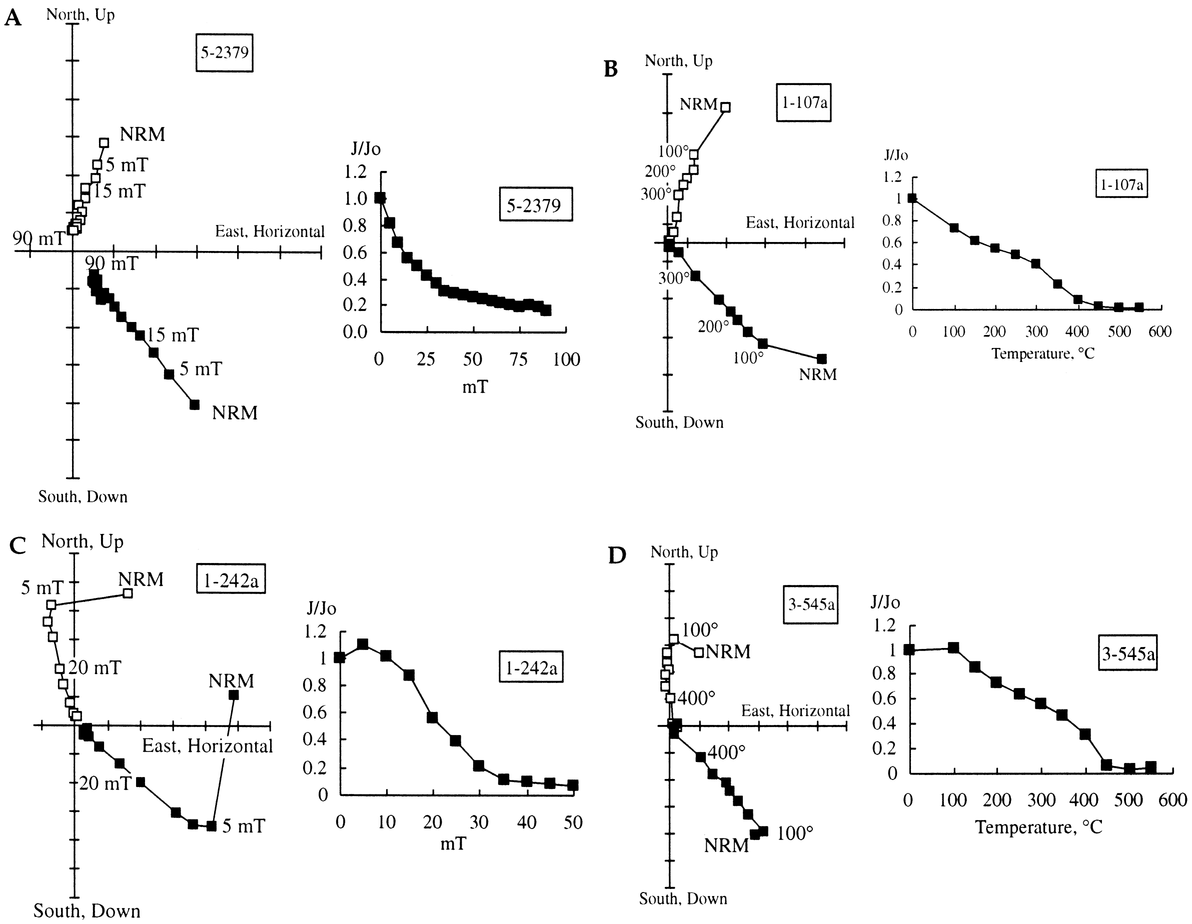

Fig. 2. Examples of demagnetization procedure. Demagnetization procedure is illustrated by normalized magnetic intensity J/J_0 as a function of the demagnetizing alternating field. Vector plots show projections onto horizontal planes (open symbols) and vertical planes (solid symbols). (A) Vector directions showing stable behavior. Removal of 85% of the NRM occurs at about 75 mT. The directions are stable even at low J/J_0 values. (B) Results of a thermal demagnetization experiment. Vectors showing stable behavior and complete removal of the NRM at 500ºC. (C) A soft overprint (probably VRM) is removed by AF of 5 mT. Stronger AF of about 40 mT removes about 90% of the NRM. (D) A soft overprint is removed upon heating to 100ºC. Higher temperatures of about 450ºC remove the NRM almost entirely.

and metamorphic rocks, and late Tertiary basalts exposed in the Lisan catchment.

3. Field tests

3.1. Horizontal and vertical variations

To understand how the NRM varies in space and in time we compared the scatter of fifteen horizontally and seventeen vertically sampled sites. At each site twelve samples were collected along about 0.5 m. Samples from a single horizontal level average about 23 years, and therefore record the same paleomagnetic direction. Scatter is probably introduced during sampling, handling, and variability of the recording process. Twelve specimens sampled as close as possible vertically span about 300 years. Significant changes in field direction during this time due to SV are expected to increase the overall scatter between samples in addition to the non-field uncertainties.

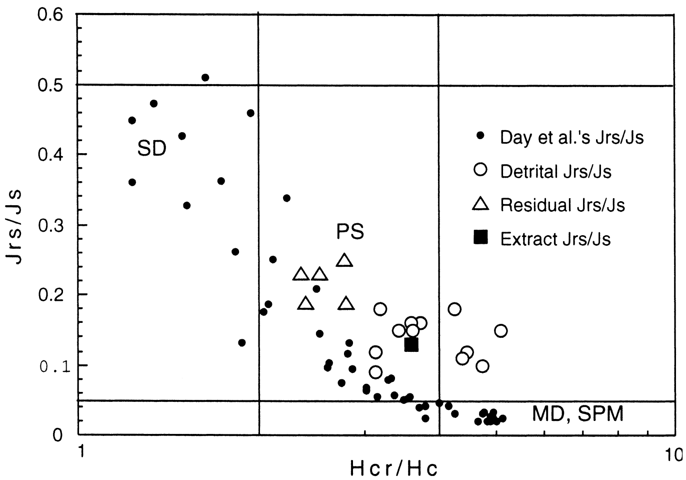

Fig. 3. The Lisan hysteresis parameters compared with Day et al.'s [12] data (solid circles). J_{rs} = saturation remanence, J_s = saturation magnetization, H_c = coercivity and H_{cr} = coercivity of remanence. Open triangles refer to the residual material that remained after extracting the magnetic grains (solid boxes) from the detrital material (open circles). The presence of single-domain (*SD*) and pseudo-single-domain (*PSD*) grains in the residue suggests that the separation process was somewhat selective.

The results (Table 1) show that the directions are more scattered in the vertically sampled sites. It is clear from the precision parameters ($\kappa = 269 \pm 150$) and angular standard deviations ($\theta_{63} = 6 \pm 2°$) that the horizontal sites are comparable to that of rapidly cooled Holocene basalt flows from Hawaii [13]. In contrast, $\kappa = 69 \pm 65$ and $\theta_{63} = 12 \pm 4°$ in the vertically sampled sites indicate larger dispersion that probably reflect SV [14].

3.2. Secular variation (SV)

The directional data (Fig. 4) appear to contain three variations. The first is rapid directional fluctuation, shifting up to several tens of degrees from sample to sample. The second is a more gradual directional change of 30°–50° within several tens of centimeters to several meters. The third type is a general trend in inclination becoming shallower with increasing age. The Fisher mean direction of 878 horizons is $D = 005°$, $I = 45°$, $\alpha_{95} = 1°$, $\kappa = 22$ (Fig. 5).

To examine the reproducibility, we collected a duplicate set of samples from 1045 to 1250 cm, a section that shows a distinct eastward deviation of declination. The second set was collected at the same site and reproduces the behavior of the first set (Fig. 4).

4. Lock-in depth

A series of tests was performed to investigate the temporal relations between the magnetization and syn-depositional deformations in the Lisan.

4.1. Syn-sedimentary slump test

Intraformational folded layers of various dimensions are common throughout the Lisan Formation (Fig. 6A). The folded layers that extend laterally over several centimeters to tens of meters formed by subaqueous slumping. The original thickness of the folded layers varies from a few millimeters up to a few tens of centimeters, the thickest being 80 cm.

The in-situ magnetic directions from these folds invariably cluster around the expected direction but rotating the laminae back to horizontal deflects the vectors from the expected direction (Fig. 6B). The ratio of the precision parameters is 6/226 indicating that the magnetization postdates the slumping [15]. Additional suites of samples were collected from different levels in two slumped layers; layer A is 80 cm and layer B is 50 cm thick. The in-situ directions are all very close (<20°) to the expected whereas correction for the tilt shifts the directions up to 90° from the expected, regardless of the stratigraphic position (Fig. 6C).

Table 1
A comparison between horizontally and vertically sampled sites

Elevation (cm)	*N*	*D* (°)	*I* (°)	κ	α_{95} (°)	θ_{63} (°)
Horizontally sampled:						
40	12	355	51	178	3	6
82	12	355	51	511	2	4
95	12	353	41	233	3	5
95	12	358	50	469	2	4
95	12	0	51	351	2	4
117	12	357	52	298	2	5
192	12	349	50	535	2	4
252	12	359	48	348	2	4
305	12	357	53	219	3	5
1247	12	355	43	216	3	6
1707	12	3	37	73	5	9
1944	12	1	38	315	2	5
1957	12	4	43	68	5	10
2142	12	4	41	48	6	12
3547	12	0	44	181	3	6
Arithmetic average:	*N = 15*			*269*	*3*	*6*
Std. deviation:	*N = 15*			*150*	*1*	*2*
Fisher average:	*N = 15*	*358*	*46*	*172*	*3*	*6*
Vertically sampled:						
2– 28	12	358	38	51	6	11
26– 48	12	360	44	39	6	13
41– 75	12	347	40	16	10	20
77– 100	12	349	21	77	5	9
101– 132	12	351	25	39	7	13
123– 156	12	348	28	34	7	14
239– 274	12	353	28	299	2	5
290– 347	12	353	26	125	4	7
503– 535	12	350	55	66	5	10
635– 661	12	1	37	35	7	14
1240–1280	12	8	36	40	6	13
1605–1765	12	9	48	49	6	12
1930–1951	12	12	45	25	8	16
1955–1975	12	1	41	65	5	10
2129–2156	12	6	53	72	5	10
2585–2615	12	11	70	64	5	10
2703–2730	12	7	59	29	8	15
Arithmetic average:	*N = 17*			*66*	*6*	*12*
Std. deviation:	*N = 17*			*65*	*2*	*4*
Fisher average:	*N = 17*	*358*	*41*	*31*	*6*	*15*

Each site includes twelve samples taken continuously from fifteen layers and seventeen vertical stretches along the columnar section. The horizontal sites represent about 23 years while the vertical sites span about 250–350 years. For each site we calculate mean declination, inclination, precision parameter (κ), 95% confidence limit (α_{95}), and angular standard deviation (θ_{63}). Arithmetic averages with standard deviations and Fisher means for each set are at the bottom.

These results clearly show that magnetization postdates folding. Moreover, these folds indicate that the upper layer of up to 80-cm-thick Lisan sediments (equivalent to ~930 years) had a high enough water content to undergo slumping. The magnetization was obviously locked-in later after the sediment consolidated. The 'mixed layer' test (below) also supports this interpretation.

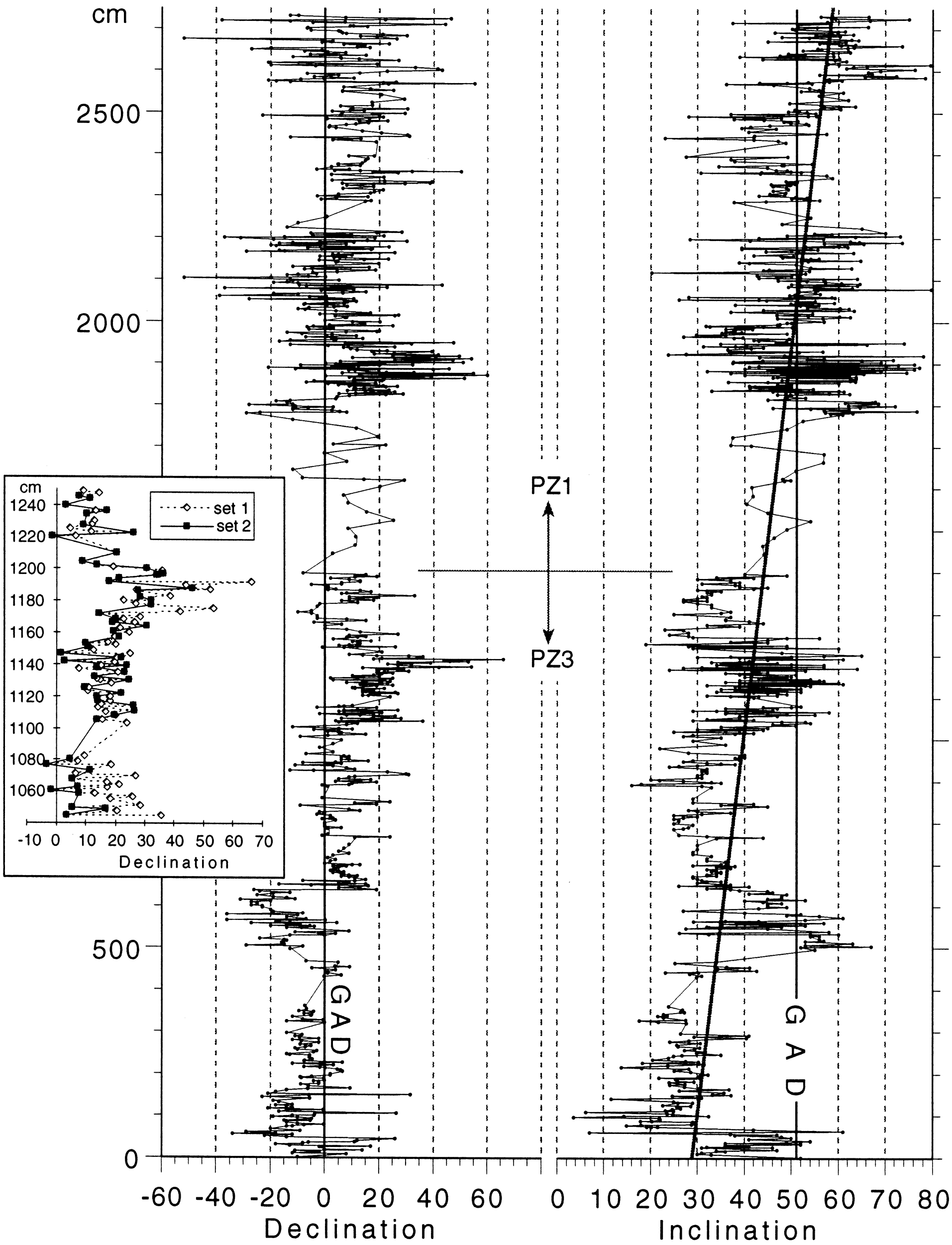

Fig. 4. Inclinations (right) and declinations (left) in sites PZ3 (up to 1400 cm) and PZ1 (1445–2730 cm). Each point represents one sample except for the twelve-sample horizons (listed in Table 1) that are represented by their Fisher means. The geocentric axial dipole (GAD) direction is represented by solid lines. A linear regression through all the inclinations shows a trend of upward increase, Inc. $= 29 + H$, where H is the height in meters ($R = 0.618$). U-series ages [9] are shown at right. Inset. Results of a reproducibility test. Two sampling sets show similar declination pattern. The magnitude of eastward deviation here is similar to excursions reported in other studies. The 30° declination anomaly is larger than the misfit between the two sets.

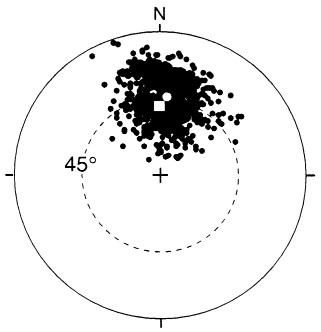

Fig. 5. An equal-area projection of all the measured directions (solid circles). Mean direction (open circle) is 45°/005°. Expected GAD (open box) is 51°/000°.

4.2. Mixed layer test

'Mixed layers' are layers that consist of mixtures of up to 50 cm of fragmented laminae, resembling a sedimentary breccia. Their formation has been attributed to earthquake shaking that disrupted the unconsolidated sediment at the bottom of the lake [2,3]. The mixed layers provide us with a natural redeposition experiment, for we can test whether the mixed layers record the field that prevailed immediately after the earthquake, or a later field (Fig. 7). The two cases differ in the preservation of the SV record prior to the earthquake. In the first scenario, this record is lost, while in the second scenario

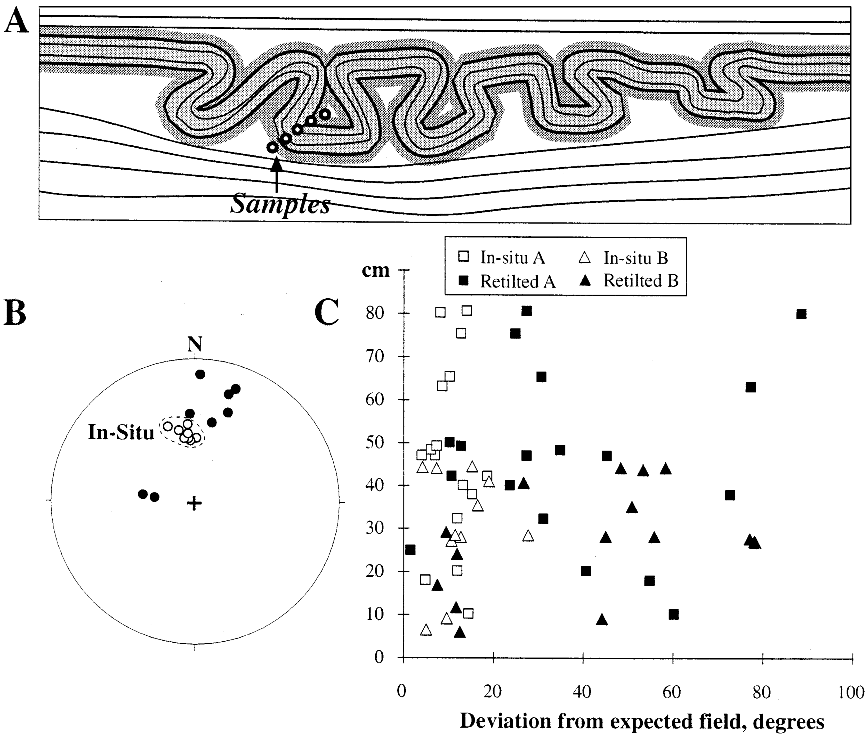

Fig. 6. A fold test in slumped layers (A) shows that magnetic directions in-situ are the same as the expected direction, which prevails in undisturbed layers. A schematic set of samples shows how folded layers were sampled from bottom to top. (B) A stereographic presentation of a fold test. The in-situ population (open symbols) is tightly clustered: $\kappa = 226$, $\alpha_{95} = 3.2°$. Tilt correction (solid symbols) offsets the vector away from the expected direction and increases dispersion with $\kappa = 6$, $\alpha_{95} = 22°$. (C) The angular distance between the expected direction of the magnetic field and the measured directions at various heights in layers A (boxes) and B (triangles). All the in-situ directions (open symbols) deviate by less than 20° from the expected and when the layers are rotated back to horizontal the directions depart up to 90° from the expected direction (solid symbols). The rotated directions are dispersed because the tilt correction is not uniform. The post-folding magnetization is observed in the 50-cm-thick layer B as well as the 80-cm-thick layer A, indicating that at these depths the magnetic particles can still realign with a new ambient field.

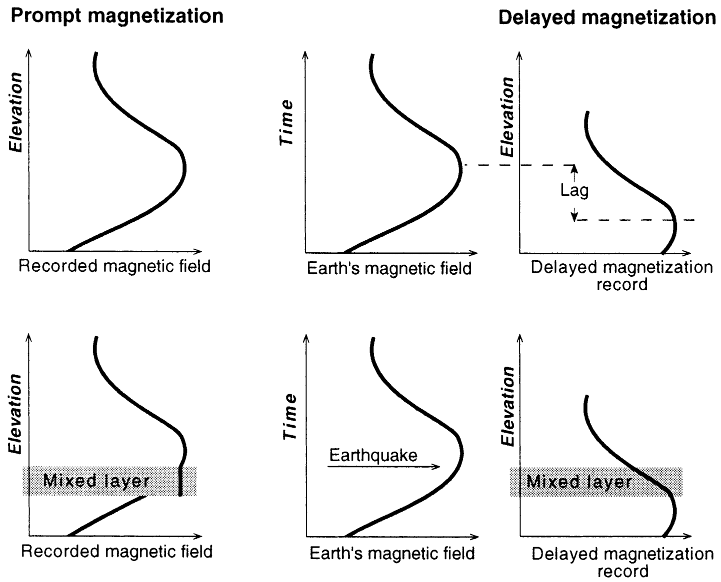

Fig. 7. Top. A schematic illustration of two scenarios of the Earth's magnetic field (center) recorded in sediments, prompt magnetization (top left) and delayed magnetization (top right). Bottom. An earthquake induces mixing of the uppermost sediment. A mixed layer (shaded) acquires new magnetization either uniformly if magnetization is acquired promptly (lower left), or variable if the acquisition of magnetization lags behind the Earth's field (lower right).

the mixed layers record SV of later time. We compared the dispersion of magnetic directions within two mixed layers with the scatter outside the mixed layer and with the dispersion within a single horizon in the mixed layer (Fig. 8). The directional variation in the mixed layers suggests that the magnetization lags behind sedimentation by an interval longer than the time equivalent to the thickness of the mixed layer (>400 years).

4.3. Intraclast test

Conglomerate tests are usually employed to examine the temporal relationship between the magnetization and the conglomerate layers. The soft Lisan sediments cannot form conglomerate, but we performed a similar test on a single cobble-size intraclast embedded in a mixed layer that abuts a syn-depositional fault. The vertical lamination in the clast indicates that it fell down the ~50 cm adjacent fault scarp into the mixed layer in the downthrown block (Fig. 9).

The in-situ remanent magnetization of the clast and of the layers that slumped down the fault scarp are similar to that of the mixed layer (Table 2). The clast was embedded in the mixed layer before its consolidation. It was sufficiently cohesive to survive the subaqueous transport down the fault scarp but its magnetization has been remodified becoming similar to that of the mixed layer.

Table 2
Mean magnetization directions of a mixed layer, an intraclast, and a fold adjacent to a fault (Fig. 9)

Site	N	D (°)	I (°)	α_{95}	κ
Mixed layer	4	351	41	6	173
Clast in-situ	5	346	55	8	76
Clast retilted	5	141	3	49	3
Fold in-situ	3	351	43	14	49
Fold retilted	3	322	−2	16	41

5. Discussion

5.1. Timing of magnetization

The magnetization of all the deformed elements (folded layers, mixed layers, and an intraclast in the mixed layer) was acquired after deformation. This

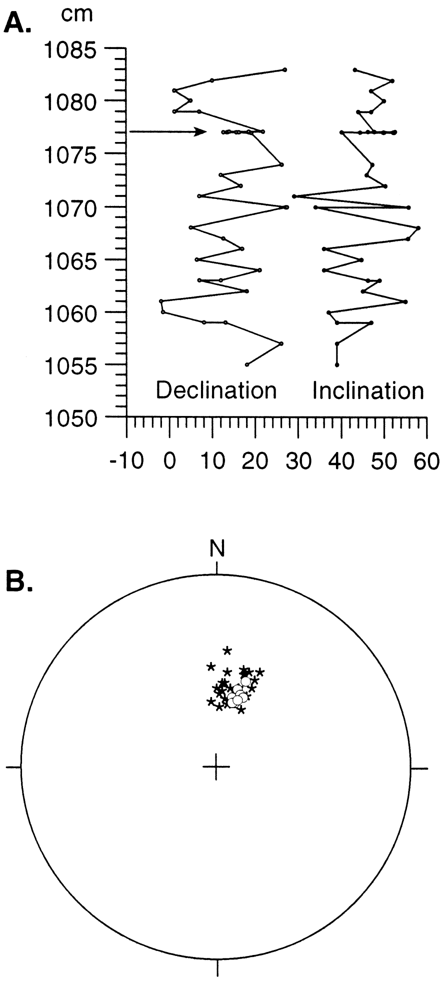

Fig. 8. A 'mixed layer test'. (A) Declinations and inclinations of samples in a 28-cm-thick mixed layer, from 1055 to 1083. Nine samples from level 1077 (arrow) cluster significantly tighter than the rest of the samples. (B) Equal-angle projection of the same points shows the small scatter of the horizontal set of samples (open circles) and the significantly larger scatter of the vertical set (stars).

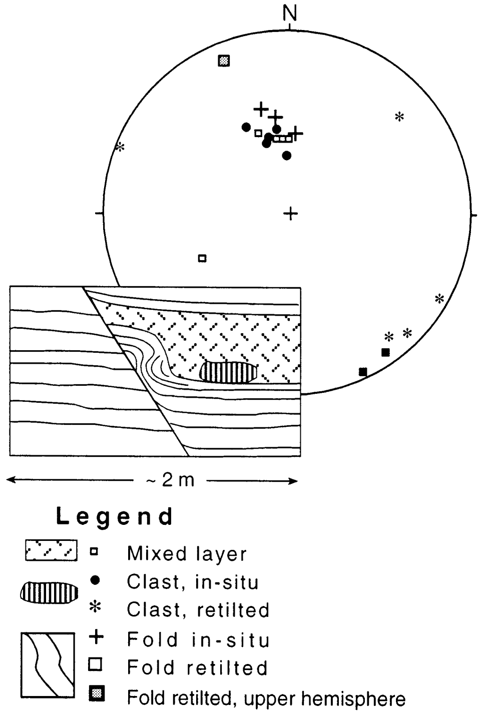

Fig. 9. An intraclast embedded in a mixed layer, and a slump abutting a fault show post-faulting magnetization. In-situ directions of the fold, the intraclast, and the mixed layer (except for one sample) are north trending with 40º–55º inclinations. Tilt-corrected directions are scattered (Table 2).

deformation is intraformational, and thus the magnetization does not postdate the entire Lisan Formation. The deformation features and the tests indicate that the Lisan sediments remained water-saturated for hundreds of years, enabling the magnetic particles to rotate in response to the magnetic torque; only after consolidation was the magnetization locked-in. The post-deformation magnetization acquired at the base of an 80-cm-thick layer indicates that the time between deposition and locking-in may be as long as 900 years. This estimate agrees with several other studies [14], although Tauxe [16] concluded that in quiet sedimentary environments, the realignment of magnetic particles due to a change in the geomagnetic field is negligible. Tauxe [16] argued that the magnetization is locked even before consolidation and it is only vulnerable to strong mechanical disturbances such as earthquakes, turbidity currents, etc. Estimates of the lock-in depth in pelagic sediments are between 30 cm [17] and only 3–4 cm [18]. In pelagic sediments (0.01–0.001 mm/year deposition rate) this depth range is equivalent to 300–9000 years. Okada and Niitsuma [19] measured 42 cm lock-in depths in siltstone of high deposition rate (1.8–3.7 mm/year). This depth is equivalent to 110–230 years. The estimated time of magnetization lock-in in the Lisan is within the range proposed by Hartl and Tauxe [18]. The detailed mechanism of

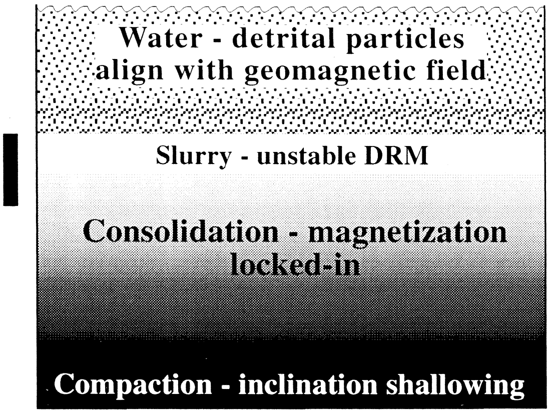

Fig. 10. A scheme of locking-in of the magnetization. The vertical bar represents the depths on the order of tens of cm that is equivalent to hundreds of years. Until locked, the magnetization is unstable as the particles can rotate and realign with a changing field direction. At larger depths of several meters compaction may cause inclination shallowing.

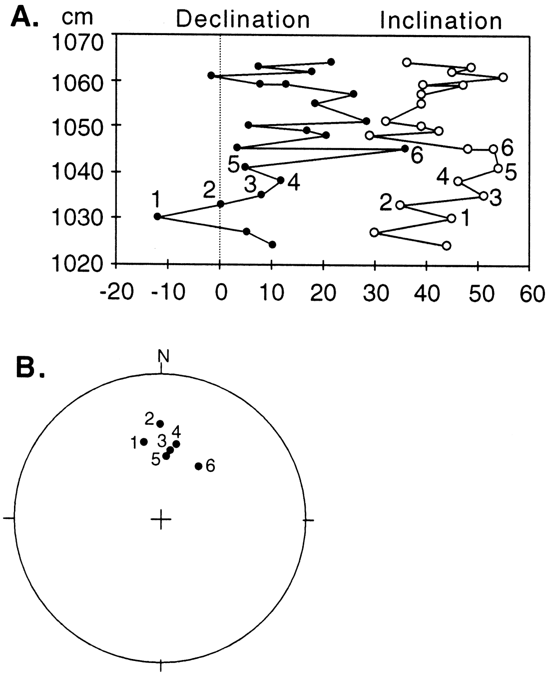

Fig. 11. (A) Examples of rapid fluctuations of the measured field. Declinations (solid circles) change gradually from 348° at 1030 cm (sample 1) to 12° at 1038 cm (sample 4) whereas the inclinations (open circles) zig-zag. The angular changes are 13° from sample 1 to sample 2, 17° from 2 to 3, 6° from 3 to 4, and 18° from 5 to 6. The total angular change from 1030 cm to 1045 (1 to 6) is 32°. Sedimentation rate of 0.86 mm/year yields an angular velocity of 0.25°/year from 1 to 6 but ~1°/year between intermediate points. (B) Equal-area projection of points 1–6.

locking-in and what controls the depth and time lag of magnetization are still open questions. Our data support the model shown in Fig. 10.

5.2. Secular variation

The SV curve shows three directional variations: high-frequency swings (10^1–10^2 years), low-frequency variation of the mean direction (10^3 years), and a trend of inclination steepening toward the top of the section (~1°/m). These variations rule out complete post-Lisan remagnetization. The horizon test (Table 1) shows that dispersion in a single horizon is very small, similar to that within lava flows. Similarly, the layers that were extensively sampled (twelve samples in the same 2 cm stratigraphic horizon) show significantly tighter clustering of magnetic directions than any vertical section. The variation is principally vertically (and time) dependent.

Interesting features of the field behavior emerge from the directional data. A few of the fast apparent changes are caused by a single sample that deviates markedly from the samples above and below it, but most of the directional swings span several samples and display serial correlation, suggesting that they record SV (Fig. 11). The rapid movement is probably the combined effect of true changes in the geomagnetic field and sampling, handling, and measurement processes. Assuming that the scatter within the horizontally sampled sites gives a measure of the non-field errors we estimate them at less than 6°. The small scatter of the directions within single horizons (Table 1) and the reproducible pattern (Fig. 4) are evidence that the high-frequency fluctuations mostly reflect the behavior of the field. We are not able to quantify the proportion of geomagnetic field and non-field contributions but apparently signals larger than 15°, as well as directional changes that span several samples are probably true geomagnetic SV. Similar observations led Valet et al. [20] to the same conclusions.

We estimated the rates of change in the present record by dividing the angle between successive directions by the time difference. The time difference is taken as the elevation difference between the two samples divided by an assumed constant sediment accumulation rate of 0.86 mm/year.

The fastest angular change is 4.6°/year with an average of 0.57° ± 0.57°/year. More rapid changes occur around 1 m, 6 m, 12 m, and 19 m. The changes above 20 m are more variable and distinct peaks are hard to define.

The high-frequency fluctuations observed appear in SV curves of other Quaternary sediments (e.g., [19,21–23]), from lava flows (e.g., [13,24]), and also from Cretaceous shales [20]. The directional swings of up to 40° change in a few decades are intriguing. Historical records suggest that such rapid changes are probably very rare [25]: angular change in the last 2 ka is of the order of 10^{-1}°/year. Measurements of the historical field show rates of change from 10^{-3} to 10^{-1}°/year. For example, the declination in England changed gradually from 11.5°E in 1576

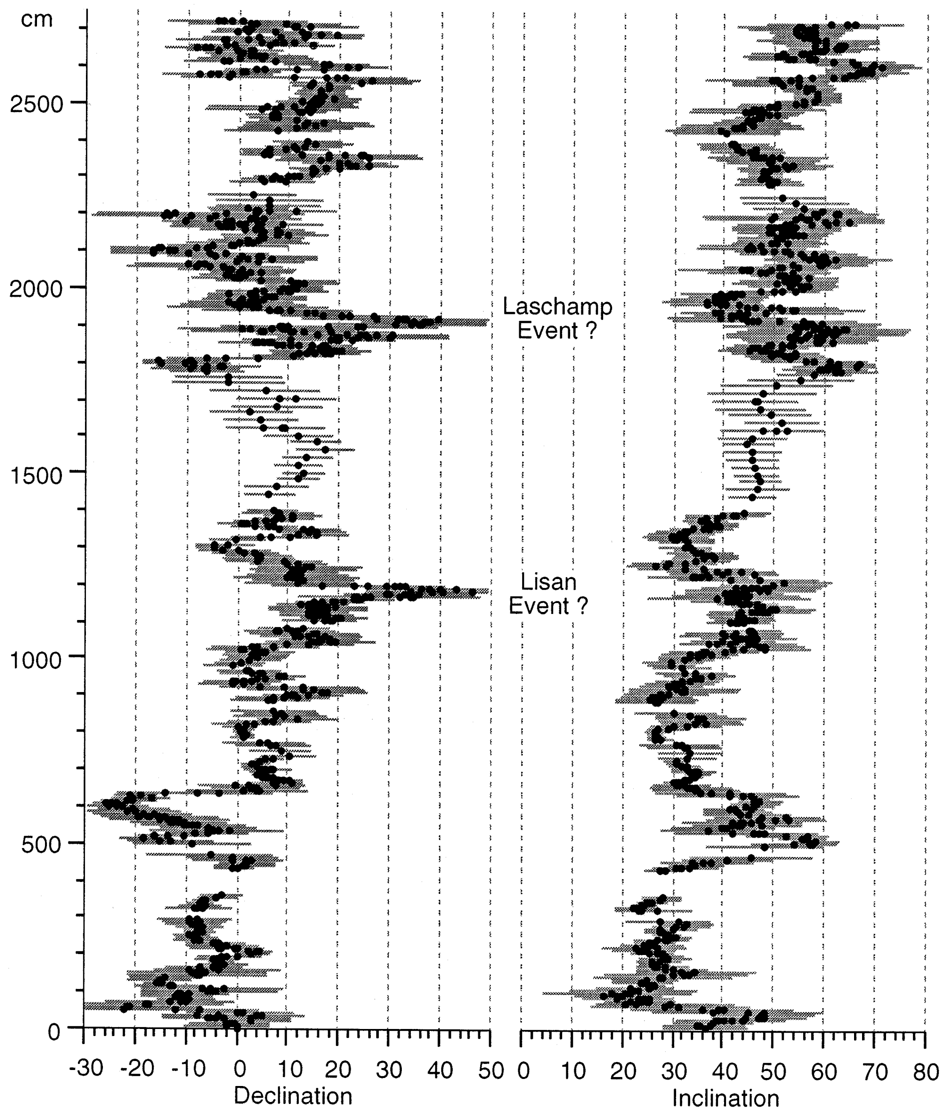

Fig. 12. The smoothed directions with corresponding α_{95} angles (gray bars). Each point in the smoothed curve is the Fisher mean of six consecutive samples. The averaged groups are moved by single-sample steps.

to 24ºW in 1823 [14]. The declination change in China between A.D. 850 and 1100 was 30º [25]. Suggestions for very rapid paleodirectional changes include a complete reversal within 38 years [19] and up to 6º daily change during a reversal [26,27]. If correct, extremely rapid changes are possible, but they are not as frequent as we have observed in the Lisan. The angular changes in the Lisan Formation are mostly within the range of the historical record, but episodes with high rates are more frequent than the common historical rates, and the peak rates in the Lisan are up to ten times faster than historical record.

In order to examine the effect of noise and outliers we smoothed the directional variation by a six-point Fisher mean (Fig. 12). Integrating the distribution of angular change rates calculated from the raw data (Fig. 13) shows that an angular change of less than 0.1°/year prevailed during 13% of the record and for 83% of the time the angular change is below 1°/year. The smoothing results in a maximum change rate of 0.66º/year and a mean rate of 0.10 ± 0.10º/year. During 68% of the time the change rate is below 0.1°/year.

There is no 'objective' procedure for choosing the 'correct' smoothing method but we believe that the prominent features of the smoothed curve reflect the behavior of the geomagnetic field.

5.3. Inclination shallowing

The inclinations in the Lisan Formation are significantly shallower than GAD in the lower part and become steeper upward. A linear regression (Fig. 4) shows an increase of 1°/m ($R = 0.62$). The trend may reflect progressive compaction that caused rotation of inclined elongated magnetic particles. This hypothesis should be tested independently.

5.4. Geomagnetic excursions

Merrill and McFadden [28] distinguish between 'reversal excursion' in which the virtual geomagnetic pole (VGP) departs by more than 90º from its time-averaged position for the epoch, and excursions in which the VGP deviates by more than 40º but less than 90º. They also emphasize the requirement for convincing data recorded at multiple sites.

Fig. 14 shows that several VGPs deviate more than 40º from the geographic north (i.e., they plot south of latitude 50º). These points cluster at ~12 m, where the declinations change gradually from north to northeast and then turn back to north and at ~19 m where directional changes are rapid, the

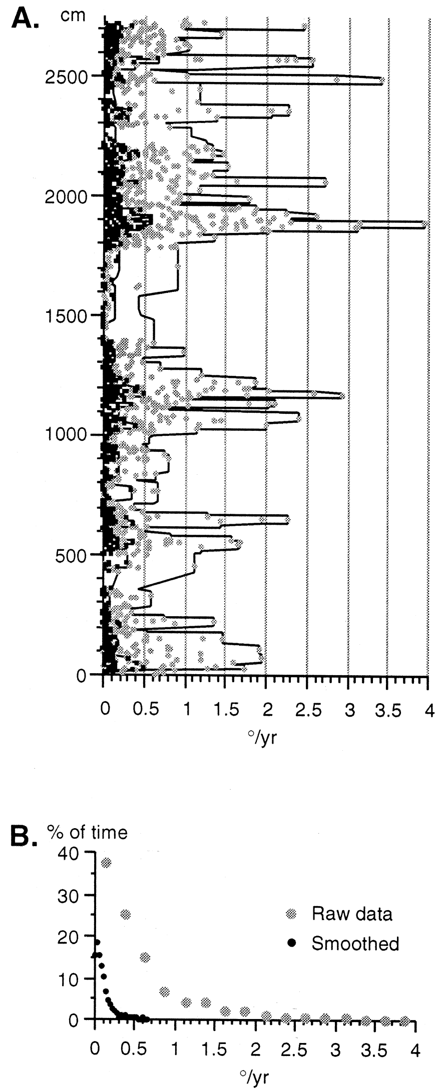

Fig. 13. Distributions of annual angle changes calculated from the raw Lisan data (gray symbols) and smoothed (solid symbols). (A) The angular change per year in the studied section showing clear peak values at 1 m, 6 m, 12 m, and 19 m. Above 20 m clear peaks are hard to define. Envelopes show persistence of general shape and levels of peaks. (B) The time fractions in which different angular change rates occurred.

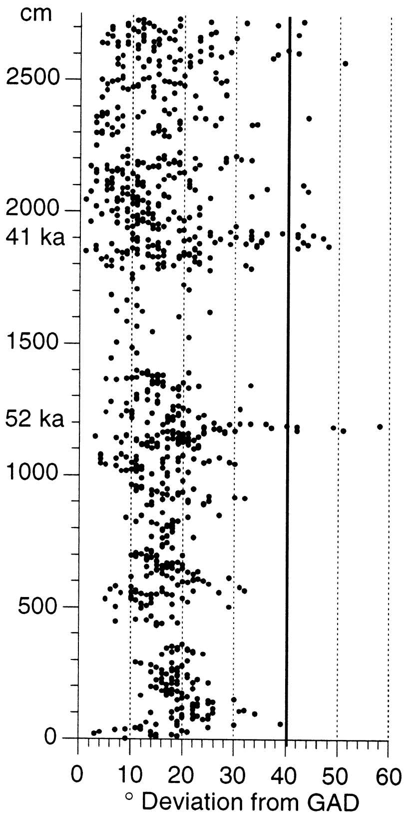

Fig. 14. Deviations of VGPs from the geocentric axial dipole (GAD). Deviations by more than 40° are conspicuous at 12 m and 19 m, corresponding to 52 ka and 41 ka, respectively [9].

declinations are 40°–60°, and the inclinations are over 70° (Fig. 4).

The paleomagnetic record at a single locality is not sufficient to verify a magnetic excursion. Sampling of additional comparative contemporaneous sections is required. The most widely accepted excursions are also characterized by geomagnetic intensity drop and we currently have no paleointensity data. Still, it is noteworthy that the U-series age at 19 m is 41 ka [9] which coincides with the timing of the Laschamp excursion event [24,29–31]. The duration of the event observed in the Lisan, ~18.5–19.5 ka, conforms with that suggested by other workers [32]. Moreover, the anomalous directions coincide with larger and faster direction changes, similar to Valet et al.'s observations of a significant increase of the fluctuations during a reversal [20]. We therefore suspect that the Laschamp is recorded at about 19 m in PZ1. The anomaly observed at ~12 m corresponds in time to 52 ka [9]. No geomagnetic event is known at this time elsewhere, save perhaps a 49–52 ka inclination anomaly in the Gulf of California interpreted as the Laschamp event [33]. We tentatively term it the *Lisan geomagnetic event*. Its existence may be confirmed by future studies.

6. Conclusions

(1) NRM in the Lisan Formation was acquired several hundreds of years after deposition, evident in post-deformation magnetization of a variety of syn-sedimentary features.

(2) The mean direction of the magnetic field is 45°/005° ($\alpha_{95} = 1°$; $\kappa = 22$) and the mean VGP is at 84°N, 171°E (dp = 1.7; dm = 1.3).

(3) Three types of secular variation are observed: high-frequency swings, low-frequency variation of the mean direction, and a trend of inclination steepening toward the top of the section.

(4) During 83% of our record the rate of change is less than 1°/year. Most of the directional change rates in the Lisan are comparable to the historical changes. The most rapid directional changes in the Lisan are significantly more frequent and up to ten times faster than those in the historical record.

(5) No reversed polarity is observed, but excursions may be recorded where the VGPs deviate by more than 40° from the geographic north. These occur at stratigraphic levels where U-series ages are about 52 ka and 41 ka. The latter may correlate with the Laschamp excursion but the 52 ka 'Lisan' declination event is not observed elsewhere. The verification of these events requires repetition in other sections.

Acknowledgements

This project is part of a large-scale research on the geology of the Lisan Formation conducted by Abraham Starinsky (A.S.), the Institute of Earth Sciences, the Hebrew University of Jerusalem. It was funded by the US–Israel Binational Science Foundation grant #9200346 to A.S., M.O.M., H.R., and

M.S. We are grateful to Amotz Agnon, Alexandra Schramm, and Steve Goldstein for constructive and fruitful discussions and help in fieldwork. Thanks to Ori Gonen and Revital Ken-Tor for assistance in operating the magnetometer and in fieldwork, and to Rami Weinberger, Yuval Bartov, Ofra Klein, Noya Shilony, Amir Sagy, and Malka Machlus, for help in the field. Reviews by Gillian Turner and Niels Abrahamsen are highly appreciated. ***[RV]***

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