The locking-in of remanence in upper Pleistocene sediments of Lake Lisan (palaeo Dead Sea)

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More than 1500 oriented samples were collected from an outcrop of the Lisan Formation ranging in age between 67 and 32 ka. The samples consist of alternating aragonite and detritus laminae deposited in Lake Lisan, the ancestor of the present Dead Sea. The mean sedimentation rate was calculated from U series ages as 0.86 mm/a (Schramm 1997), which indicates that each 2 cm thick sample provides a magnetic snapshot of about 23 years duration. Hence even short-lived geomagnetic events are potentially recorded in the Lisan Formation. Demagnetization experiments show that the natural remanent magnetization (NRM) is commonly very stable; 878 horizons yield a mean direction Dec. = 5°; Inc. = 45° ($\alpha_{95} = 1°$; $k = 22$). Stability tests were performed on layers that exhibit a variety of intraformational soft-sediment subaqueous deformations. The slumped layer tests show post-deformation acquisition of stable remanence (Fig. 1), as earlier reported by F. Addison (in Tarling (1983), p. 60) on far fewer samples. Other tests were done on 'mixed layers', i.e. layers up to 50 cm thick composed of mixtures of fragmented laminae resembling sedimentary breccia. Their formation has been attributed to earthquake shaking that disrupted the unconsolidated sediment at the bottom of the lake (Marco & Agnon 1995; Marco *et al.* 1996). The mixed layers provide a natural redeposition experiment for testing whether the mixed layers record the field that prevailed immediately after the earthquake, or a later field. The two cases differ in the preservation of the secular variation (SV) record before the earthquake. In the first scenario, this record was lost, whereas in the second scenario the mixed layers recorded SV of a later time. The dispersion of magnetic directions within mixed layers was compared with the scatter outside the mixed layer and with the dispersion within a single horizon within the mixed layer (Fig. 2). 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, i.e. >400 years.

Three modes of directional geomagnetic variation were observed in the stratigraphic sequences and, by inference, in time: (1) rapid directional fluctuations, shifting erratically up to several tens of degrees from sample to sample; (2) more gradual variation with directional changes of tens of degrees within several tens

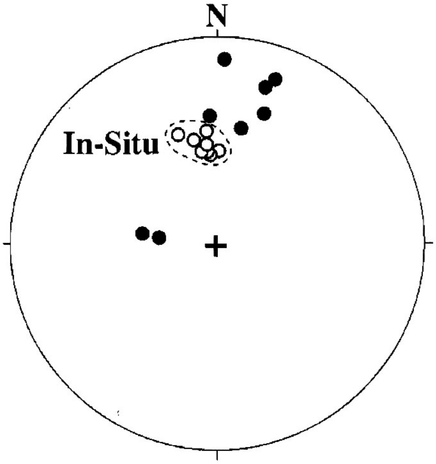

Fig. 1. A stereographic presentation of a fold test. The *in situ* population (○) is tightly clustered: $R = 0.996$, $k = 226$, $\alpha_{95} = 3.2°$. Tilt correction (●) offsets the vectors away from the expected direction and increases dispersion with $R = 0.863$, $K = 6$, $\alpha_{95} = 22°$.

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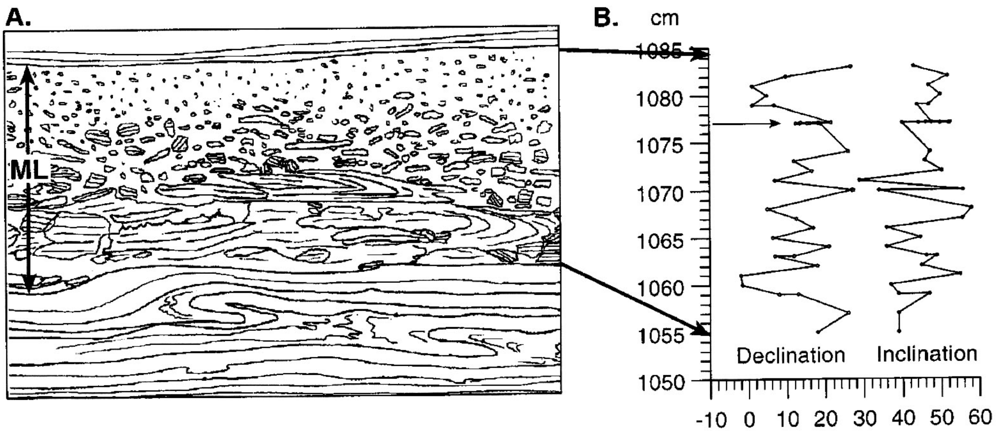

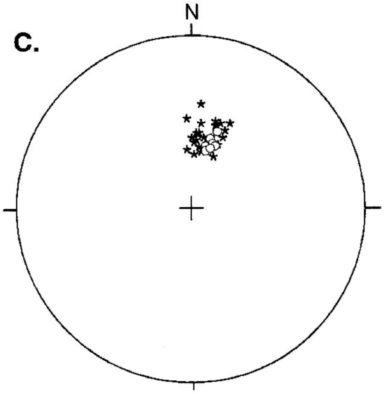

Fig. 2. A 'mixed layer' test. (**a**) A typical mixed layer (ML) shows a gradual upward transition from folded laminae, through fragment-supported texture, to matrix-supported texture at the top. Such mixed layers have been interpreted as earthquake deformations. The overlying undisturbed laminae are post-seismic (traced from a photograph). (**b**) Declinations and inclinations of samples in the 28 cm thick mixed layer, from 1055 to 1083 cm. Nine samples from level 1077 (arrow) that represent about 23 years cluster significantly tighter than the rest of the samples, which show SV. (**c**) Equal angle projection of the same points shows the small scatter of the horizontal set of samples (open symbols) and the significantly larger scatter of the vertical set (stars).

of centimetres to several metres; (3) a general trend in inclinations which became shallower with increasing age (Fig. 3). The rapid changes are particularly interesting because historical records suggest that such rapid changes of the geomagnetic field are probably rare. A few of the fastest apparent changes in the Lisan are caused by a single sample direction that deviates markedly from the samples above and below it, but most of the swings span several samples and are thus serially correlated, suggesting that they may record (SVs) of the geomagnetic field.

To understand how the NRM varies in space and in time, a comparison was made of the scatter of 15 horizontally and vertically sampled sites. At each site 12 samples were collected along a 1 m line. The small scatter in the horizontal sites corresponds to a precision parameter of $k = 269 \pm 150$ and angular standard deviation of $\alpha_{63} = 6 \pm 2°$, which are comparable with those of rapidly cooled Holocene basalt flows from Hawaii (McWilliams *et al.* 1982). In contrast, in the vertically sampled sites the precision and circular standard deviations are larger, $k = 69 \pm 65$ and $\alpha_{63} = 12 \pm 4°$, indicating that they probably reflect geomagnetic SV (Fig. 4). To examine the reproducibility, a duplicate set of samples was collected from a section between 1045 and 1250 cm where a distinct eastward deviation of declination had been observed. The second set, collected at the same site, reproduced the same general shape as the first set, with differences of the order of 15° (Fig. 5). The largest signal was of the order of 30°.

The rates of change in the Lisan record were estimated by dividing the angle between successive samples by the time difference (assuming constant sediment accumulation rate of 0.86 mm/a). The fastest angular change is 4.6°/a, with an average of 0.57° ± 0.57°/a. During 87% of the time the angular changes in the Lisan Formation are less than 1°/a, i.e. within the range of the historical record, but episodes with high rates are common and have peak rates of change up to ten times faster than in historical records. All the sources for scatter, except the

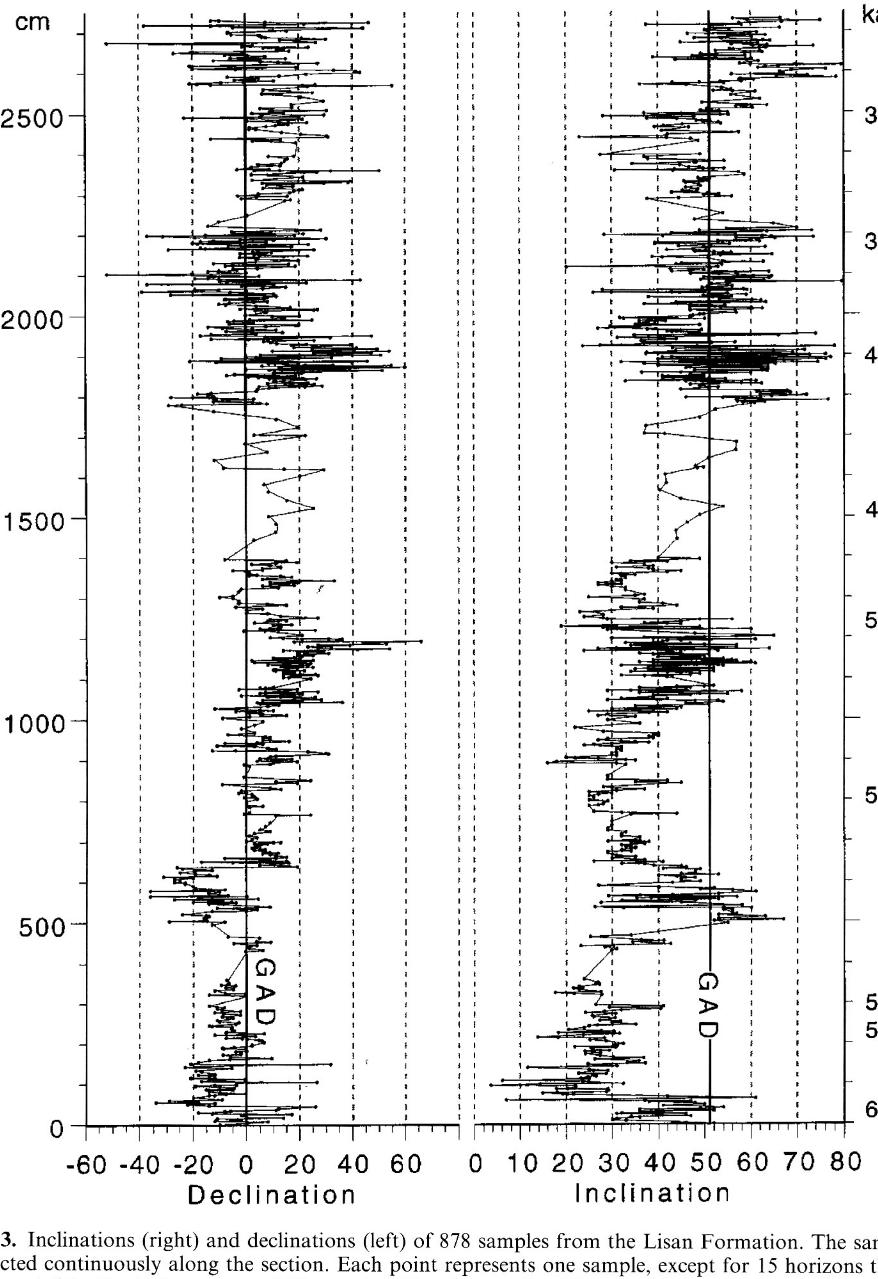

Fig. 3. Inclinations (right) and declinations (left) of 878 samples from the Lisan Formation. The samples were collected continuously along the section. Each point represents one sample, except for 15 horizons that are represented by the Fisher means of 12 samples. U-series ages by Schramm (1997) are shown at right.

geomagnetic field, probably cause random noise. The errors in sample orientation and measurement are estimated to total to less than 5°, and disturbance of the sample in the plastic boxes may also contribute up to 3 but such errors should characterize samples equally, whether they are from levels of slow or rapidly fluctuating directional change. It is considered that the small scatter of the directions within single horizons and the reproducible pattern (Fig. 5) are evidence that the high-frequency fluctuations mostly reflect the behaviour of the field, with only a small amount of scatter caused by geological processes and measurement errors.

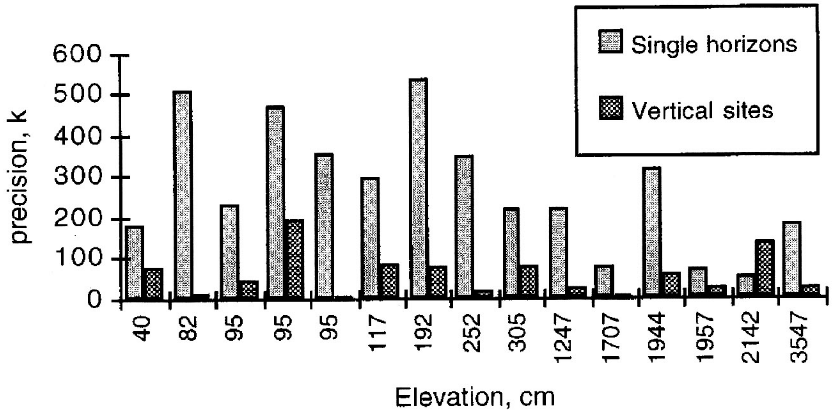

Fig. 4. Horizontal versus vertical dispersion. Precision parameters (k) of 12 sample sites show significantly larger dispersion where samples were collected vertically along 30–40 cm of the section than from single horizons.

To reduce noise, remove outliers, and emphasize the geomagnetic field behaviour, the SV curve has been smoothed. Each point in the smoothed curve is the Fisher mean of six consecutive samples. This window was then moved in single-sample steps (Fig. 6). Recalculating the angular change rate using the smoothed curve yielded a maximum of 0.66°/a with mean 0.10° ± 0.10°/a, and 68% of the time the apparent change rate is below 0.1°/a. Although there is no 'objective' procedure for choosing the 'correct' smoothing method it is felt that the prominent features of the smoothed curve reflect the behaviour of the geomagnetic field. No reversed NRMs were observed, but geomagnetic field excursions may be present where the virtual geomagnetic poles (VGPs) deviate by more than 40 from geographic North. Such events are observed at 12 m and 19 m (dated as 52 ka, and 41 ka, respectively); the latter may represent the Laschamp excursion event. No geomagnetic event is known at 52 ka time elsewhere, save perhaps a 49–52 ka inclination anomaly in the Gulf of California interpreted as the Laschamp event (Levi & Karlin 1989), so this is tentatively termed the Lisan geomagnetic event, although its existence needs to be confirmed by future studies.

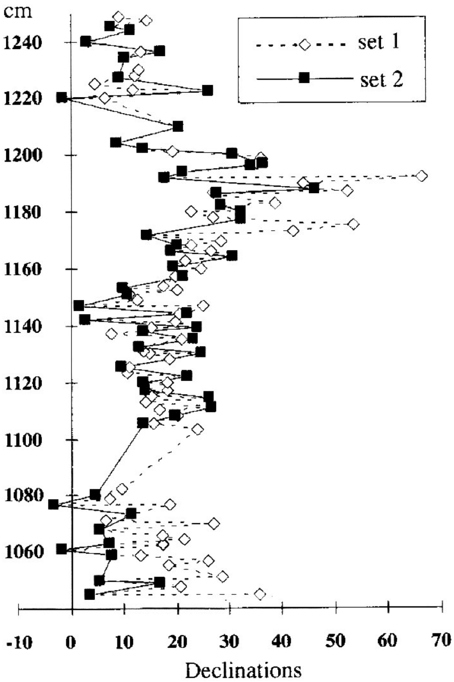

Fig. 5. A reproducibility test. Two sampling sets collected by different people from the same site to test reproducibility show similar declination pattern. The sampling noise is estimated at up to 15° but the signal is larger than 30°.

It is concluded that the characteristic remanent directions isolated in these samples are largely attributable to geomagnetic field variations. However, such remanent vectors can be traced systematically through both disturbed and undisturbed layers. The brecciated seismite layers have a sharp upper boundary with undisturbed overlying layers, but their lower boundaries are commonly gradational into the underlying undisturbed layers. Such seismic fluidization of the uppermost part of the sediment during earthquake activity provides a natural redeposition experiment. The magnetization in these disturbed layers clearly postdates the disturbance but is consistent within

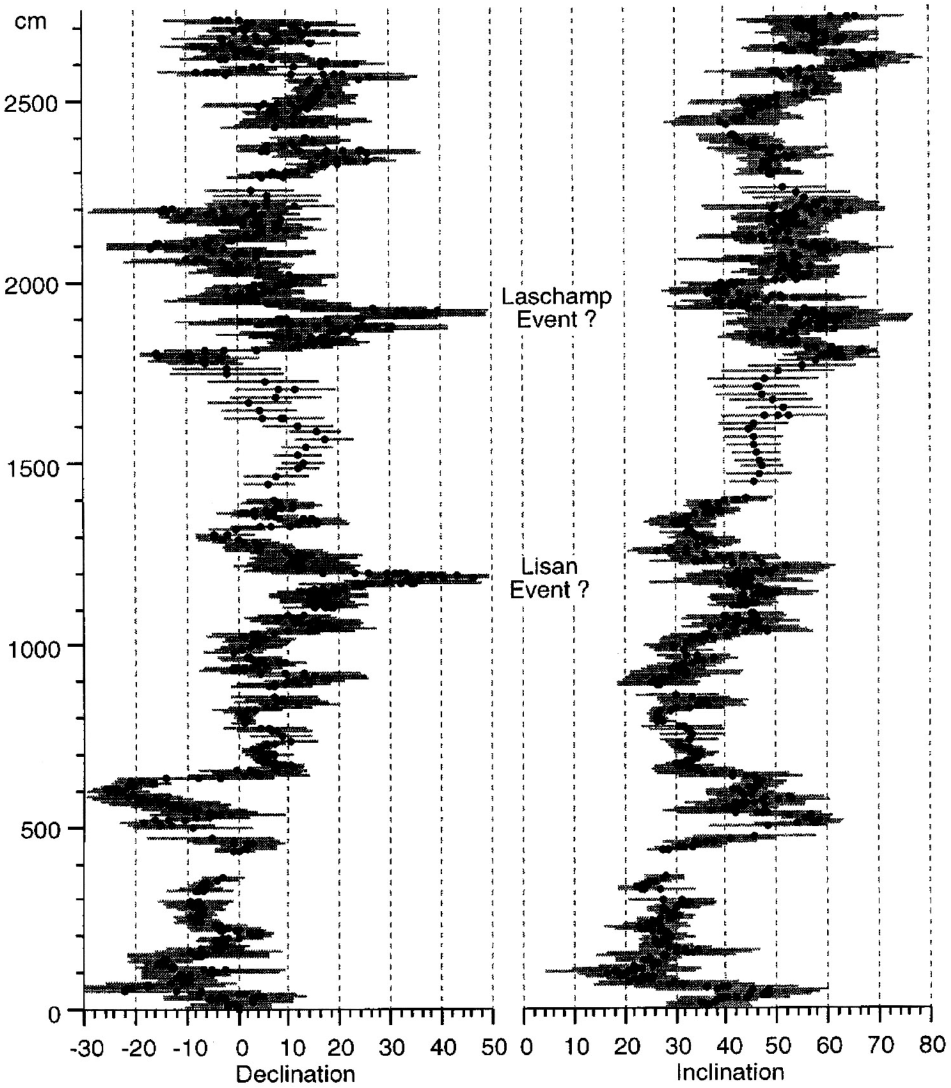

Fig. 6. The smoothed directions (filled symbols) with corresponding (α_{95} angles (grey). Each point in the smoothed curve is the Fisher mean of six consecutive samples. The averaged groups are moved by single sample steps. The declination deviation at 1900 cm was dated to 41 ka, the age of the Laschamp excursion event (Levi *et al.* 1990; Nowaczyk *et al.* 1994).

each layer and forms part of a regular pattern with the underlying layers. The Lisan Formation therefore provides evidence for the time scale of the locking-in of a remanence. Sediments down to a depth of about 1 m are dewatering and can be reset by SV changes, but below *c.* 1 m the increase in cohesivity means that they are no longer fluidized during the passage of seismic waves and are able to retain their directions of remanence. This means that the magnetic mineral orientations were locked at a depth corresponding to a few centuries after the original deposition, in agreement with several other estimates elsewhere (e.g. Butler 1992). However, such finds contrast with the conclusions of Tauxe (1993) that, in quiet sedimentary environments, any realignments of magnetic particles by change in the geomagnetic field were negligible, and such magnetizations locked in even before consolidation were vulnerable only to strong mechanical disturbances such as earthquakes, turbidity currents, etc. Estimates of the locking-in depth in pelagic sediments are between 30 cm (Kent & Schneider 1995) and 3–4 cm (Hartl & Tauxe 1996). In the low accumulation rates of the pelagic sediments (0.01–0.001 mm/a) this depth range is equivalent to 300–9000 years. The locking-in of magnetization in the Lisan Formation is within the time range proposed by Hartl & Tauxe (1996), but its depth is closer to that proposed by Kent & Schneider (1995). The detailed mechanism of locking-in and what controls the depth and time delay of magnetization are still open questions.

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References

BUTLER, R. F. 1992. *Paleomagnetism.* Blackwell Scientific, Oxford.

HARTL, P. & TAUXE, L. 1996. A precursor to the Matuyama/Brunhes transition field instability as recorded in pelagic sediments. *Earth and Planetary Science Letters*, **138**, 121–135.

KENT, D. V., & SCHNEIDER, D. A. 1995. Correlation of paleointensity records in the Brunhes/Matuyama polarity transition interval. *Earth Planetary Science Letters*, **129**, 135–144.

LEVI, S. & KARLIN, R. 1989. A sixty thousand year paleomagnetic record from Gulf of California sediments: secular variation, late Quaternary excursions and geomagnetic implications. *Earth and Planetary Science Letters*, **92**, 219–233.

——, AUDUNSSON, H., DUNCAN, R. A., KRISTJANSSON, L., CILLOT, P. Y. & JAKOBSSON, S. P. 1990. Late Pleistocene geomagnetic excursion in Icelandic lavas: confirmation of the Laschamp excursion. *Earth and Planetary Science Letters*, **96**, 443–457.

MARCO, S. & AGNON, A. 1995. Prehistoric earthquake deformations near Masada, Dead Sea graben. *Geology*, **23**, 695–698.

——, STEIN, M., AGNON, A. & RON, H. 1996. Long term earthquake clustering: a 50,000 year paleoseismic record in the Dead Sea Graben. *Journal of Geophysical Research*, **101**, 6179–6192.

MCWILLIAMS, M. O., HOLCOMB, R. T. & CHAMPION, D. E. 1982. Geomagnetic secular variation from ^{14}C-dated lava flows on Hawaii and the question of the Pacific non-dipole low. *Philosophical Transactions of the Royal Society of London, Series A*, **306**, 211–222.

NOWACZYK, N. R., FREDERICHS, T. W., EISENHAUER, A. & GARD, G. 1994. Magnetostratigraphic data from late Quaternary sediments from the Yermak Plateau, Arctic Ocean: evidence for four geomagnetic polarity events within the last 170 ka of the Brunhes Chron. *Geophysical Journal International*, **117**, 453–471.

SCHRAMM, A. 1997. *Uranium series and C14 dating of Lake Lisan (paleo Dead Sea) sediments: implications for C14 time-scale calibration and relation to global paleoclimate (PhD thesis)*, Göttingen University, Germany.

TARLING, D. H. 1983. *Palaeomagnetism, Principles and Applications in Geology, Geophysics and Archaeology*. Chapman and Hall, London.

TAUXE, L. 1993. Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice. *Reviews of Geophysics*, **31**, 319–354.