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Magnetic properties of Lake Lisan and Holocene Dead Sea sediments and the fidelity of chemical and detrital remanent magnetization

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ABSTRACT

We have studied the magnetic properties of wet and dry late Pleistocene Lake Lisan sediments and the Holocene Dead Sea sediments. Our initial prediction was that the properties of both would be quite similar, because they have similar source and lake conditions, unless diagenetic change had occurred. Rock magnetic and paleomagnetic experiments revealed three stages of magnetization acquisition. Our findings suggest two magnetic carriers in the Holocene Dead Sea and wet Lisan sediments: titanomagnetite and greigite. The titanomagnetite grains are detrital and carry a detrital remanent magnetization (DRM), whereas the greigite is diagenetic in origin and carries a chemical remanent magnetization (CRM) that dominates the total natural remanent magnetization (NRM) of Holocene Dead Sea and wet Lisan sediments. The magnetization of dry Lisan sediments is a DRM and resides in multidomain (MD) grains. We propose that magnetic properties of the Lisan Formation and Holocene Dead Sea sediments can be explained by a model that incorporates dissolution, precipitation, and alteration of magnetic carriers. At the time of deposition, titanomagnetite grains of varying size were deposited in Lake Lisan and the Holocene Dead Sea, recording the geomagnetic field via a primary DRM. Sedimentation was followed by partial or complete dissolution of titanomagnetite in anoxic lake bottom conditions. As the kinetics of dissolution depends upon surface area, the single-domain (SD) grains dissolved faster, leaving only the larger pseudo-single domain (PSD) and MD grains. Titanomagnetite dissolution occurred simultaneously with precipitation of greigite in anoxic, sulfate-reducing conditions probably related to bacterial degradation of organic matter. This

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process added a secondary CRM that overwhelmed the DRM and the primary geomagnetic record. Later, when the level of Lake Lisan dropped, these sediments were exposed to air. At this time, the greigite was oxidized, removing the CRM from the system and leaving only the original detrital PSD and MD titanomagnetite grains as the dominant DRM carriers. Presently, wet Lisan sediments have not been completely altered and therefore contain secondary greigite preserved by the original formation water that carries a secondary CRM. Thus, the magnetization in the Holocene Dead Sea and the wet Lisan magnetic record cannot be considered as an accurate, reliable geomagnetic record, while magnetization of dry Lisan sediments is a primary DRM.

Keywords: magnetite, greigite, rock magnetism, Dead Sea, early diagenesis, Lake Lisan.

INTRODUCTION

Lacustrine sequences are frequently used to study geomagnetic field variations because they are rapidly deposited and are relatively easy to date (e.g., Kawai et al., 1975; King et al., 1983; Thouveny et al., 1993; Tauxe, 1993; Creer and Morris, 1996; Peck et al., 1996; Williams et al., 1998; Brachfeld and Banerjee, 2000, to name only few). There is growing evidence that the magnetic recording process in lake sediments is strongly influenced by environmental conditions in the catchment area and in the depositional basin. Important among these conditions are variations in grain size and postdepositional diagenetic processes (Nowaczyk et al., 2001, and references therein). The former affects the fidelity of the sediments as a recorder of relative paleointensity, while the latter also affects the fidelity of sediments as a recorder of ancient field direction.

We report a study that demonstrates (1) how detrital remanent magnetization (DRM) can be affected by diagenetic processes that occur in the lake bottom environment, adding a chemical remanent magnetization (CRM); and (2) how magnetic minerals carrying this CRM were later altered upon aerial exposure, producing directional and intensity artifacts in the measured record.

SEDIMENTATION IN LAKE LISAN AND THE HOLOCENE DEAD SEA

Dry Lake Lisan Sediment

Widely exposed in the Dead Sea region, the Lisan Formation was deposited in Lake Lisan, a less saline precursor to the modern Dead Sea (Fig. 1). We studied the Lisan Formation in the southern part of the Dead Sea graben, where it is comprised mainly of alternating laminae of white aragonite and dark detritus together with occasional thick layers of clastic sediment and gypsum. Aragonite was chemically precipitated at the upper surface of Lake Lisan, whereas detritus (calcite, dolomite, aragonite, quartz, and clay) was introduced by annual winter flooding (Begin et al., 1974). The detritus was derived from the lake's drainage system as direct and redeposited wind-blown loess material.

Aragonite in the Lisan Formation is superbly preserved because of the extremely dry conditions of the Dead Sea region and because interstitial chloride salts inherited from the original lake were retained, preventing its transformation to calcite (Katz and Kolodny, 1989; Stein et al., 1997). Lake Lisan was too saline to support bottom burrowers, leaving the original sedimentary structures intact in very fine detail.

The Lisan Formation was deposited between ca. 70 ka and 14 ka based on dating of aragonite laminae by ^{14}C and U-Th dating (Kaufman, 1971; Kaufman et al., 1992; Schramm et al., 2000; Bartov et al., 2002). The average sedimentation rate is 0.86 ± 0.02 mm/yr. During most of its existence, Lake Lisan was stratified (Katz et al., 1977; Stein et al., 1997). Under these conditions, the lower brines were separated from the upper, less saline waters, allowing reducing conditions to prevail in the lower part of the lake and at the sediment-water interface.

Holocene Dead Sea Sediments

After shrinkage of Lake Lisan at 17–13 ka, the lake stabilized at an elevation of ~–400 m (Frumkin et al., 1991; Neev and Emery, 1995; Enzel et al., 2000, 2003, Bookman et al., 2004). The Holocene Dead Sea sequence records the sedimentological, limnological, and tectonic history of the lake during the Holocene (Ken-Tor et al., 2001; Yechieli et al., 1993; Enzel et al., 2000). Holocene Dead Sea sediments are exposed along the periphery of the Dead Sea and were recovered in boreholes along the western shore of the lake (Migowski et al., 2004). The Holocene Dead Sea consists of lacustrine to fluvial sediments that reflect lake-level fluctuations in the arid Dead Sea environment. Holocene deposits are ~20–30 m thick on the western shore of the lake's northern basin (Enzel et al., 2000; Migowski et al., 2004; Yechieli et al., 1993), and ~80 m thick in the southern basin (Neev and Emery 1995).

Like the Lisan Formation, the Holocene Dead Sea sequence is comprised of alternating aragonite and detrital lamina (~1–2 mm thick) but also contains thicker (>10 cm) clastic layers. The aragonite precipitated chemically from the water column as described previously for the Lisan Formation. The detrital layers are clay and silt derived from the lake's catchment area and redeposited wind-blown material representing flood input during rainy seasons. The

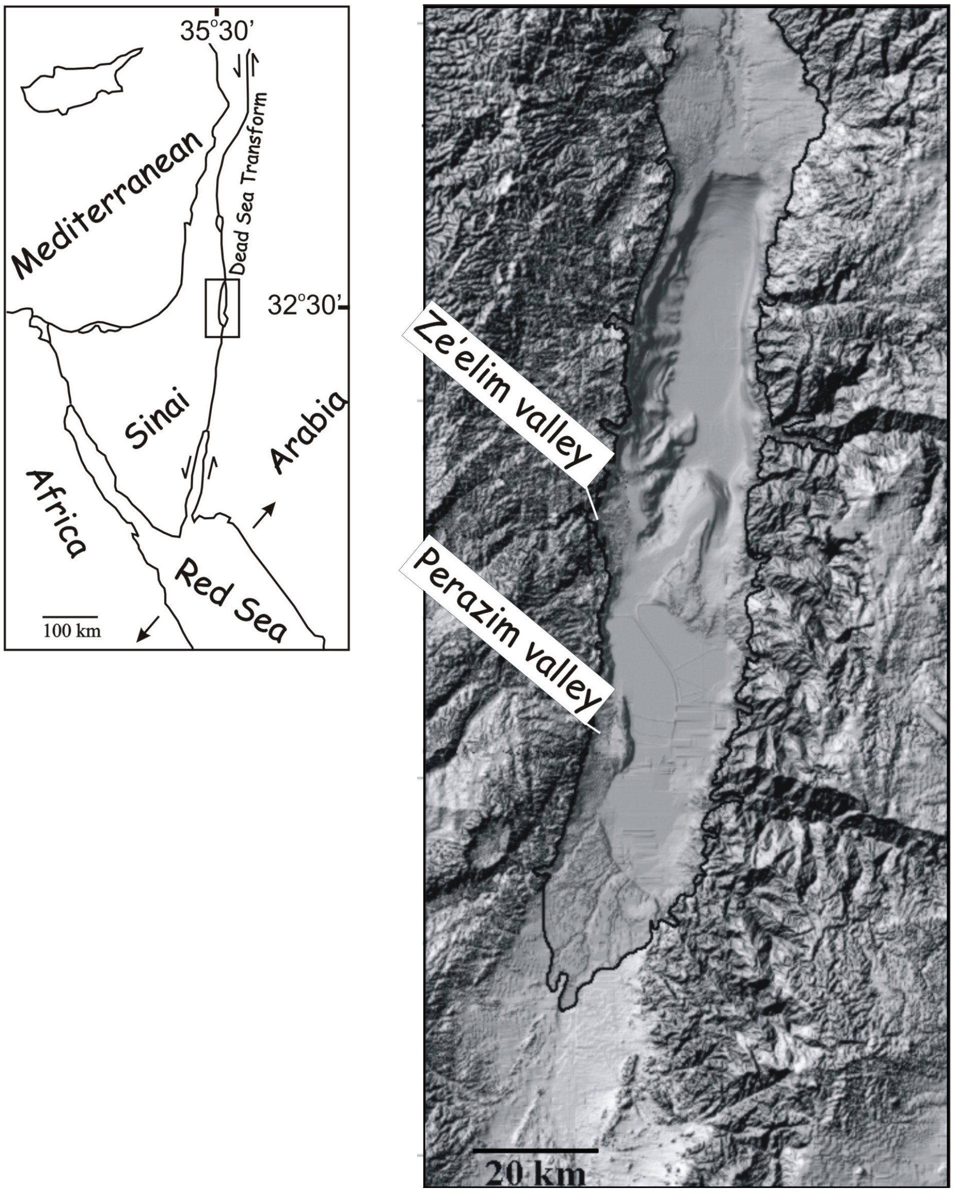

Figure 1. Location map of Lake Lisan and Dead Sea basins (after Bartov et al., 2002). Black line delineates the highest stand of Lake Lisan at −165m.

section is punctuated by unconformities representing periods of low lake level and erosion. As with the Lisan Formation, the lake in which the Holocene Dead Sea sediments were deposited was stratified, with upper, fresher waters separated from lower, more saline waters. Reducing conditions prevailed in the lower part of the lake and at the sediment-water interface.

A chronology of Holocene Dead Sea sedimentation was established by Ken-Tor et al. (2001) and Migowski et al. (2004) using radiocarbon methods on organic debris within the detrital layers. Sedimentation rates range from 3 to 13 mm/yr. In much of the section, the sedimentation rate is significantly faster than the average rate for the late Pleistocene Lisan Formation. These higher rates probably reflect the proximity of these sections to the fan-delta.

Paleomagnetism of the Lisan Formation

The Lisan sediments were deposited rapidly and essentially continuously, and they are superbly preserved, precisely dated, and probably annually laminated. Together, these qualities make Lisan sediments an almost ideal candidate for a high-resolution study of the history of the geomagnetic field, qualities that motivated Marco et al. (1998) to study the rock magnetic properties and the geomagnetic paleosecular variation (PSV) of the Lisan Formation. Their main findings were as follows:

- A weak (10^{-6} emu) remanent magnetization resides in the detrital layers;
- The aragonite layers are diamagnetic;

- Titanomagnetite is the magnetic carrier in the detrital layers. The magnetization is probably a DRM and may be adequate to record the geomagnetic field;
- The hysteresis parameters indicate that the titanomagnetite grains are of pseudo-single domain (PSD) and multidomain (MD) size. No single-domain (SD) grains were identified (Figure 3 in Marco et al., 1998).
- The measured PSV record contains evidence for the Laschamp geomagnetic excursion at 41 ka (Figures 12 and 14 in Marco et al., 1998).

Two findings of the Marco et al. (1998) study are puzzling because (a) the hysteresis parameters indicate the presence of PSD and MD grains only. However, the nature and sources of the Lisan detritus component suggests that SD grains should be part of the grain size spectra because its origin is redeposited wind blown loess material; and (b) relative paleointensity record could not be obtained from the Lisan sediment, probably due to the lack of SD grains. Thus, the Laschamp geomagnetic excursion was identified by the directional record only. Our (H. Ron and M. McWilliams) further attempts to obtain a relative paleointensity record from the Lisan Formation failed as well.

To resolve these ambiguities, we conducted a rock magnetic study that compared the Lisan Formation with the Holocene Dead Sea sediments. Our study began with four assumptions. First, we assumed that the detrital source was the same or very similar for both Lisan and Holocene Dead Sea sediments. Second, we assumed that the lake conditions that could influence magnetization were similar (e.g., stratified water bodies, hypersaline conditions with reducing conditions at the lake bottom). Third, we assumed that the sedimentary environment was similar for both deposits. Finally, we relaxed our original assumption of "superb preservation" and allowed the possibility that chemical alteration may have occurred in the Lisan sediments and that this alteration may have affected the ferromagnetic minerals.

With these caveats, our initial prediction would be that the rock magnetic properties of the Lisan Formation and of the Holocene Dead Sea would be quite similar, unless diagenetic change had occurred. This is not what we found. In the sections that follow, we show how DRM may be affected by lacustrine chemistry to produce a CRM that dominates the magnetization. We next illustrate how the CRM carriers were altered during and after subaerial exposure, eliminating smaller grains and leaving behind only the larger grains that carry PSD and MD magnetizations. The existence of these processes in very young Late Pleistocene and Holocene lake deposits illustrates the importance of rock magnetic experiments to the interpretation of paleomagnetic data in terms of actual geomagnetic field behavior.

PROCEDURES

Sampling

The Lisan Formation was sampled in Perazim Canyon at localities PZ1 and PZ3 (Fig. 1 and section 1.2 in Marco et al., 1998). We collected samples from the lower part of the exposed sequence where the sediments are wet (the lower ~4–5 m in PZ1 and PZ3 [the number in the sample name is the elevation in cm above the base]), as well as from higher up in the sequence where the samples are dry. The sampling rationale was based on the idea that if the dry sediments had been affected by chemical alteration due to air exposure, then the wet sediment might have been affected less by this process. If so, this might imply that wet sediment contains formation water that tends to preserve the original magnetic particles.

The Holocene Dead Sea sediments were sampled at Ze'elim Gorge. For detailed field descriptions and chronology, see Figure 1 and the columnar section Figure 2 in Ken-Tor et al. (2001). Here, we collected oriented samples for paleomagnetic measurement and large blocks from which detritus and aragonite laminae were separated for rock magnetic experiments. Oriented samples were collected as 2 cm plastic cubes and in 2.5-cm-diameter quartz glass cylinders. After collection in the field, the samples were sealed in plastic and chilled to retard alteration. The samples were collected from the ~50–100 cm level and 200–300 cm level of Ze'elim gorge (see Figure 2 in Ken-Tor et al., 2001).

Paleomagnetic Experiments

Our paleomagnetic experiments were designed to compare the magnetic properties of three types of sediments (wet Lisan, dry Lisan, and Holocene Dead Sea) using alternating field (AF) and thermal demagnetization. We measured natural remnant magnetization (NRM) intensity, decay of NRM as a function of peak alternating field and/or temperature, median destructive field (MDF) observed during AF demagnetization, and Curie temperature (T_c).

Measurements of NRM were done using 2G cryogenic magnetometers with integrated AF coils at the Hebrew University and GeoForschungZentrum Potsdam (GFZ) paleomagnetic laboratories. Paired samples of wet Lisan and Holocene Dead Sea sediments were demagnetized by AF and thermal methods in a stepwise fashion. AF demagnetization of wet Lisan sediments reached a peak field of 60 mT or 80 mT in 5mT steps, and AF of Holocene Dead Sea sediment reached a peak field of 120 mT in 10 mT steps. Thermal demagnetization was done in a shielded ASC TD-48 furnace with temperatures ranging from room temperature up to 600 °C in 50 °C steps. The AF data for dry Lisan sediments were taken from Marco et al. (1998).

RESULTS

AF Demagnetization of Dry and Wet Lisan versus Holocene Dead Sea Sediments

Figure 2 shows normalized intensity plots (J/J_o versus AF peak field) from AF demagnetization experiments of 20 arbitrarily selected dry Lisan samples, 20 samples of wet Lisan sediment, and 8 samples of Holocene Dead Sea sediments. The three sediment types yield surprisingly different results. The Lisan decay curves are concave and retain their magnetization in low field values, while the Holocene Dead Sea decay curves are slightly convex and retain magnetization in a much higher field and gradually increased above an ~80mT peak alternating field.

The average NRM moment for dry Lisan sediment is $5.0*10^{-3}$ A/m (n = 26), for wet Lisan sediment the average NRM moment is $3.2 * 10^{-2}$ A/m (n = 24), whereas the same value for Holocene Dead Sea sediment is 1.2 A/m (n = 30). The MDF for dry Lisan is 13 mT (n = 26), wet Lisan is 18 mT (n = 24), and Holocene Dead Sea is 38 mT (n = 30).

These results imply that remanence carriers in the Lisan and Holocene Dead Sea are significantly different. Likely explanations for the difference include a different magnetic mineralogy and/or a change in grain size of the magnetic carrier. The wet and dry Lisan groups also differ in initial intensity of NRM and MDF, suggesting some difference in remanence carrier.

Thermal versus AF Demagnetization of Wet Lisan Sediment

Figure 3A shows the results of AF and thermal demagnetization of two samples of wet Lisan sediment. The AF experiments show a smooth decrease in intensity and what appears to be a single magnetization. At 30 mT, 90% of the NRM is removed; the MDF is ~20 mT. The mean NRM intensity of 24 wet Lisan samples is $3.2 * 10^{-2}$ A/m, almost an order of magnitude larger than dry Lisan. Thermal demagnetization produces a 20%–30% intensity drop after heating to 100–200 °C, followed by a similar intensity drop after heating to 150–350 °C, and a final drop after heating to 400–550 °C, when the magnetization reaches ~1% of the initial NRM value. The vector plots of Figure 3B show a two-component vector corresponding to the first low-temperature steps. The first component does not head toward the origin, whereas the second one (~150 °C to 400 °C) is stable and heads toward the origin; it is similar to the direction seen by the AF. No stable direction of magnetization is observed above ~400 °C.

These results suggest that the mineral that carries the stable magnetization has a T_c of 350–400 °C. While the presence of a higher T_c mineral is possible, it is too small to be resolved on the standard thermal demagnetization vector diagram, yet it can be seen on the normalized intensity plot. If so, the AF experiment cannot resolve between the two due to significant overlap of coercivity spectra.

Thermal and AF Demagnetization of Holocene Dead Sea Sediment

Figure 4 shows results of AF and thermal demagnetization of representative samples of Holocene Dead Sea sediment. AF demagnetization of sample 2A produces a 95% intensity drop in ~90 mT, associated with a single magnetization whose MDF is ~45 mT. Demagnetization above 90 mT produces a gradual intensity increase and erratic directional behavior. Thermal

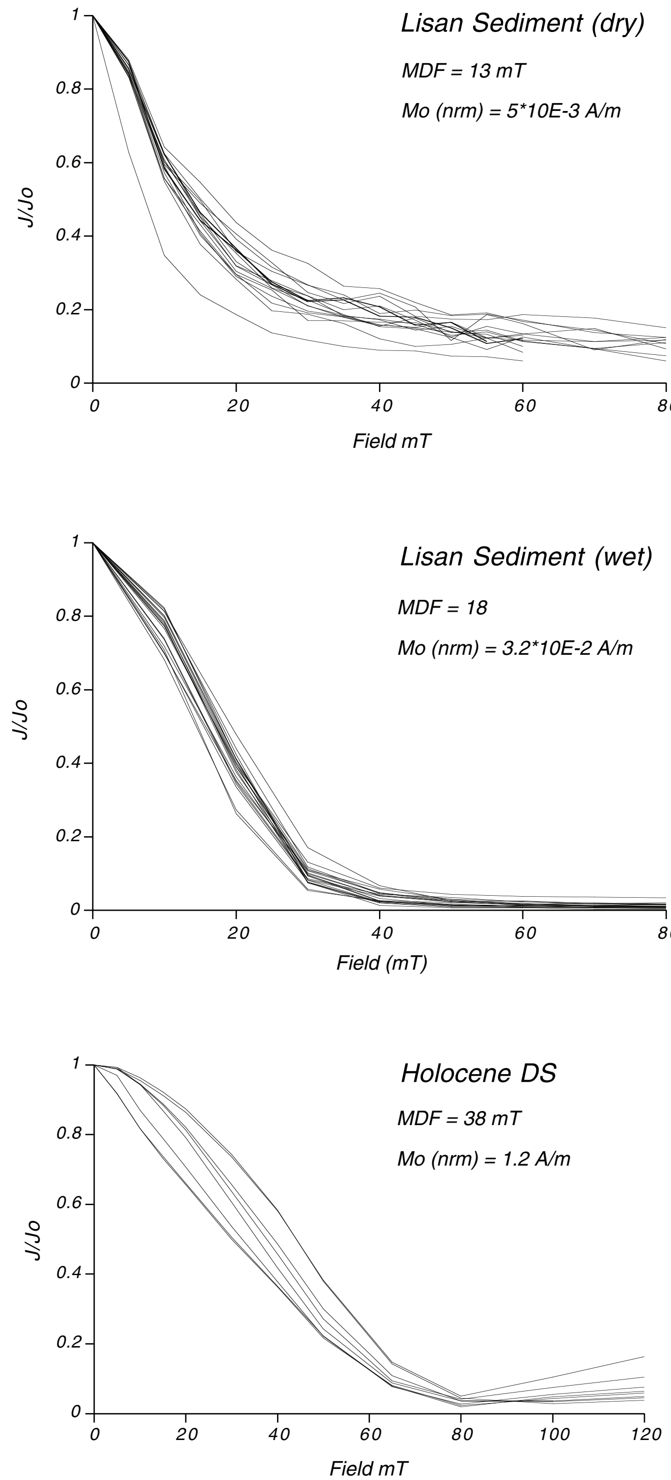

Figure 2. Normalized intensity (J/J_0 versus field in mT) plots of alternating field demagnetization experiments of arbitrarily selected 20 dry Lisan samples (top), 20 wet Lisan samples, and 8 samples of Holocene Dead Sea sediments (bottom). MDF—median destructive field.

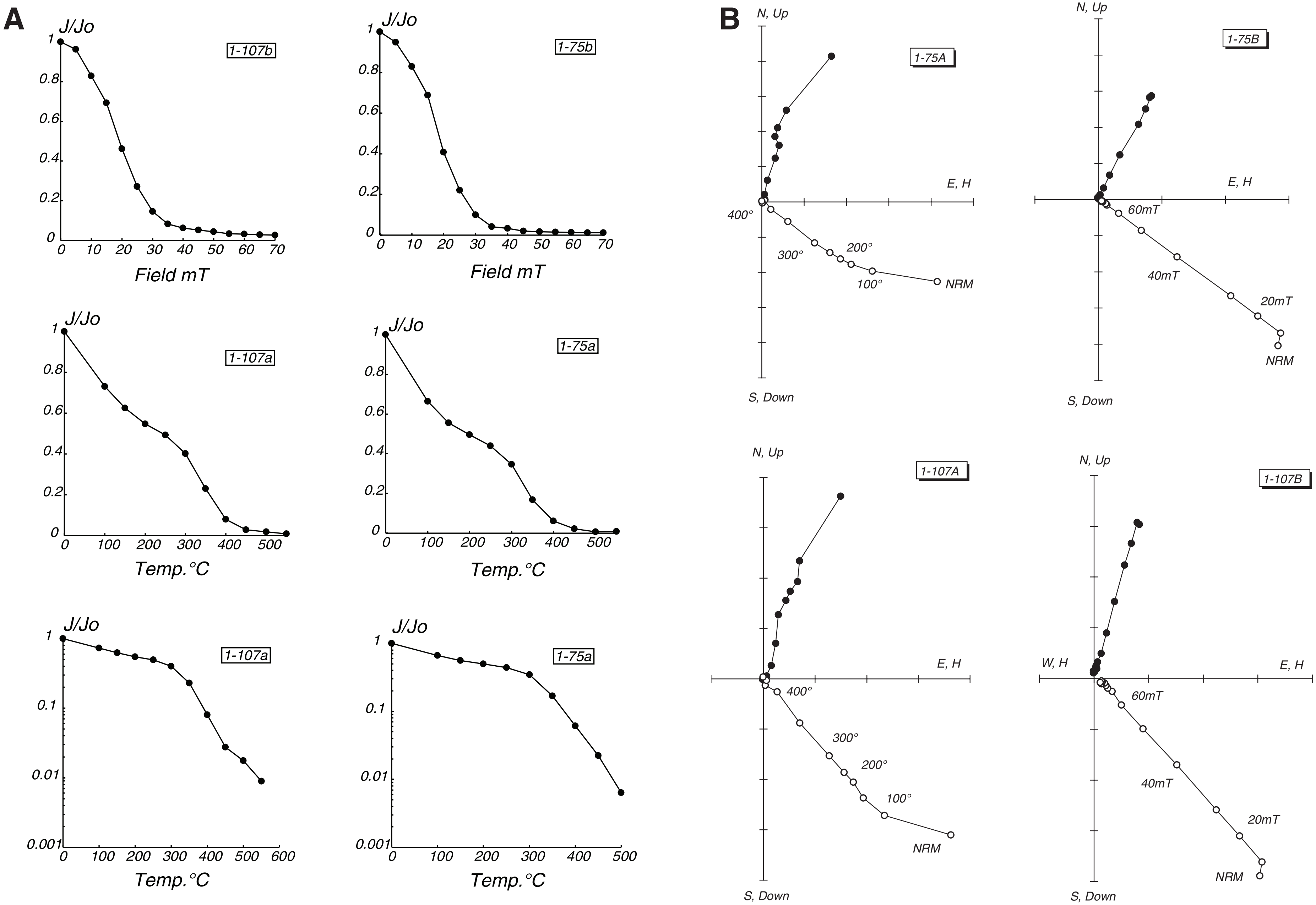

Figure 3. Results of alternating field (AF) and thermal demagnetization of two wet Lisan samples. (A) Normalized intensity (J/J_0) plots of AF and thermal demagnetization experiments. (B) End point vector plots. Solid symbols denote the declination and plotted on horizontal (H) planes; open symbols denote the inclination plotted on an east-west oriented vertical plane. NRM—natural remanent magnetization.

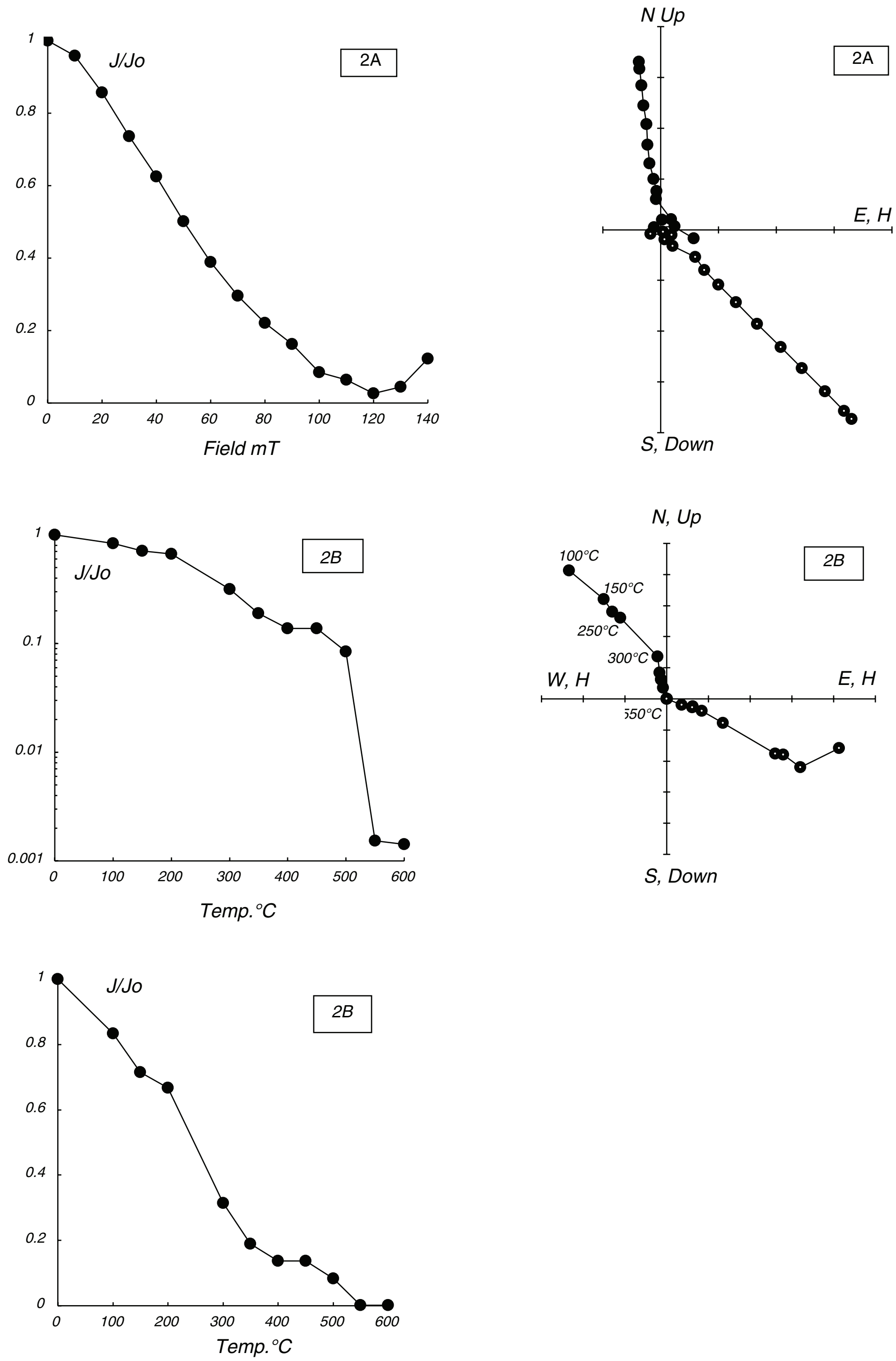

Figure 4. Results of alternating field and thermal demagnetization of two samples of Holocene Dead Sea sediment. Left plots are the normalized intensity (J/J_0) plots, and right plots show the end point vector plots. Solid symbols denote the declination and are plotted on horizontal planes; open symbols denote the inclination, plotted on the east-west–oriented vertical plane.

demagnetization of sample 2B (taken from the same stratigraphic level as 2A) shows a two-component magnetization. One is carried by a mineral with a T_c of ~350 °C and a second with a T_c of ~550 °C. The first carries up to ~90% of the total NRM. The AF experiment suggests that both are ferromagnetic cubic phase minerals whose coercivity spectra have a considerable overlap.

ROCK MAGNETIC EXPERIMENTS

Hysteresis of Dry Lisan (Previous Data)

Hysteresis properties of dry Lisan sediments were measured (by Ron and McWilliams; see Marco et al., 1998) on a MicroMag™ apparatus at the Institute of Rock Magnetism. Measurements were done on samples of detrital laminae, aragonite laminae, a "magnetic" fraction extracted from one detrital layer, and the "nonmagnetic" residuum produced during this extraction. Figure 5 compares the hysteresis parameters from these components. The detritus is ferromagnetic, while the aragonite is almost purely diamagnetic. This suggests that the NRM of the dry Lisan sediments resides mostly in the detrital laminae. The hysteresis parameters of the "magnetic" extract and the residuum are essentially indistinguishable; the residuum appears to contain less magnetic material per unit mass and is of somewhat smaller grain size. The hysteresis parameters indicate that the grain size of the dry material is PSD and MD. No single domain fraction was isolated in the dry sediment.

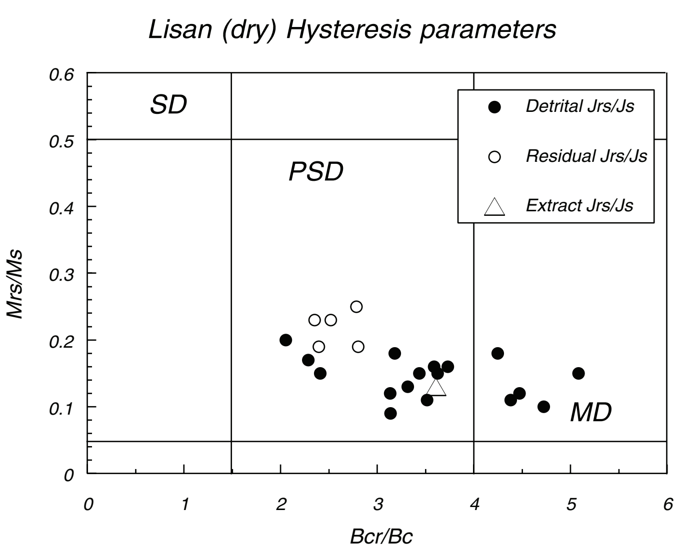

Figure 5. Plot of dry Lisan hysteresis parameters (Day et al., 1977). Mrs—saturation of remanence; Ms—saturation magnetization; Bc—coercivity field; Bcr—coercivity of remanence; SD—single-domain; MD—multidomain; PSD—pseudo-single domain. Open circles refer to the residual material that remained after extracting the magnetic grains (open triangle) from the detritus material (solid circles). Jrs—saturation of remanence; Js—J saturation.

Hysteresis Comparisons of Dry Lisan, Wet Lisan, and Holocene Dead Sea

Hysteresis properties of 10 aragonite laminae and 10 detrital laminae from dry Lisan, wet Lisan, and the Holocene Dead Sea were measured at the GFZ paleomagnetic laboratory using a MicroMag™ apparatus. Figure 6A compares hysteresis loops before diamagnetic (right) and paramagnetic (left) slope corrections and also moment of remanence (M_r) of representative samples from the six types of materials. It is clear that the aragonite laminae (left) contain a ferromagnetic component. The M_r value of wet aragonite is one order of magnitude larger than the dry aragonite, and the M_r value of Holocene Dead Sea sediment is larger by two orders of magnitude. The M_r values of detrital laminae (right) are significantly higher than their aragonite counterparts by an order of magnitude, whereas M_r values show an increased trend of one and two orders of magnitude of wet detritus and Holocene Dead Sea detritus relative to dry detritus. Figure 6B shows hysteresis loops of the same samples after slope corrections for the diamagnetic and paramagnetic effects.

In Figure 7, we plot the hysteresis parameters of all samples on a Day plot (Day et al., 1977). The detrital laminae follow a clear trend in grain size from about SD-PSD behavior to PSD-MD grain size. The same trend is evident in the aragonite laminae, yet data from wet and dry Lisan sediments are more scattered. The results suggest that the Holocene Dead Sea sediments are characterized by a SD-PSD magnetic grain size, wet Lisan sediment is dominantly PSD, and the magnetization of dry Lisan sediment is controlled by larger PSD-MD size grains.

Thermomagnetic and Curie Temperatures

Thermomagnetic experiments were done using a variable field translation balance (VFTB) apparatus at GFZ. Curie temperature, T_c, was determined by measuring the high temperature-dependency of saturation magnetization. The magnetic intensity of Lisan samples was too weak to be measured with this device, thus we could determine T_c for only Holocene Dead Sea sediments. Figure 8 shows a two-step temperature drop, the first at ~350 °C and the second at ~580 °C, indicating two magnetic carriers, similar to the results of the thermal demagnetization experiment.

DISCUSSION

The experiments described here suggest that the magnetic properties of Lisan and Holocene Dead Sea sediments differ, implying that their magnetic mineralogy and grain size may also differ. Figure 2 compares the MDF, shape of normalized intensity curves, and J_0 (nrm) for each of the sediment types. The first two suggest an increase of coercivity and large grain size dominance from dry Lisan to Holocene Dead Sea, with the coercivity of wet Lisan in between. The increased intensity during AF experiment, above 80 mT, suggests that remanence is carried by greigite

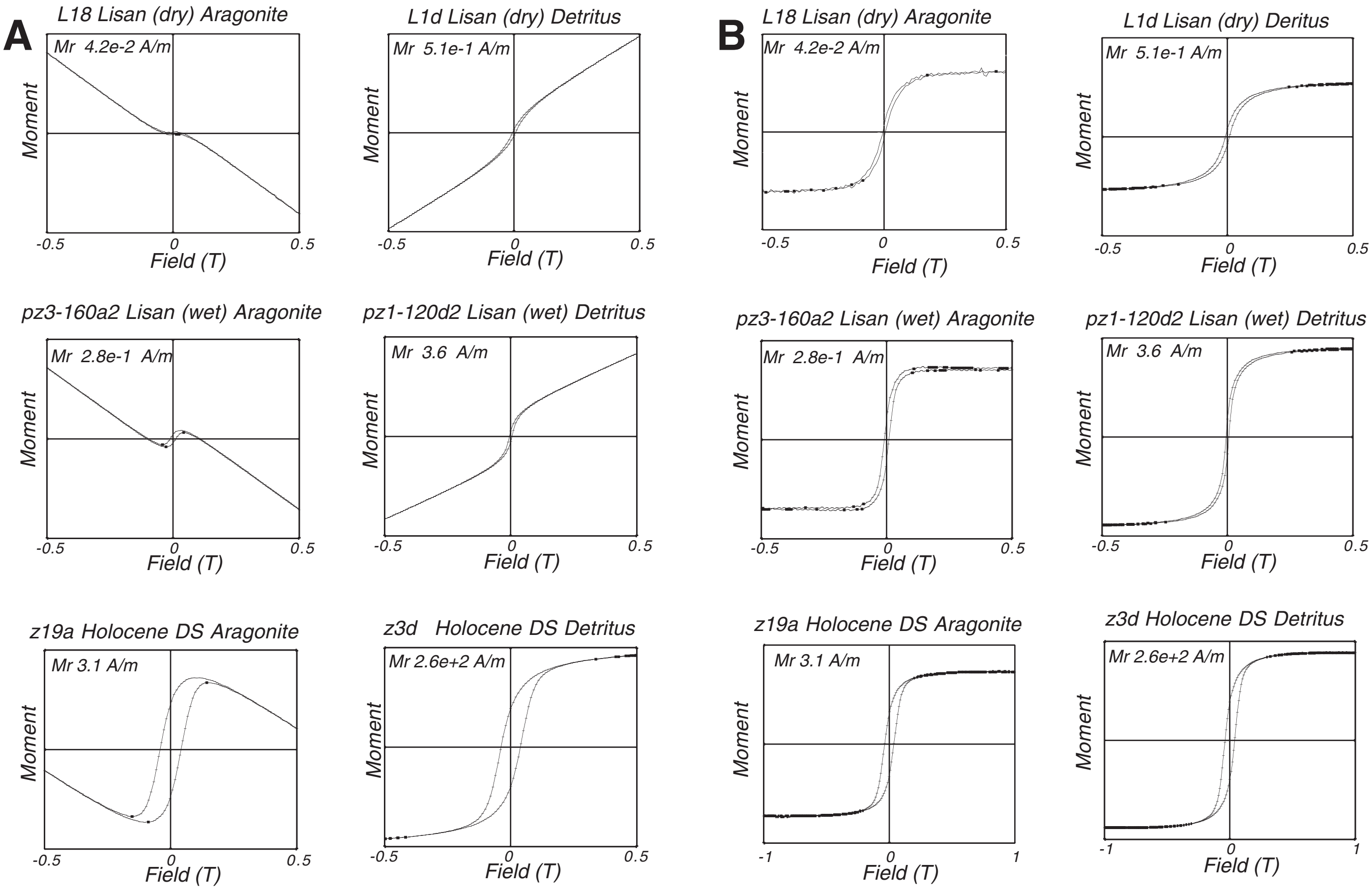

Figure 6. Hysteresis loops of aragonite and detritus laminae taken from dry and wet Lisan and Holocene Dead Sea sediments. (A) Comparison of hysteresis loops before diamagnetic (right) and paramagnetic (left) slope corrections and moment of remanence (M_r) of representative samples. (B) Hysteresis loops of the same samples after slope corrections for the diamagnetic and paramagnetic effects. Each plot is labeled with sample identification number, type of material, and moment of remanence (M_r).

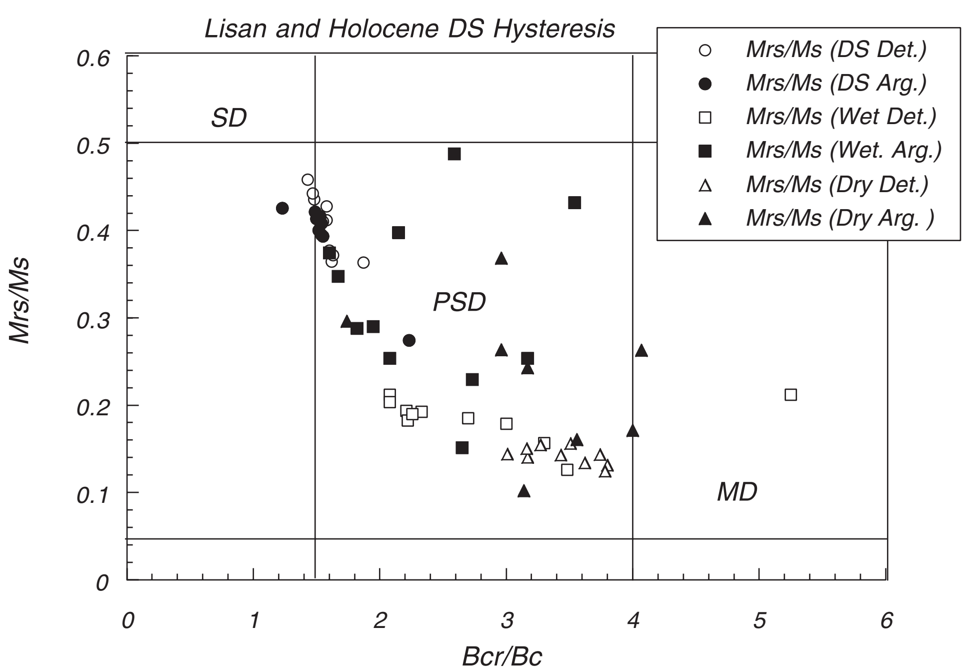

Figure 7. Hysteresis parameter (Day et al., 1977) plot of aragonite and detritus material taken from dry and wet Lisan and Holocene Dead Sea (DS) sediment. Mrs—saturation of remanence; Ms—saturation magnetization; Bc—coercivity field; Bcr—coercivity of remanence; SD—single-domain; MD—multidomain; PSD—pseudo-single domain. Open symbols refer to the detritus material and solid symbols refer to aragonite material.

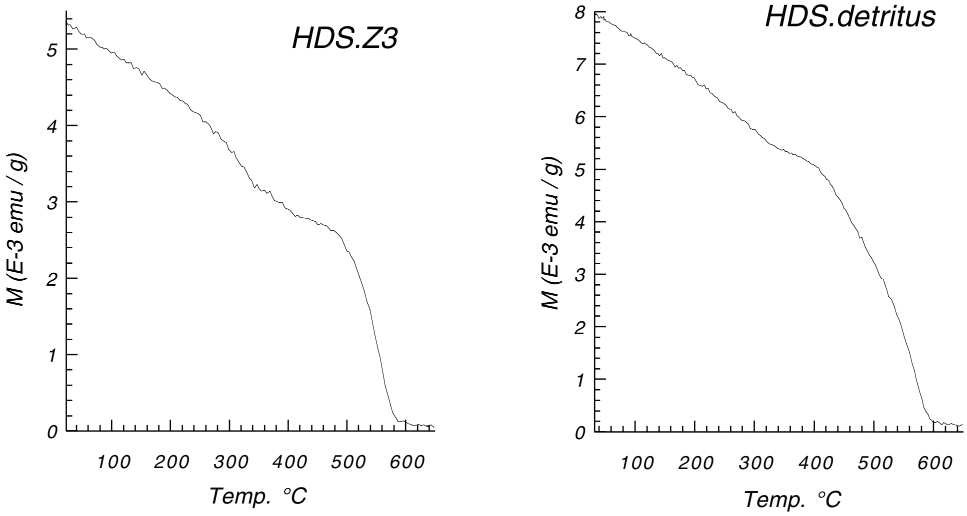

Figure 8. Saturation of magnetization (M) as function of elevated temperature, of two Holocene Dead Sea (HDS) sediment samples, shows two steps indicating Curie temperatures of two independent magnetic phases.

(Fe_3S_4), which may dominate the NRM intensity (Roberts, 1995). If so, magnetization of Holocene Dead Sea is gyroremanent magnetization (GRM) (Smith and Merrill, 1980; Snowball, 1997; Hu et al., 2002).

The Holocene Dead Sea and wet Lisan thermal demagnetization experiments support this finding. The data support the presence of dual carriers in both Holocene Dead Sea and wet Lisan sediments. Thermal demagnetization indicates two T_c values, one at ~350 °C and the second at ~550 °C. These T_c are clearly associated with the two-component magnetization seen in Holocene Dead Sea sediment, a conclusion further supported by the thermomagnetic experiments (Fig. 8). The vector resolution of wet Lisan shows only one stable component removed between 150–400 °C. The presence of the higher temperature stable component is unclear, yet the presence of a high temperature carrier is evident from the normalized intensity plot. The thermal demagnetization and thermomagnetic experiments point out the presence of two magnetic carriers, both Holocene Dead Sea and wet Lisan; one is the greigite with a T_c of ~350 °C (Roberts, 1995; Sagnotti and Winkler, 1999), and the second is Ti-magnetite.

Our micromagnetic measurements and hysteresis parameters permit two inferences about domain composition. First, the M_r data indicate that while both types of laminae contain ferromagnetic material, it is concentrated in the detrital laminae as compared to the aragonite. This is true for all three sediment types. Second, the domain composition is SD-PSD in Holocene Dead Sea, PSD in wet Lisan, and MD-PSD in dry Lisan. The SD-like component (in Holocene Dead Sea and wet Lisan) is in the form of greigite (Snowball, 1991), whereas the MD component is contributed by Ti-magnetite, which is present almost solely in the detrital laminae.

The lower AF demagnetization efficiency of the dry Lisan sediments points to the presence of a very high coercivity phase, which is probably the Fe hydroxide goethite (FeOOH), probably produced by oxidation of the diagenetic sulphide greigite. If so, the Lisan Formation has been subjected to weathering by oxidation upon exposure and drying.

Our findings suggest two magnetic carriers in the Holocene Dead Sea and wet Lisan sediments: titanomagnetite and greigite. The titanomagnetite grains are detrital and carry a DRM, whereas the greigite is diagenetic in origin and carries a CRM that dominates the total NRM of Holocene Dead Sea and wet Lisan sediments.

If so, the presence of digenetic greigite in the wet Lisan sediments suggests better preservation and less alteration due to exposure and oxidation. We suggest that the moisture in this sediment may be primary formation water, because if it were meteoritic water, (a) the greigite would have been oxidized, and (b) the interstitial chloride salts inherited from the original lake were retained, preventing transformation of aragonite to calcite (Katz and Kolodny, 1989; Stein et al., 1997).

SUMMARY AND CONCLUSIONS

Our a priori assumptions were (1) that the sources of Lisan and Holocene Dead Sea detritus are similar or perhaps identical; (2) the lake conditions affecting magnetization were similar; (3) an overall similarity in sedimentary environment for Lisan and Holocene Dead Sea; and (4) differential chemical alteration affecting the ferromagnetic minerals may have occurred in the Lisan sediments. Based on these assumptions, the rock magnetic properties of Lisan and Holocene Dead Sea should be quite similar unless diagenetic process and chemical alteration change occurred.

We propose that magnetic properties of the Lisan Formation and Holocene Dead Sea sediments can be explained by a model that incorporates dissolution. At the time of deposition, titanomagnetite grains of varying size were deposited in Lake Lisan and Holocene Dead Sea, recording the geomagnetic field via a primary DRM. Sedimentation was followed by partial or complete dissolution of titanomagnetite in anoxic lake bottom conditions. Because the kinetics of dissolution depends upon surface area, the SD grains dissolved faster and tend to vanish, leaving only the larger PSD and MD grains. Titanomagnetite dissolution occurred simultaneously with precipitation of greigite in anoxic, sulfate-reducing conditions probably related to bacterial degradation of organic matter (Curtis, 1987; Roberts and Turner, 1993). This process added a secondary CRM that overwhelmed the DRM and the primary geomagnetic record. Later, when the level of Lake Lisan dropped, these sediments were exposed to air. At this time, the greigite was oxidized (Jelinowska et al., 1999), removing the CRM from the system and leaving only original detrital PSD and MD titanomagnetite grains as dominant DRM carriers. Presently, wet Lisan sediments have not been completely altered and therefore contain secondary greigite preserved by original formation water that carries a secondary CRM.

For this reason, the CRM in Holocene Dead Sea and wet Lisan cannot be considered as an accurate geomagnetic record that tracks the field at the time of deposition, while the magnetization of dry Lisan is a primary DRM and displays the record of directional secular variation of the geomagnetic field, which is probably noisy due to its high content of MD grains. It is now clear why a paleointensity record could not have been obtained from the Lisan Formation—the variation in concentration of grain size and diagenetic process (Nowaczyk et al., 2001) was produced by eliminating the SD part of the grain size spectra by dissolution in a reducing environment at the bottom of Lake Lisan.

We suggest that the oxidation products of the greigite might be goethite and sulfur, that both are abundant in the Lisan sediment. However, this question remains open at the current level of investigation.

We want to point out that if a layered water body and reduction conditions at the water-sediment interface are two required conditions for the growth of greigite in the sediments, it is probably an important ferromagnetic component in lake sediments, as reported by Snowball (1991), Roberts and Turner (1993), Roberts (1995), Sagnotti and Winkler (1999), Jelinowska et al. (1999), and Hu et al. (2002), to name only few.

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