Rock varnish evidence for a Younger Dryas wet period in the Dead Sea basin

Tanzhuo Liu,[1] Wallace S. Broecker,[1] and Mordechai Stein[2]

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[1] Rock varnish from 14.6 to 13.2 ka recessional shorelines of late glacial Lake Lisan and fan delta surfaces between 280 and 365 m bmsl (meters below mean sea level) along the western margins of the Dead Sea contains replicable layering patterns, characterized by a low Mn and Ba orange/yellow surface layer and a high Mn and Ba dark basal layer. The deposition of the dark basal layers immediately after the lake recession represents a wet period coinciding with the Younger Dryas (YD) cooling (12.9–11.6 ka), manifesting the influence of midlatitude westerly winds in the eastern Mediterranean-central Levant (EM-CL). In contrast, varnish from the distal base of fan deltas contains only orange/yellow surface layers, diagnostic of the Holocene relatively dry climate. The absence of the dark basal layers in the varnish further indicates a YD high stand at ~365 m bmsl and a lake level rise of at least 100 m from its Bølling-Ållerød lowstand. This rise stands in contrast to the abrupt drop of the lake level during the Heinrich (H1) cold event, illustrating the opposite response of the EM-CL climate to changes in the North Atlantic climate. The YD wet event most likely reflects a southward shift of the Atlantic meridional overturning circulation-modulated midlatitude westerly wind belt in the EM-CL region. **Citation:** Liu, T., W. S. Broecker, and M. Stein (2013), Rock varnish evidence for a Younger Dryas wet period in the Dead Sea basin, *Geophys. Res. Lett.*, *40*, 2229–2235, doi:10.1002/grl.50492.

1. Introduction

[2] The Younger Dryas (YD) cooling was the most recent of many late Pleistocene rapid climatic fluctuations, such as Heinrich events (H1–H6) in the North Atlantic region [*Alley*, 2000; *Bond et al.*, 1993]. The far-field effects of this millennial-scale cold snap have left numerous imprints in marine and terrestrial geological records across the globe [*Broecker et al.*, 2010]. In the desert regions of the northern hemisphere, however, evidence for the YD cooling is very rare and often manifested as a short-lived wet pulse in lake level records or lacustrine deposits. In the dry lands of western United States, for example, large pluvial lakes, such as Lahontan and Bonneville, experienced a small lake level rise during the period of the YD cooling [*Oviatt*, 1997; *Briggs et al.*, 2005]. In the Dead Sea basin (DSB) of the central Levant region, sedimentary records recovered from drilled cores along the Dead Sea shore indicate a relatively wet period during the YD cooling [*Stein et al.*, 2010], yet no direct evidence was found in the onshore terraces for an YD stand. In this paper, we present new rock varnish evidence that the YD cooling at the termination of the last glaciation resulted in a significant water level rise of postglacial Lake Lisan, with a regional manifestation of wet/cold climate indicative of the influence of Atlantic meridional overturning circulation (AMOC)-modulated northern hemisphere westerly winds.

2. Rock Varnish as Desert Wetness Recorder

[3] Rock varnish is a slowly accreting (1–40 μm/kyr) manganese-ferrous dark coating on subaerially exposed rock surfaces mostly seen in arid to semiarid deserts of the world [*Dorn and Oberlander*, 1981]. Because of its sedimentary origin, varnish often contains a layered microstratigraphy that records past climate change [e.g., *Liu et al.*, 2000; *Broecker and Liu*, 2001; *Liu and Broecker*, 2008]. In the Great Basin of western United States, Mn- and Ba-poor varnish layers, which are orange/yellow in ultrathin sections (5–10 μm thick) under transmitted polarized light, were formed during the overall dry period of the Holocene; Mn- and Ba-rich dark layers were deposited during the last glacial time when the Great Basin was much wetter than at present [*Broecker and Liu*, 2001]. Previous studies [*Liu et al.*, 2000; *Liu*, 2003] showed that wet events represented by the glacial age dark layers in the western United States varnish correlate in time with cold episodes of the YD and H1–H6 in the North Atlantic region. Recent studies [*Liu and Broecker*, 2007, 2008, 2013] further demonstrated that fine-grained, fast-accumulating varnish recorded late Pleistocene and Holocene millennial-scale wet events that were synchronous with millennial-scale cooling events in the North Atlantic and Greenland [*Bond et al.*, 1997; *Stuiver and Grootes*, 2000]. Hence, rock varnish can be used as a unique wetness recorder to study past climate changes, especially wetness variations of the world's deserts [*Broecker and Liu*, 2001].

3. Regional Settings

[4] During the Neogene-Quaternary times, the tectonic depressions along the Dead Sea Transform were filled by several fresh to hypersaline water-bodies (e.g., the Sea of Galilee, Dead Sea, and its late glacial precursor Lake Lisan) (Figure 1). The large drainage area of the lakes receives rains that originate at eastern Mediterranean due to the cyclonic activity [*Ziv et al.*, 2006]. The majority of midlatitude westerly wind-driven storm tracks reaching the region originate in the North Atlantic, with the warm Mediterranean Sea acting as a source of moisture [*Rindsberger et al.*, 1983]. The hypersaline Dead Sea and Lake Lisan are considered

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.
[2]The Geological Survey of Israel, Jerusalem, Israel.

Corresponding author: T. Liu, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA. (tanzhuo@ldeo.columbia.edu)

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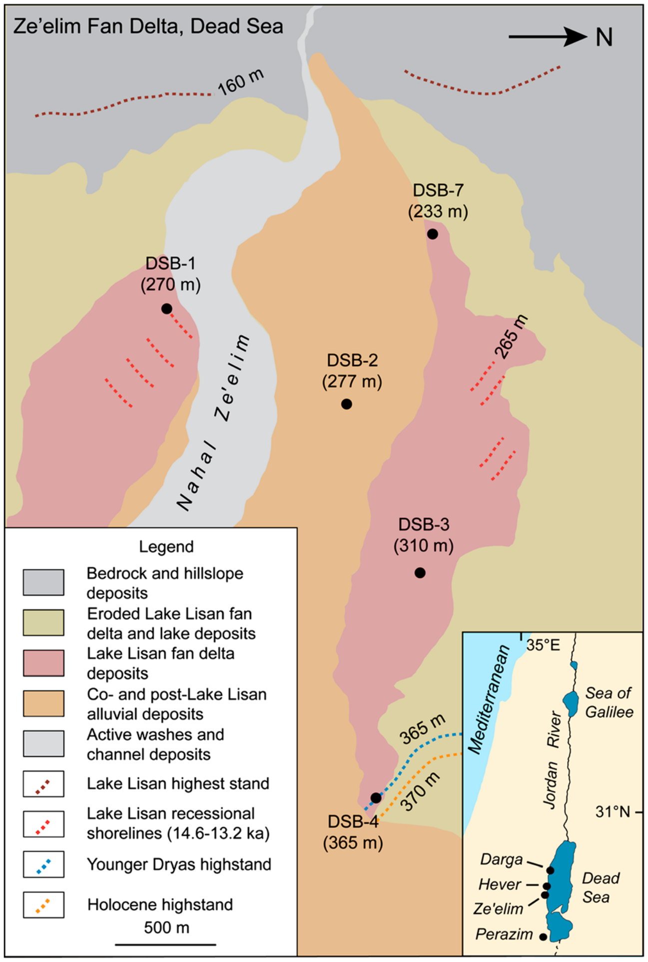

Figure 1. Rock varnish sampling sites on Ze'elim fan delta surfaces in the Dead Sea basin. Shoreline elevations are reported in m bmsl.

terminal lakes whose levels, configuration, and compositions are sensitive to the climate-hydrological conditions in the lake's drainage area and in the entire central Levant region [*Enzel et al.*, 2008; *Kushnir and Stein*, 2010].

[5] The last glacial Lake Lisan reached its highest stands of 160–200 m bmsl (meters below mean sea level) during the cold interval of MIS2 between ~30 and 17.4 ka and deposited a long sequence of primary aragonite and silty-detritus sediments [*Bartov et al.*, 2003; *Haase-Schramm et al.*, 2004; *Torfstein et al.*, 2013 and references therein] (Figures 4b). Then, the lake began retreating in response to the deglacial global warming that generally imposed more arid conditions in the eastern Mediterranean-central Levant (EM-CL) until it reached the Holocene lowstand at 400 m bmsl [*Migowski et al.*, 2006]. Yet the postglacial lake retreat was not monotonous, and its level fluctuated abruptly [*Stein et al.*, 2010]. During the time interval of H1 (17.4–16 ka), the lake level dropped from ~260 to ~330 m bmsl, leading to a massive deposition of primary gypsum [*Bartov et al.*, 2003; *Torfstein et al.*, 2013]. Subsequently, at 16–14.6 ka, the lake level rose to ~260 m bmsl, depositing again a sequence of laminated aragonite and silty-detritus. During the Bølling-Ållerød (B-A) warm period (14.6–13.0 ka), the lake dropped abruptly to levels below 465 m bmsl and then rose again during the YD cooling at 12.8–11.6 ka before it finally declined to its mean Holocene water level at 400 ± 30 m bmsl [*Stein et al.*, 2010] (Figure 4b). During this period, numerous sets of recessional shoreline features were produced on Ze'elim, Hever, and Darga fan deltas [*Neev and Emery*, 1967; *Bartov et al.*, 2007]. This paper focuses on the documentation and climatic interpretation of microstratigraphies in rock varnish developed on these recessional shorelines and associated fan delta surfaces.

4. Methods

[6] Rock varnish is well developed and preserved in the DSB. It is often formed on chert-dominated alluvial fan boulders, wave-abraded cobbles, and hillslope deposits of late glacial Lake Lisan age. Rocks on the west ramp of ancient fortress Masada (built at ca. AD 73) and historical shorelines of the Dead Sea are also coated with young patchy varnish. For the purpose of this study, varnish samples were collected from the late glacial Lake Lisan recessional shorelines and alluvial fan surfaces at Ze'elim and Darga fan deltas that range in elevation from 233 to 368 m bmsl (Figures 1, 2a, and 2b). Because these shorelines and associated fan surfaces were abandoned as the lake retreated from ~260 to 465 m bmsl between 14.6 and 13.2 ka [*Stein et al.*, 2010], the date provides a maximum-limiting age for the formation of rock varnish on them.

[7] Varnish samples were assessed by ultrathin sectioning, microprobe chemical mapping and line profiling, and layering pattern analysis. Ultrathin sections (~5–10 μm thick) of varnish samples were photographed using a Leica DMLB polarized light microscope, equipped with Leica MPS60 photoautomat camera system. The color pictures thus obtained provide high-resolution (~1 μm) images of varnish microstratigraphy for layering pattern analysis. Varnish ultrathin sections displaying unambiguous and reproducible layering patterns were then selected for microprobe analysis. Chemical mapping and line profiling of varnish ultrathin sections were acquired on a fully automated five-spectrometer CAMECA SX100 electron probe, with the use of qualitative and quantitative modes of wavelength dispersive X-ray spectrometry, respectively. The use of a focused probe beam ensured high-resolution (~2 μm) detection of Mn, Ba, and other elemental fluctuations in varnish microstratigraphy. Both microscopic images and microprobe chemical data were used to assist identification and interpretation of varnish layering patterns.

5. Results

[8] Analyses of the varnish samples reveal layering patterns that are characterized by relatively thick (50–150 μm) orange/yellow surface layers and relatively thin (5–20 μm) dark basal layers. These patterns are replicated in samples between 280 and 365 m bmsl on Ze'elim and Darga fan deltas (Figure 3). Varnish from shorelines and fan delta surfaces above 280 m bmsl contains more complicated layering patterns, with a 5–10 μm thick orange/yellow basal layer overlain directly by a dark layer, and then by an orange/yellow surface layer (Figures 3a and 3b). Microprobe elemental mapping indicates that dark layers are enriched in Mn and Ba, while orange/yellow layers are depleted in Mn and Ba (Figures 2c and 2d). Microprobe line profiling shows that the dark layers contain 20%–35% Mn and 1%–3% Ba

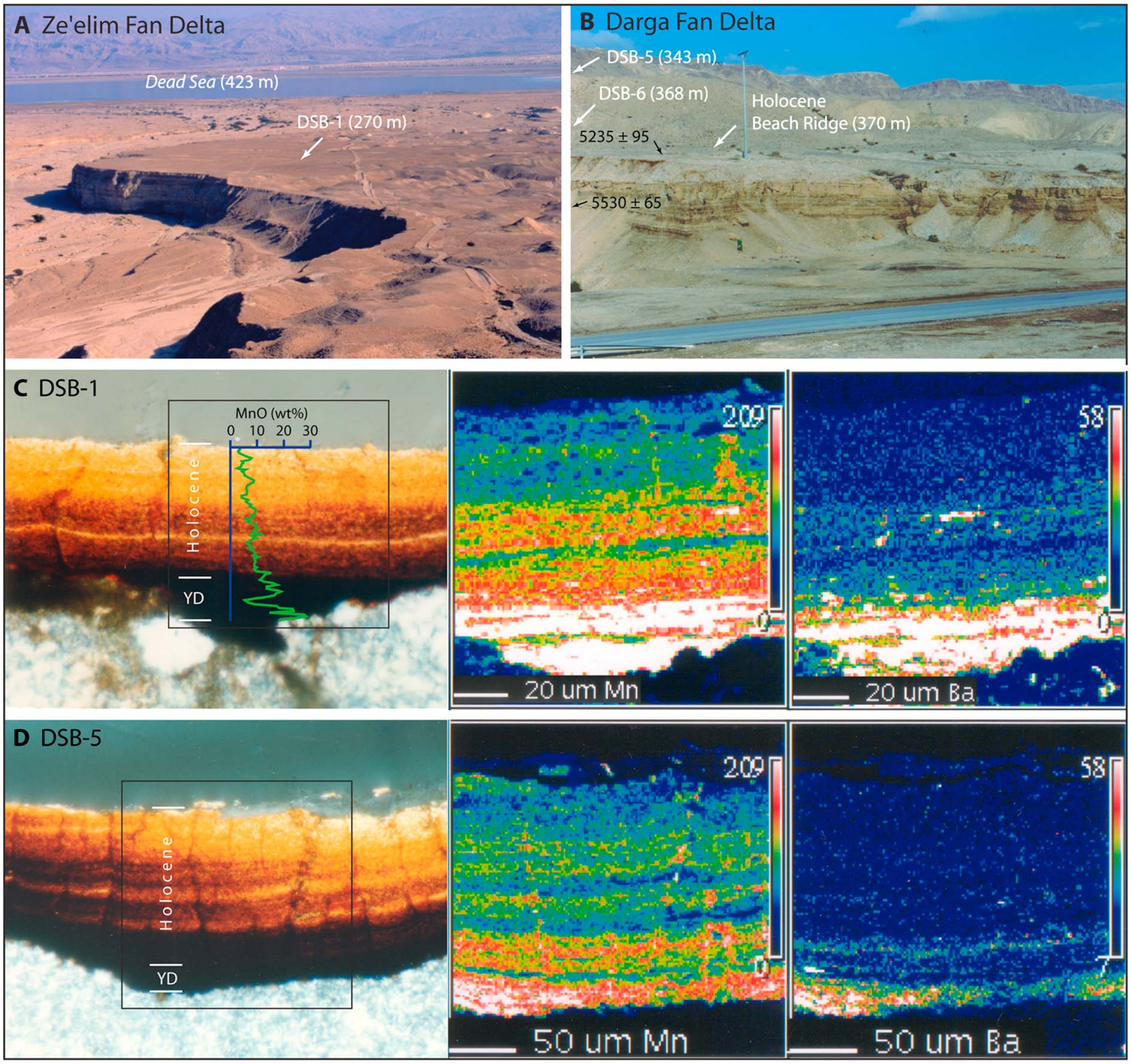

Figure 2. (a) Late glacial Lake Lisan (14.6–13.2 ka) recessional shorelines on Ze'elim fan delta. (b) Holocene high stand (370 m bmsl) of the Dead Sea at the base of Darga fan delta. (c and d) Electron microprobe elemental mapping of Ma and Ba variations in varnish microstratigraphies from Ze'elim and Darga fan deltas (the framed areas were probe mapped). Dark basal layers in optical varnish microstratigraphies are rich in Mn and Ba, representing the YD relatively wet climate. Orange and yellow surface layers are poor in Mn and Ba, indicative of the overall Holocene dry climate. Note that narrow dark bands within the orange/yellow surface layers contain much less amounts of Mn and Ba than the dark basal layers and record millennial-scale weak wet phases during the Holocene [cf. *Liu and Broecker*, 2007]. The mid-Holocene lake sediments in Figure 2b constrained by two radiocarbon dates (in ^{14}C years BP) on charcoal (one 0.35 m and the other 4 m below the surface) were deposited at 6.3–6 ka when the Dead Sea level fluctuated around 370 m bmsl. They are likely correlated with the mid-Holocene wet phase represented by dark band 2 in Figure 3 (also see the ~6.2 ka Ba peak in Figure 4a).

oxides, and the orange/yellow layers contain only 5%–20% Mn and 0.5%–1% Ba oxides (Figures 2c and 3c). These results are similar, in both optical characteristics and chemical contents, to those observed in varnish from the drylands of the western United States [*Liu et al*., 2000; *Broecker and Liu*, 2001], suggesting that the layering signals recorded in the Dead Sea varnish reflect past climatic fluctuations, especially wetness variations.

[9] The timing for the formation of basal layers in the varnish can be determined by the age of sampled shorelines and fan delta surfaces [cf. *Liu and Broecker*, 2013]. Previous studies [*Stein et al*., 2010] suggested that Lake Lisan dropped from its high stand above 260 m bmsl to its B-A lowstand below 465 m bmsl between 14.6 and 13.2 ka. A newly published U-Th chronology, which yields a tuned age of 14.5 ± 0.5 ka for the "Additional Gypsum Unit" that caps the Lisan Formation at Perazim Valley [*Torfstein et al*., 2013], suggests a minimum lake level of 268 m bmsl at that time. Varnish from surfaces above 280 m bmsl contains a layering sequence with an orange/yellow basal layer (Figures 3a and 3b, marked as "B-A"). Given 200 years of a lag time for varnish initiation on subaerially exposed rocks [*Liu and Broecker*, 2007], the orange/yellow basal layer in the varnish was likely deposited in a relatively dry period

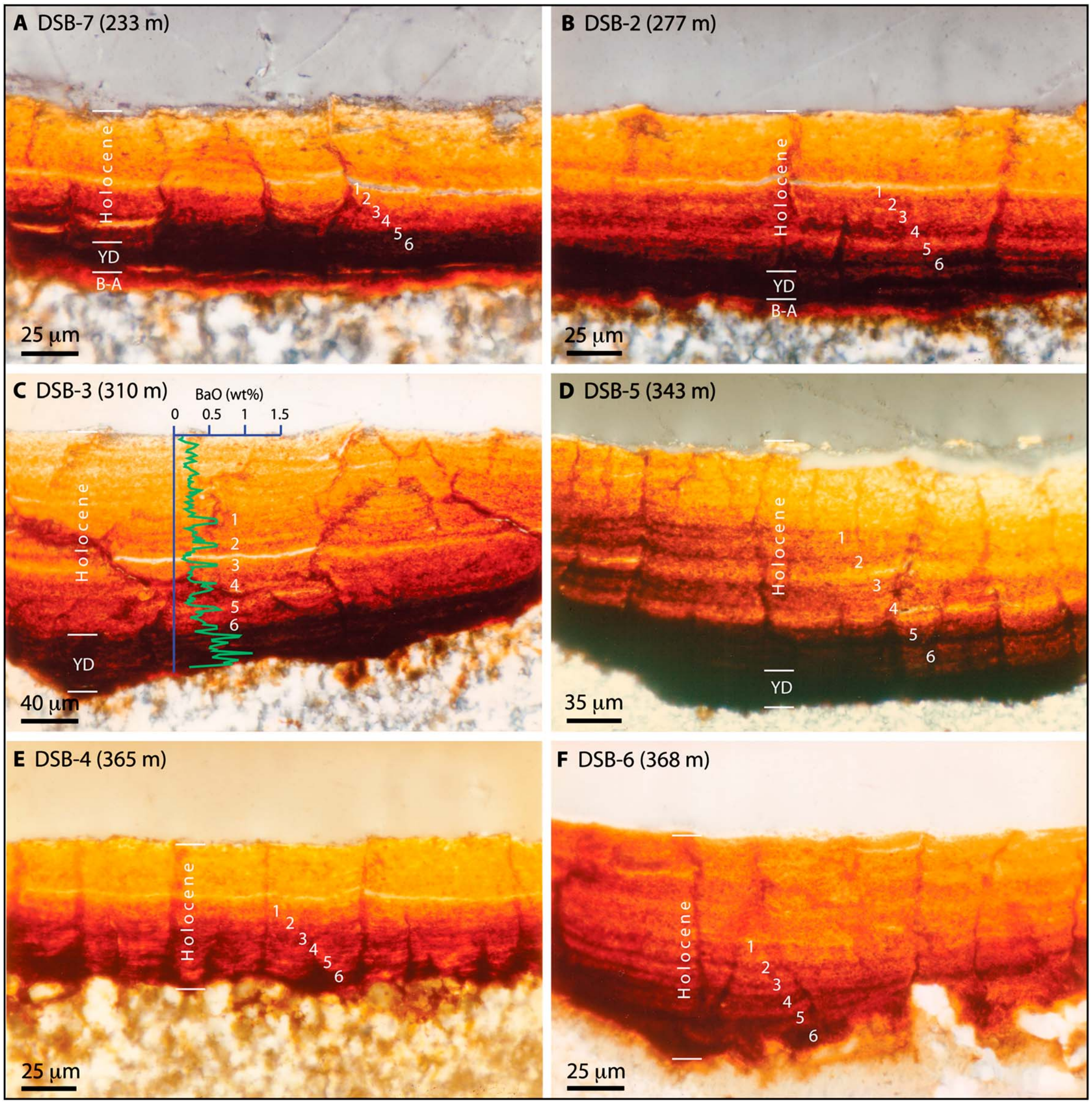

Figure 3. Layering patterns observed in varnish from 14.6 to 13.2 ka recessional shorelines and fan delta surfaces in the DSB. (a and b) Varnish above 280 m bmsl contains a layering sequence with the B-A orange/yellow basal layer, overlain by the YD dark layer, and then by the Holocene orange/yellow surface layer. (c and d) Varnish between 280 and 365 m bmsl shows a layering sequence with the YD dark basal layer overlain by the Holocene orange/yellow surface layer. (e and f) Varnish between 365 and 370 m bmsl displays only the Holocene orange/yellow surface layer. Note that six roughly evenly spaced weak dark layers (marked as 1–6) appear within the lower portion of the Holocene layering sequence, representing six early Holocene weak wet phases in the DSB [cf. *Liu and Broecker*, 2007].

[cf. *Liu et al*., 2000] after 14.3 ± 0.5 ka, in accord with the B-A warm interval in the region [*Stein et al*., 2010]. Varnish from surfaces between 280 and 365 m bmsl contains a layering sequence with a dark basal layer (Figures 3c and 3d, marked as "YD"). If the lower bound (~13.2 ka) of the reported age range for the lake recession provides a reasonable time constraint on the subaerial exposure of once submerged surfaces 42–75 m below 268 m bmsl, the dark basal layer in the varnish at 310 and 343 m bmsl (i.e., DSB-3, -5) was likely deposited in a relatively wet period [cf. *Liu et al*., 2000] after 13.0 ka, coinciding in time with the onset of the YD cooling at 12.9 ka. The orange/yellow surface layers in the varnish were then deposited during the subsequent dry period of the Holocene.

[10] The varnish microstratigraphies on wave-abraded rocks from the recessional shorelines and fan delta surfaces yield geomorphic evidence for a relatively low YD stand of Lake Lisan at ~365 m bmsl. As seen in Figures 1 and 3, varnish samples from the 14.6–13.2 ka recessional shorelines and fan delta surfaces between 280 and 365 m bmsl at Ze'elim and Darga display the YD dark basal layers (Figures 3c and 3d). These fan delta surfaces were cut by a set of slightly younger shorelines at their distal base below 365 m bmsl (Figure 1). Varnish samples, one from a small beach bar (365 m bmsl) at the base of Ze'elim fan delta (Figure 1) and the other (368 m bmsl) from a wave-abraded fan boulder on the terrace riser 2 m above a Holocene (6.3–6 ka) beach ridge (370 m bmsl) at the base of Darga fan delta (Figure 2b), display only the orange/

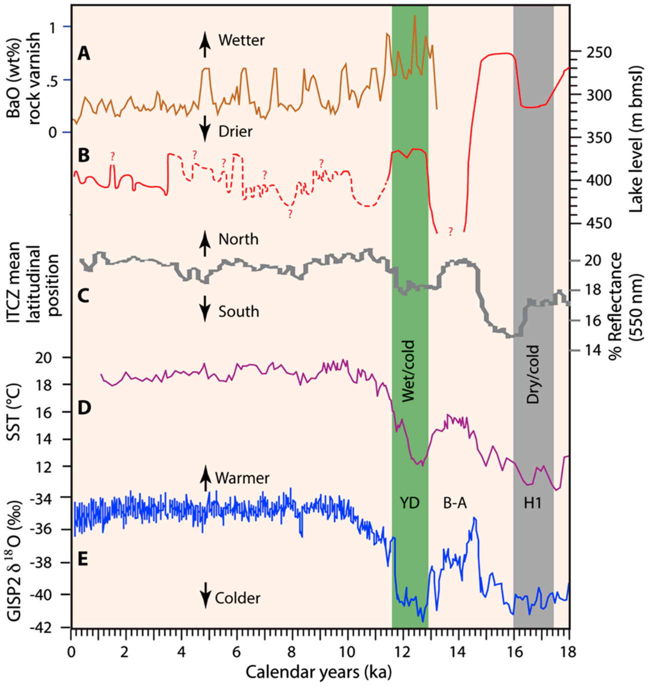

Figure 4. Water level fluctuations of Lake Lisan and the Dead Sea and their correlation to regional and global climate records. (a) BaO concentration in varnish sample (DSB-3) used as a proxy for the wetness record (see Figure 3c). (b) Lake level record (modified after *Torfstein et al.* [2013]). (c) Cariaco basin sediment reflectance, indicating the latitudinal mean position of the ITCZ in the northwestern equatorial Atlantic [*Peterson et al.*, 2000]. (d) Western Mediterranean sea surface temperature (SST) record [*Cacho et al.*, 2001]. (e) GISP2 $\delta^{18}O$ record [*Stuiver and Grootes*, 2000]. The two vertical bars mark the YD and H1 chronozones. Note that the varnish wetness record in Figure 4a is plotted against other climatic records based on assumed constant varnish accretion rate along the probe profiling line on the sample, with an age assignment of 13 ka for the initial deposition of the dark basal layer (see Figure 3c). The varnish wetness record as proxied by temporal variations in BaO concentration indicates a wet period represented by the Ba high peaks during the YD cooling, followed by the relatively dry Holocene. Also note that six Ba intermediate peaks in the varnish record represent early Holocene weak wet phases. Some of these Ba peaks are not tied to the lake level record in Figure 4b, suggesting they largely reflect past moisture condition (such as duration and frequency of dew events) in addition to precipitation [*Broecker and Liu*, 2001].

yellow surface layers that are diagnostic of the Holocene dry climate in the region [cf. *Liu et al.*, 2000] (Figures 3e and 3f). Moreover, the two samples each contain six roughly evenly spaced weak dark layers in the lower portion of their microstratigraphies. These layers are similar to those immediately overlying the YD dark layers in varnish from the recessional shorelines and fan delta surfaces (Figures 3a–3d), indicative of six millennial-scale, early Holocene relatively weak wet phases in the DSB [cf. *Liu and Broecker*, 2007, 2008] (Figures 3e and 3f). These data suggest that the small beach bar at the base of Ze'elim fan delta was constructed during the YD wet period when the level of Lake Lisan was around 365 m bmsl, and that the varnish began accumulating on beach pebbles a few hundred years after the onset of the Holocene dry period. Because it is known that the lake level fell well below 365 m bmsl during the B-A warm period [*Stein et al.*, 2010], this suggests a YD lake level rise of at least 100 m.

6. Discussion

[11] The YD wet event in the DSB as documented in this study has several important implications. First, this finding constitutes new convincing evidence that the DSB was impacted by the YD cooling, with a regional manifestation of wet/cold climatic regime (Figure 4). Previous studies of a sedimentary core drilled on the Ze'elim terrace at the west shore of the Dead Sea concluded that the DSB, as well as the EM-CL, were arid during the YD [*Yechieli et al.*, 1993]. Their conclusion relied on the assumption that a thick salt unit found in the core was deposited during the YD. However, recent ^{14}C dating of this salt unit discovered that its age lies between 11 and 10 ka [*Stein et al.*, 2010]. The reinterpretation of the chronology of the Ze'elim core indicated that the marly sequence below the salt unit was deposited during the YD at 13.2–11 ka. In most recently drilled cores along the Dead Sea margins, the 11–10 ka salt unit was deposited on an unconformity (the U-Th ages of the underlying Lisan aragonitic sequences range between 40 and 20 ka). Thus, the deposition of the salt unit (that reaches 15 m in thickness) required a lake level rise above the unconformity before its deposition [*Stein et al.*, 2010] (Figure 4b). In fact, the Ze'elim marly unit that underlies the salt is the only one preserved in the marginal terraces of the Dead Sea. *Stein et al.* [2010] estimated that the lake rose ~100 m above the 465 m bmsl unconformity. It should be noted, however, that $\delta^{18}O$ data from a Soreq Cave speleothem in the Judean Hills when interpreted as precipitation record would indicate a more arid climate in the YD than that in the Holocene [*Orland et al.*, 2012]. Yet it was already demonstrated that the speleothem $\delta^{18}O$ data mainly reflect the Mediterranean water composition (the source effect), and its application as paleo-rain recorder is not straightforward [cf. *Kolodny et al.*, 2005]. Our varnish data favor a wetter-than-Holocene climate during the YD cooling, as represented by the Mn- and Ba-rich dark layers in varnish microstratigraphies (Figures 3a–3d and 4a).

[12] Secondly, the YD wet/cold regime in the DSB likely reflects the climatic influence of midlatitude westerly winds in the northern hemisphere. High water levels observed in pluvial lakes in western North America and western China have long been attributed to periods of high precipitation associated with westerly wind-driven storm tracks in northern midlatitudes [e.g., *Kutzbach and Wright*, 1985; *Li*, 1990; *Anderson et al.*, 2002]. The overall high stands (160–280 m bmsl) of Lake Lisan generally persisted during much of the last glaciation, indicating westerly winds or EM cyclones-dominant wet/cold climatic conditions in the EM-CL [*Bartov et al.*, 2003; *Enzel et al.*, 2008; *Torfstein et al.*, 2013]. On the other hand, short episodes of dry/cold climate intermittently prevailed in the EM-CL during the last glacial [*Stein et al.*, 2010], as exemplified by a rapid drop of Lake Lisan during the extremely cold phase of H1 (Figure 4b). Such dry/cold climatic condition was attributed to the cold-water input to the Mediterranean that originated in the collapse of the AMOC, causing the reduction of evaporation and less precipitation in the EM-CL [*Bartov et al.*, 2003].

[13] Third, the YD wet period in the DSB implicates a southward displacement of the AMOC-modulated midlatitude westerly wind belt in the EM-CL. Data on sediment reflectance from the Cariaco basin indicate a southward migration of the Intertropical Convergence Zone (ITCZ) during the YD cold snap [*Peterson et al*., 2000] (Figure 4c). Studies of deep-sea sediment cores from the Southern Ocean [*Anderson et al*., 2009] suggest a concurrent southward shift of the ITCZ and westerly wind belts during the YD and H1, in response to sea ice formation resulting from a partial reduction or complete shutdown of the AMOC in the North Atlantic [*McManus et al*., 2004]. Since the latitudinal migration of the westerly wind belt is largely considered to regulate the position of winter storm tracks and thus precipitation distribution in the northern midlatitudes [e.g., *Kutzbach and Wright*, 1985; *Hostetler and Bartlein*, 1990], the YD wet climate in the DSB most likely reflects the southward shift of the AMOC-modulated westerly wind belt from its northernmost position achieved during the B-A warm period (Figure 4c). *Enzel et al*. [2008] proposed that the southward shift of EM cyclones forced by the ice- and snow-covered Europe and Turkey was mainly responsible for the overall high stands of Lake Lisan during the late Pleistocene, a scenario that is principally similar to our above argument. More importantly, the relatively warmer Mediterranean Sea (2°C–3°C) during the YD than during the H1 (Figure 4d) might also enhance cyclogenesis and precipitation along the westerly wind-driven storm tracks in the EM-CL thus leading to the YD lake level rise and the wet/cold climatic regime in the DSB and its watershed [cf. *Bartov et al*., 2003].

7. Conclusion

[14] Mn- and Ba-rich dark layers in rock varnish from the DSB record a short-lived wet event that appears to be a far-field manifestation of the YD cooling in the North Atlantic, with an associated lake level rise of at least 100 m from the B-A lowstand. This rise stands in contrast to the abrupt drop of the lake level during the H1 cold event, illustrating the opposite response of the EM-CL climate to changes in the North Atlantic climate. The YD wet event most likely reflects the influence of southward shift of the midlatitude westerly wind belt in the EM-CL. Results from this study also demonstrate the great potential of varnish microstratigraphy as a unique means of reconstructing the wetness histories of the Near East as well as other desert regions of the world where continuous climate records are often rare and difficult to retrieve or interpret.

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