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Possible connection between large volcanic eruptions and level rise episodes in the Dead Sea Basin

Revital Bookman [a,*], Sagi Filin [b], Yoav Avni [c], Daniel Rosenfeld [d], Shmuel Marco [e]

[a] Department of Marine Geosciences, Charney School of Marine Sciences, University of Haifa, Mt. Carmel, Haifa 31905, Israel
[b] Department of Transportation and Geo-Information Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel
[c] Geological Survey of Israel, 30 Malchei Yisrael St., Jerusalem 95501, Israel
[d] Institute of Earth Sciences, The Hebrew University, Jerusalem 91904, Israel
[e] Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv 69978, Israel

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ABSTRACT

The June 1991 Pinatubo volcanic eruption perturbed the atmosphere, triggering short-term worldwide changes in surface and lower troposphere temperatures, precipitation, and runoff. The following winter was anomalously wet in the Levant, with a ~2-m increase in the Dead Sea level that created a distinct morphological terrace along the lake's shore. Given the global radiative and chemical effects of volcanogenic aerosols on climatic systems, we tested the hypothesis that the 1991–92 winter shore terrace is a modern analogue to the linkage between past volcanic eruptions and a sequence of shore terraces on the cliffs around the Dead Sea Basin (DSB). Sixteen shore terraces, detected using airborne laser scanning data, were interpreted as indicating short-term level rises due to episodes of enhanced precipitation and runoff during the dramatic drop in Lake Lisan's (palaeo-Dead Sea) level at the end of the Last Glacial Maximum. The terraces were compared with a dated time series of volcanogenic sulfate from the GISP2 ice core, and similar numbers of sulfate concentration peaks and shore terraces were found. Furthermore, a significant correlation was found between SO_4 concentration peaks and the heights of the terraces. This correlation may indicate a link between the explosivity of past eruptions, the magnitude of stratospheric injection, and their impact on the northern hemisphere water balance. The record of such short-term climato-hydrological effects is made possible by the dramatic desiccation of Lake Lisan. Detailed records of such events, albeit rare because of their vulnerability and short longevity, provide an important demonstration of global climatic teleconnections.

1. Introduction

The Dead Sea Basin (DSB), the lowest place on Earth's continents, is a tectonic depression surrounded by high escarpments. The Dead Sea, a terminal water body located within the basin, drains a 42,000 km^2 catchment, one of the largest in the Levant (Fig. 1). The lake surface receives ~75 mm/yr of rain, but its lake level variations reflect mainly precipitation changes in the much wetter headwaters (>600 mm/yr). Precipitation that nourishes the runoff to the lake originates from upper-level, low-pressure troughs that pass over southern Europe and the Mediterranean from west to east (Ziv et al., 2006). These systems drive cold and relatively dry air over the relatively warm Mediterranean Sea surface, which leads to the formation of surface low-pressure systems. The moistened marine air is lifted to produce clouds and precipitation enriching the Levant coastal plains and mountain ridges to the east feeding the Jordan River, its tributaries and subsequently the Dead Sea (Kushnir and Stein, 2010). Thus, the Dead Sea level can serve as a sensitive "rain gauge" for the region (Enzel et al., 2003), although the role of evaporation was also considered in water balance calculations (Yechieli et al., 1998; Rohling, 2013).

During historical periods, the Dead Sea level fluctuated around 400 below mean sea level (bmsl) (Bookman (Ken-Tor) et al., 2004; Bookman et al., 2006). In the early 20th century the natural lake level reached a high-stand of ~390 m bmsl. However, since the 1930s, the construction of a dam at the Sea of Galilee outlet, and the increased diversion of the Jordan River water and industrial use of the Dead Sea brine, have initiated a continuous process of a drastic level drop, which has accelerated since the 1970s at a rate of >1 m/year (Lensky et al., 2005).

* Corresponding author.
E-mail address: rbookman@univ.haifa.ac.il (R. Bookman).

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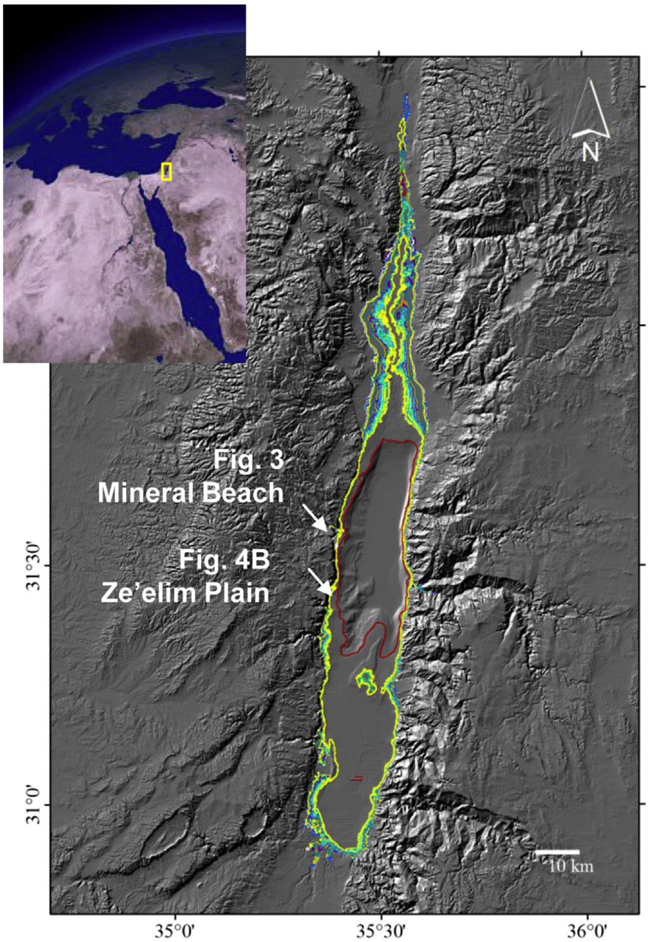

Fig. 1. Shaded relief map of the Dead Sea Basin (Hall, 1996). The desiccation of Lake Lisan is marked in colored lines as determined by the shore terrace elevations generated from the airborne laser scanning-based digital models of the shore terrace elevations. Marked in red is the modern Dead Sea level elevation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Lake Lisan desiccation shore terraces

During its geological history, the DSB has hosted several water bodies that have left high-resolution climatic records. The youngest lacustrine phases in the basin are Lake Lisan (70–13 ka, e.g. Haase-Schramm et al., 2004) and the Holocene Dead Sea. At the end of the Last Glacial period, the lake desiccated, leaving a series of leveled shore terraces on the margins of the basin (Fig. 1). These terraces are composed of locally-derived coarse clastic sediments deposited parallel to the lake margin extending horizontally along tens to thousands of meters (Fig. 2). Observations along the modern retreating Dead Sea shore and lakeshores in a similar setting (Adams and Wesnousky, 1998) indicate that terraces develop in response to lake level rise usually after floods have transported coarse sediments into the lake.

New airborne laser scanning data from a section of the DSB western margin provide high-density sub-meter resolution and spatial extent of modern and late Pleistocene shore terraces (Fig. 3). The digital elevation models enable the detection and measurement of these geomorphic features. Applying a model for shoreline extraction from the point cloud (Baruch and Filin, 2008), we present the 3D geomorphic description of a sequence of sixteen shore terraces between 275 and 340 m bmsl (Table 1). We argue that the terraces were formed during short-term level rises superimposed on the main level drop of Lake Lisan. The fast drop and steep escarpments ensured the continuity of this high-resolution level record from the highest (oldest) to the lowest (youngest) terrace.

According to the dated Lake Lisan level curve (Bartov et al., 2003) and the LiDAR absolute elevations, the terraces were deposited at a short interval during the last stages of the lake desiccation. The age of the terrace sequence is constrained to the top of the Lisan Formation dated by U–Th chronology to 14.5 with and uncertainty of 0.5 ka (Haase-Schramm et al., 2004; Torfstein et al., 2013). The overlying Ze'elim Formation is dated by radiocarbon to 11,315 $\pm$ 80 years BP, calibrated to $\sim$13.2 (13.56–12.87; 2σ range) ka cal BP (Yechieli et al., 1993; Stein et al., 2009). The age was obtained from the marl unit deposited above an unconformity constraining the younger age for the terrace sequence. The Holocene Dead Sea levels were lower than the youngest and lowest terrace, not reaching above 370 m bmsl (Migowski et al., 2006). The chronological range and number of terraces impose a frequency of approximately one short-term level rise per century. Direct dating of individual terraces is challenging. In contrast to buried lacustrine sequences within the DSB (e.g. Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006), the terraces remain exposed, thereby allowing scarce young vegetation growth that will give erroneous radiocarbon ages. Optically-stimulated luminescence dating was previously tested on Lisan shore terraces (Matmon et al., 2003), but the time range of the entire terrace sequence falls within the error range of the method.

3. The 1991–1992 anomalous wet winter and the Pinatubo eruption

Although shore terrace sequences along the margins of the DSB have previously been described (Bowman, 1971), their hydro-climatological significance has never been interpreted. The question of climatic trigger for the short-term level rises superposed on the major Lake Lisan desiccation is addressed here using a modern analogue. The modern saw-tooth-like Dead Sea level record has been continuously documented since the beginning of the 20th century (Weinberg, 2009). Along the retreating shores, leveled terraces are known to build up during the winter wet season, leaving a high-resolution elevation record that can be correlated with the historically documented record (Klein, 1986; Filin et al., 2014). The laser scanning data from the current shore zone identified a distinctive $\sim$2-m high terrace, which was formed during the 1991–92 winter level rise (Fig. 4).

The 1991–92 winter was characterized by above-average precipitation over the DSB drainage area. In the Jerusalem rain station, which closely correlates with stations in the DSB headwaters (Enzel et al., 2003), the annual precipitation (1255 mm) was 227% of the mean long-term precipitation record (552 mm) available since 1846 (Isrel Meteorological Service, 2013). The Degania Dam, located at the Sea of Galilee's outflow to the southern Jordan River, was opened that winter and in the following winter, allowing ten times more water discharge (260 million m^3 year^{-1}) than the flow during the previous period (20 million m^3 year^{-1}; Weinberg, 2009). The overall increased discharge to the DSB that winter raised the lake level by approximately 2 m. An upper low salinity water layer was restored, meromictic conditions persisted for a few years (Gertman and Hecht, 2002), and an unusual phenomenon of unicellular green alga *Dunaliella parva* development was evident in the upper water column during the following spring (Oren, 1995). This level rise resulted in the conspicuous shore terrace, easily recognizable along long stretches of the modern retreating shores (Fig. 4). In conclusion, although the modern lake level drop is controlled by the anthropogenic diversion of freshwater, the 1991–92 level rise and

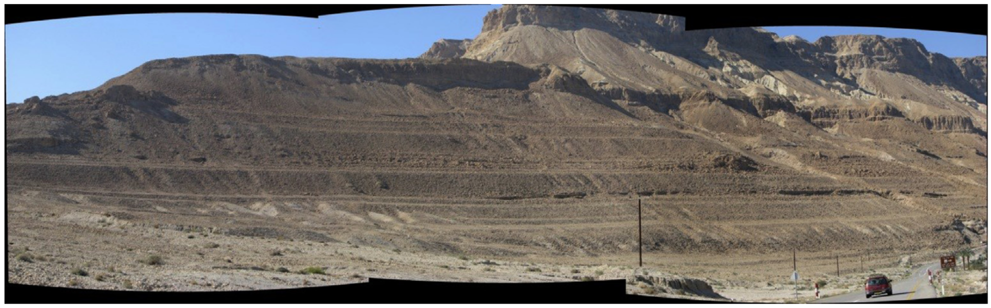

Fig. 2. Lake Lisan desiccation shore terraces on the western escarpment of the Dead Sea Basin.

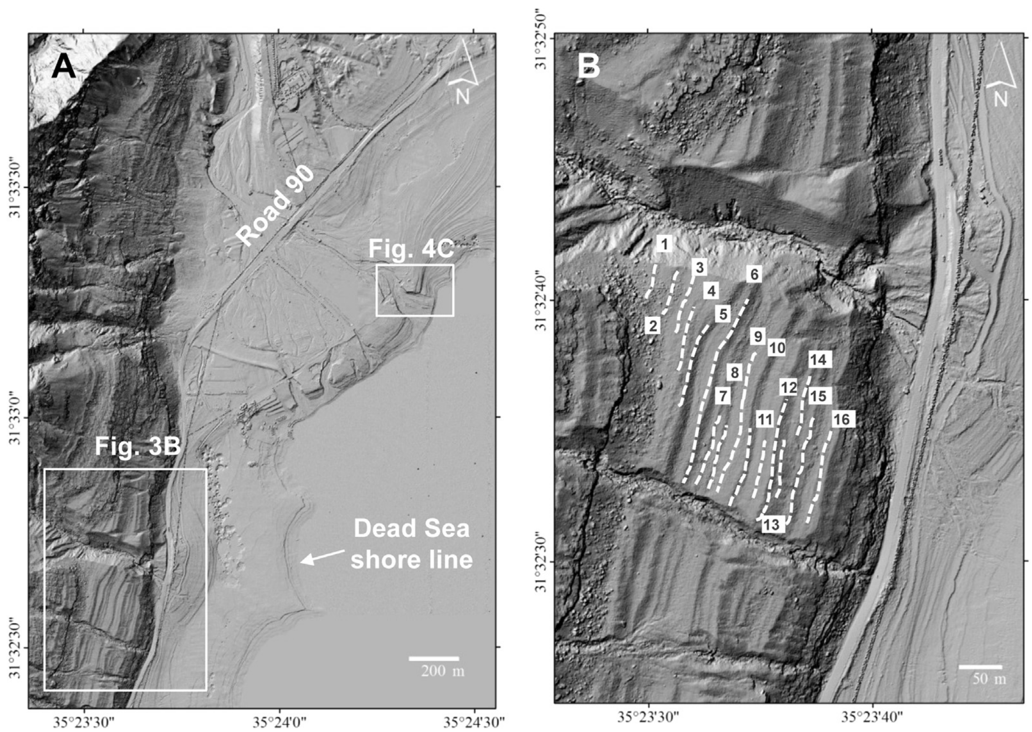

Fig. 3. (A) Shaded relief map of the shore terraces sites as derived from the laser scanning data (point density of ~4 pts/m^2). (B) Marked in dashed lines is the elevation of the terraces described in Table 1.

the distinctive shore terrace reflect the unusually rainy winter and subsequent high runoff to the Dead Sea.

The anomalous wet winter followed the June 1991 explosive eruption of Mt. Pinatubo in the Philippines. This eruption caused the largest perturbation in the last century to the particulate content of the stratosphere (McCormick et al., 1995). Observations and models of air temperatures following the eruption showed a significantly cold anomaly over the eastern Mediterranean (Robock and Mao, 1992). Remarkable ecological effects in the form of vertical water column mixing and coral death were reported in the Gulf of Eilat (Red Sea) as a result of the short-term atmospheric cooling (Genin et al., 1995). The Pinatubo eruption and the cooling anomaly over the eastern Mediterranean were determined to be the cause for the abnormally high precipitation over the Dead Sea watershed during that winter (Trenberth and Dai, 2007), which subsequently resulted in the lake level rise. The volcanic eruption preceding the Pinatubo, namely the El Chichon (Mexico, 1982), did not result in a level rise in the Dead Sea, probably because fresh water was not allowed to pass through the Degania Dam that year (Weinberg, 2009). However, both the Gulf of Eilat (Genin et al., 1995) and the Dead Sea (Oren, 1995) exhibited climatic-ecological effects similar to the effects of the Pinatubo eruption, albeit at a smaller magnitude.

Analysis of historical annual precipitation series from Jerusalem (St. Anne rain gauge) since the Krakatau eruption (1883) showed a significant positive correlation between the Dust Veil Index (DVI; Lamb, 1970) of the last 12 largest eruptions (Robock and Mao, 1992) and corresponding annual rainfall (Fig. 5A). A similar positive correlation was reported by Rosenfeld (1992). The DVI was found to explain nearly 50% of the variability in the annual rainfall (Fig. 5A), such that greater DVI means more rainfall. Other factors that were reported to affect the annual rainfall in the region are the Southern Oscillation Index (SOI) (Ziv et al., 2006) and the North Atlantic oscillations (NAO) (Kushnir and Stein, 2010). The averaged December–January–February–March (DJFM) values of the SOI and NAO were incorporated along with the DVI in a linear multiple regression model. It was found that the NAO did not contribute anything except for increased noise, but the added SOI increased the explained variability of rainfall to more than 60%. The multiple regression form is:

Table 1
Shore terraces and corresponding volcanic eruptions from the GISP2 ice core (after Zielinski et al., 1996).

Terrace no.[a]	Elevation (mbsl)	Height (m)	Volume (m^3)[b]	SO_4^{2-} Residual (ppb)	Year of signal[c]
1	275	4.7	$1.05 \cdot 10^{10}$	101	15,037
2	279	4.5	$9.79 \cdot 10^{9}$	124	14,905
3	284	1.8	$3.95 \cdot 10^{9}$	86	14,825
4	286	2.5	$5.41 \cdot 10^{9}$	81	14,811
5	288	9.9	$2.04 \cdot 10^{10}$	240	14,788
6	298	5.2	$1.02 \cdot 10^{10}$	139	14,651
7	303	2.7	$5.31 \cdot 10^{9}$	94	14,546
8	306	3.4	$6.58 \cdot 10^{9}$	117	14,533
				78	14,392[d]
9	309	2.8	$5.31 \cdot 10^{9}$	81	14,328
10	312	5.2	$9.56 \cdot 10^{9}$	147	14,324
				77	14,287[d]
11	317	2.1	$3.77 \cdot 10^{9}$	91	14,265
12	319	4.5	$8.15 \cdot 10^{9}$	104	14,201
13	324	3.3	$5.81 \cdot 10^{9}$	82	14,124
				80	14,119[d]
14	327	5.1	$8.73 \cdot 10^{9}$	86	14,113
15	332	6.5	$1.09 \cdot 10^{10}$	149	14,050
16	339	2.8[e]	$4.66 \cdot 10^{9}$[e]	92	13,892

[a] See terrace sequence in Fig. 3.
[b] Calculated using the digital topography and bathymetry of the area of the Dead Sea Depression DTM (Hall, 1996).
[c] Age errors are estimated to be about 5% (Alley et al., 1993). Temporal resolution of individual samples from the ice core record is 3–5 years (Zielinski et al., 1996).
[d] Possible Icelandic or other high-latitude eruptions directly upwind from Greenland, with no global or northern hemisphere climatic effect.
[e] Minimum terrace height and calculated volume dictated by the cliff edge, as the base of the youngest terrace is not exposed.

$$\text{Predicted Annual Rain [mm]} = 0.409\text{DVI} - 8.156\text{SOI} + 420.018$$

Fig. 5B shows the relation between the multiple regression predicted rainfall versus the actual rainfall.

The physical atmospheric model for the effect of radiative and chemical effects of the volcanic aerosol cloud produced after the Mt. Pinatubo eruption shows responses in the climate system on a hemispherical scale. Scattering of the solar radiation cooled the surface, but absorption of solar and terrestrial radiation also heated the stratosphere. This lead to a dominant mode of a stronger polar vortex during the following winter circulation in the stratosphere (polar jet) resulting in temperature anomalies in the Northern Hemisphere continents (Perlwitz and Graf, 1995); Europe was much wormer than normal, while the Middle East was cold (Robock, 2000). Recently, the connection between the Northern Hemisphere climates and precipitation in Israel was established showing the above average precipitation in the winter following the Pinatubo eruption (Givati and Rosenfeld, 2013).

4. Correlation between DSB terraces and SO_4^{2-} peaks in GISP2 ice record

Volcanic eruptions with a VEI of 6, as in the Pinatubo, occurred about once a century during the Holocene period (Simkin, 1993) at a rate that persisted throughout the Last Glacial–Interglacial cycle, though with large variations in the mean (Zielinski et al., 1996). This occurrence is similar to the frequency of shore terrace build-up during the Lake Lisan desiccation. Therefore, we hypothesized that the climatic events responsible for the short-term increased runoff are connected to climatic perturbation of cold anomalies over the Levant following large volcanic eruptions and resulting in increased precipitation. Other possible climatic mechanisms were

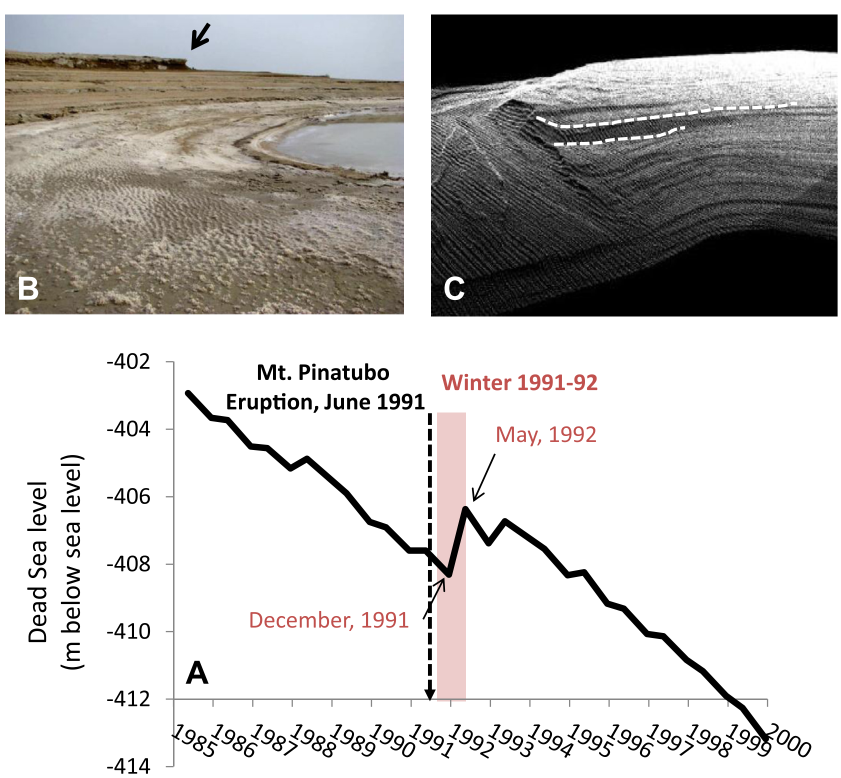

Fig. 4. (A) The Dead Sea level elevations from 1985 to 2000 (Israel Hydrological Survey data). During the 1991–92 winter, the lake level rose by approximately 2 m due to increased runoff to the lake. Marked with a dashed arrow is the Mt. Pinatubo eruption and in color the following wet winter. The anomalous lake level rise resulted in a noticeable terrace of about 2 m high along the Dead Sea western shores. (B) Marked with an arrow at Ze'elim Plain (picture taken in 1996), and (C) marked with a dashed line in Mineral Beach (for locations see Fig. 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

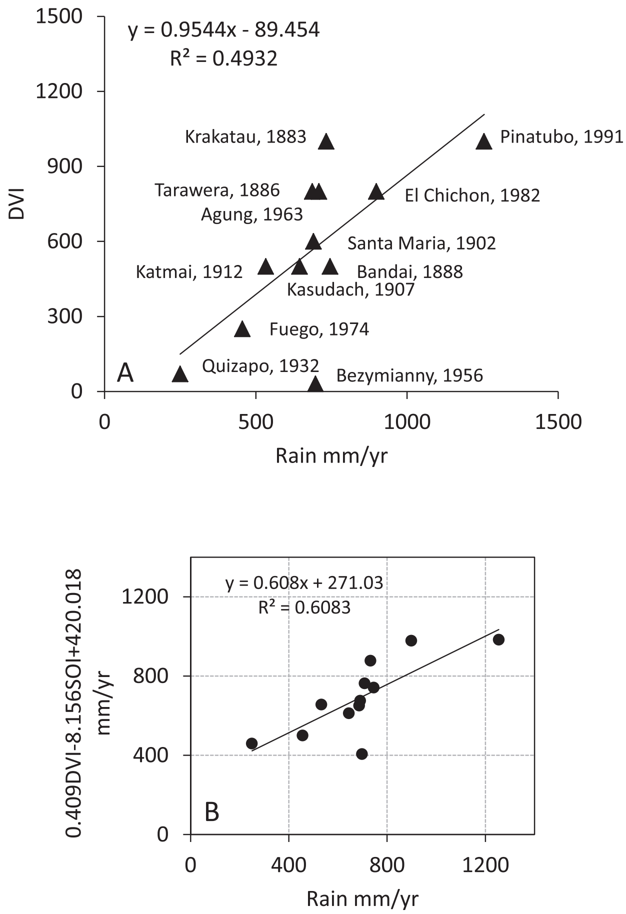

Fig. 5. Relation between the DVI of the last 12 largest volcanic eruptions (Robock and Mao, 1992) and annual precipitation time series (1847–2013) from the St. Anne rain gauge in Jerusalem (A). Relation between the multiple regression predicted rainfall versus the actual rainfall (B).

excluded due to their frequency or opposite climatic effect. Heinrich events were proposed as climatic oscillations that could explain major drops in the Lake Lisan level curve (Bartov et al., 2003; Haase-Schramm et al., 2004), but their time span, frequency, and opposite climatic effect over the DSB catchment exclude them as candidates. The modern records of seasonal rainfall, stream flow, snowfall, and lake levels from the northern DSB headwaters indicate enhanced precipitation during the winters of the El Niño in the last 25 years (Price et al., 1998). However, the frequency and lack of correlation in the DSB region prior to the 1970s (Price et al., 1998) also exclude this oscillation as the main cause for the short-term level rises during the desiccation of Lake Lisan.

Geochemical traces of the Pinatubo eruption and previous historical eruptions are evident in polar snow and ice, demonstrating the global dispersal of volcanic aerosol (Robock and Free, 1995; Cole-Dai et al., 1997; Zielinski et al., 1997). Past historical and geological volcanic activity is reconstructed from SO_4^{2-} concentration peaks in continuous ice cores combined with high-resolution dating (Zielinski, 2000). Although the number of ice cores that provide evidence for volcanic eruptions decrease as one goes back in time, the GISP2 ice core offers one of the most remarkable volcanic records (Zielinski et al., 1996). The ice core record may be incomplete, but it provides important information on the global atmospheric loading of volcanic aerosols not available elsewhere and offers the capability to predict the climatic response to large eruptions (Robock, 2000; Cole-Dai, 2010).

Zielinski and colleagues (Zielinski et al., 1996) concluded that volcanic eruptions represented by high (≥75 ppb) SO_4^{2-} concentration peaks of volcanic origin in the GISP2 ice core have impacted northern hemisphere climates. This is manifested in the comparison of the ice core record with the DSB shore terrace sequence deposited at the end of the Last Glacial period, as both records present a similar number of events/millennium.

A new timescale (GICC05) established for the Greenland Ice Core Project agrees fairly well with the GISP2 chronology (Rasmussen et al., 2006) for the time period determined for the DSB shore terrace sequence as presented above allowing a detailed comparison between the time series of aerosol peaks (Table 1 in Zielinski et al., 1996) and shore terraces. For each terrace the increase in water volume, which represents the hydrological consequences of the lake level rise, was calculated using the DSB digital topography (Hall, 1996). Then, the correlation between the two data sets (water volume and aerosol peaks) was tested for the time frame limited by the dating of the oldest and youngest shore terraces with their age uncertainties. Kept in stratigraphical order, the shore terrace heights were shifted along the SO_4^{2-} concentration record between the events dated to 16,006 and 12,719 years BP (Fig. 1, Supplementary Data). The best fit was achieved between 15,037 and 14,199 years BP (Fig. 6). This correlation increases significantly ($R^2 = 0.8$) when the three smallest peaks are excluded from the graph expanding the time period to 15,037 and 13,892 years BP, in accordance with the age estimation for the terraces as suggested above. This scenario is plausible, as high-latitude eruptions directly upwind from Greenland can produce an enhanced signal from tropospheric transport (Zielinski, 1995), recording volcanic events that could not impact meteorological conditions in the DSB region. However, identification of tephra horizons in the ice record without a chemical signal demonstrates that some peaks may be overlooked (Abbott and Davies, 2012).

The reconstruction of past volcanism using sulfate concentrations in ice does not allow an accurate evaluation of the climatic impact mostly owing to the uncertainty in distinguishing between stratospheric or tropospheric eruption. Until anomalous isotope composition of volcanic sulfate (Baroni et al., 2008) will be applied on sulfate peaks beyond historical ice records this issue will stay unsettled. Nevertheless, the DSB and the GISP2 site are both located in the northern hemisphere, therefore it is reasonable to suggest

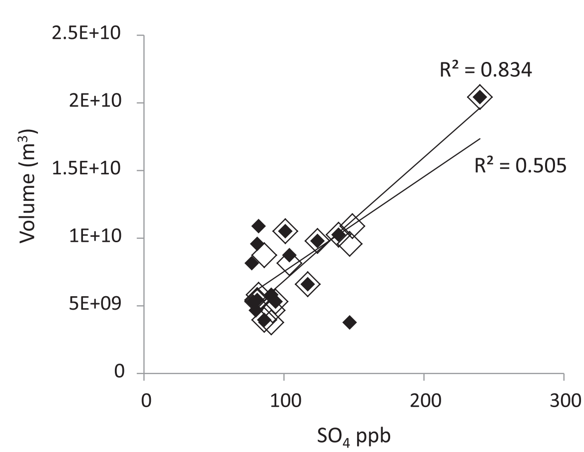

Fig. 6. Time series of volcanigenic sulfate from the GISP2 ice core record (Zielinski et al., 1996) vs. the increase in water volume that represents the lake level rises recorded as the sequence of shore terraces along the DSB escarpment. The relationship between the two data sets was tested for the time frame limited by the absolute dating of the oldest and youngest shore terraces (Haase-Schramm et al., 2004; Stein et al., 2009) at the transition from the Last Glacial to the Holocene period during the final stages of Lake Lisan. See also Supplementary Data, Fig. 1.

large volcanic eruptions injecting material into the stratosphere are likely to leave geochemical traces in the ice cores and have a climatic effect in the DSB almost simultaneously.

5. Concluding remarks

The significance of our results lies in demonstrating a possible connection between volcanic eruptions and subsequent climatic effects. The sequence of shore terraces, deposited during the Lake Lisan desiccation on the steep margins of the DSB, was preserved due to the extremely arid environment that enabled this fossilized snapshot to abrupt climatic events in the geological past. The correlation indicates that volcanic eruptions which left elevated aerosol concentrations in the Greenland ice core record amplified precipitation over the DSB, thereby increasing the lake levels. This correlation is justified by the modern analogue of the Dead Sea level rise and the shore terrace development following the 1991 Pinatubo eruption. The message of this study is significant for future high resolution climatic studies from the ICDP Dead Sea project drilled in 2011 (Stein et al., 2011). The long and relatively continuous sediment record that was recovered from the deep basin has the potential to further investigate the possible effect of large volcanic eruptions based on teleconnection with other high-resolution records such as ice cores and marine sequences.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.02.009.

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Supplementary data

Possible connection between large volcanic eruptions and level rise episodes in the Dead Sea Basin

Revital Bookman[1], Sagi Filin[2], Yoav Avni[3], Daniel Rosenfeld[4], Shmuel Marco[5]

1. Department of Marine Geosciences, Charney School of Marine Sciences, University of Haifa, Mt. Carmel, Haifa 31905, Israel
2. Department of Transportation and Geo-Information Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel
3. Geological Survey of Israel, 30 Malchei Yisrael St., Jerusalem 95501, Israel
4. Institute of Earth Sciences, The Hebrew University, Jerusalem 91904, Israel
5. Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv 69978, Israel

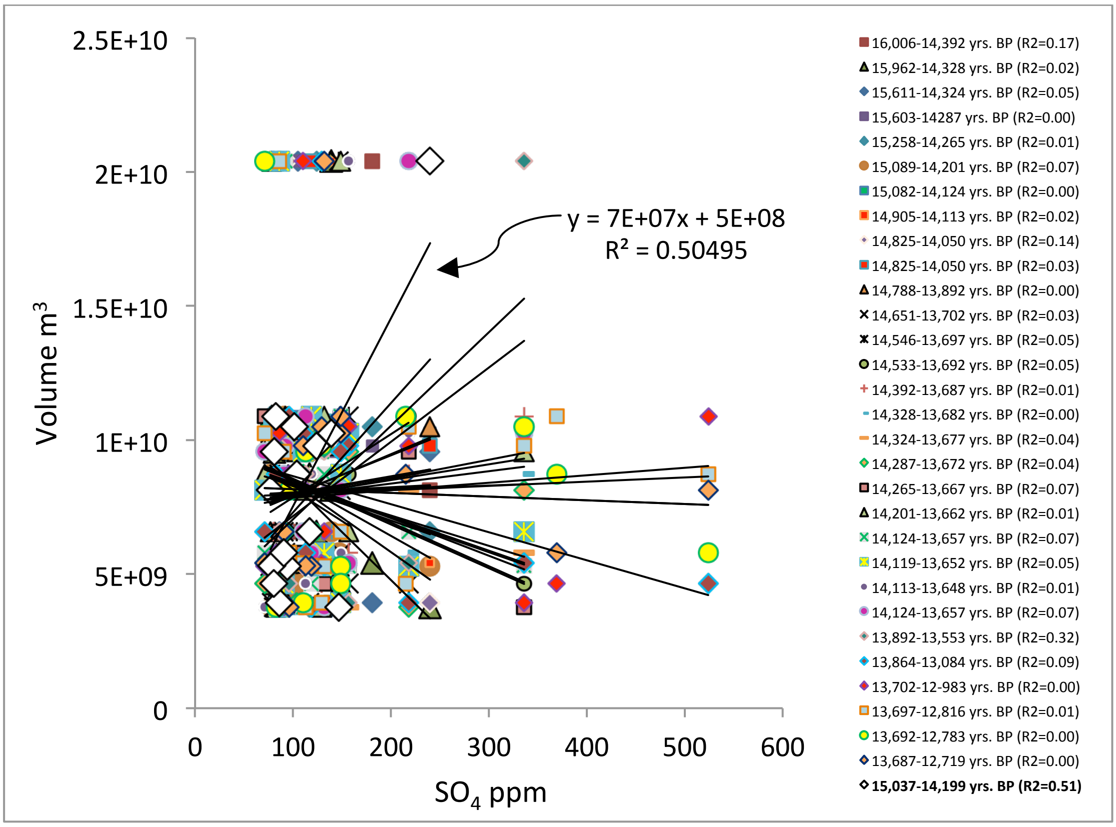

Fig. 1 – This graph presents the possible relationship between the sulfate concentration peaks from the GISP2 ice record (Zielinski et al., 1996) and increase in water volume for each shore terrace calculated using the DSB digital topography (Hall, 1996). The calculated water volume better represents the physiography of the basin and the hydrological impact of increased runoff to the lake.

The correlation between the two data sets (water volume and aerosol peaks) was tested for the time frame limited by the dating of the oldest and youngest shore terraces with their age uncertainties. Kept in stratigraphical order, the shore terrace heights were shifted along the SO_4^{2-} concentration record between the events dated to 16,006 and 12,719 years BP (Table 1 in Zielinski et al., 1996). The best fit (R^2=0.505) was achieved between 15,037 and 14,199 years BP (open diamonds) in accordance with the age estimation for the terraces as suggested in the paper based on chronologies of Late Quaternary Dead Sea basin sediments (Yechieli et al., 1993; Bartov et al., 2003; Haase-Schramm et al., 2004; Stein et al., 2009; Torfstein et al., 2013).

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