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# Pliocene–Pleistocene climate of the northern margin of Saharan–Arabian Desert recorded in speleothems from the Negev Desert, Israel

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ABSTRACT

The Middle–Late Pliocene climate was 2–3 °C warmer than today, but with similar levels of atmospheric $CO_2$. This period reflects climate conditions expected in the near future, and is therefore an important target for current data-modeling studies. This study reconstructs the Pliocene–Quaternary evolution of arid conditions on the northern margin of the Saharan–Arabian desert, using radiometrically (U–Pb) dated periods of speleothem deposition from three caves of the Negev Desert, Israel. Speleothem growth started between ~3.75 and ~3 Ma, at the end of the first significant tectonic uplift of the western shoulder of the Dead Sea Rift. Major speleothem deposition, indicating wet conditions, occurred during the Pliocene around ~3.1 Ma, with subsequent aridity during the last 3 Myr, punctuated by short wet episodes – the Pleistocene Negev Humid Periods (NHP). The oldest dated NHP occurred between ~1.7 and ~1.25 Ma, and other short humid episodes continued intermittently later. Speleothem $\delta^{18}O$ values (−6.9‰ to −11.2‰) show that the humid episodes were associated with periods of low global ice volume and warm temperatures. After correction for rainfall $\delta^{18}O$ changes associated with ice volume and temperature effects, the observed relative constancy of speleothem $\delta^{18}O$ values from Pliocene to Late Pleistocene indicates rainfall was from a common source, most probably the eastern Mediterranean Sea. The humid Pliocene conditions could be generated by more southerly position of the Mediterranean coast (allowing the access of Mediterranean precipitation to the Negev), as well as by warmer Atlantic Sea Surface Temperatures, that weakened the Azores High Pressure Cell. Maximum amounts of precipitation were 500–600 mm/a during the Pliocene and >300 mm/a during Pleistocene NHP. The Pliocene and the earliest Pleistocene NHP are associated with formation of lakes in the Negev. Low $^{87}Sr/^{86}Sr$ ratios of ~0.7078 in the Pliocene speleothems are indicative of low dust supply, low water residence time in the vadose zone and relatively high weathering rates of the cave host rock. Increase of $^{87}Sr/^{86}Sr$ ratios to 0.7082–0.7083 in the Pleistocene suggest an increased supply of desert dust, high water residence time in the vadose zone and reduced host rock weathering.



## 1. Introduction

Middle Pliocene (3.6–3 Ma) climate was 2–3 °C warmer than present, with atmospheric $CO_2$ concentrations ranging between 350 and 450 ppm (Pagani et al., 2010). This period is regarded as a potential analog for future climate change, and is a prime target for current data-modeling studies of sea surface temperatures (Dowsett et al., 2012), ice sheet extent/sea level (Dolan et al., 2011; Raymo et al., 2011), and vegetation/climate zones (Salzmann et al., 2008, 2009). Paleoclimate and modeling data show smaller polar ice sheets, and in lower latitudes increased humidity and limited extent of deserts, especially in southern Sahara and Australia. However, the sparse Pliocene terrestrial climate record is a limiting factor for the ability of models to assess the Pliocene climate and to use it as a means for prediction of future climate change.

Formation of the vast present-day deserts is usually linked to Pliocene–Quaternary global cooling (deMenocal, 2004; Han et al.,

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2007; Wilson et al., 2000), that may have contributed to reduced evaporation from the oceans, causing less moisture to reach continental areas (Wilson et al., 2000). This mechanism is still not entirely supported by geologic evidence, because of gaps in the chronology of past desertification processes. Determination of accurate timescale for desert evolution is a key issue in understanding the relationship between global climate change and desertification. In particular, the reconstruction of a precise timescale for the formation of the Saharan–Arabian Desert holds great importance for understanding of the desertification process.

deMenocal (2004) suggested that a major increase in export of large amounts of dust to the Atlantic Ocean at ~2.8 Ma provides evidence for the onset of desert conditions in the Sahara contemporaneously with the formation of the northern pole ice cap. This study suggests further expansion of the desert at 1.7 Ma, accompanied by another increase in the dust flux from the desert to the ocean. Trauth et al. (2009) suggests the onset of the major dust flux into Atlantic Ocean, Mediterranean Sea and Arabian Sea occurred between 1.9 and 1.4 Ma.

Dating of both lake levels and marine cores involves relatively large uncertainties. As a result, it is still not clear if the increased dust supply from the African land mass to the oceans occurred throughout dry phases (deMenocal, 2004), or is associated only with humid–dry transitions (Trauth et al., 2009). Clearly, the dating of terrestrial desertification cycles requires more accurate proxies, enabling the construction of a precise timescale for the aridification of the northern Africa and the Arabian Peninsula, and its relation to Pliocene–Quaternary global climate change.

Carbonate vadose speleothems (stalactites, stalagmites and flowstones) provide one of the most valuable terrestrial paleoclimate archives because of their amenability to high precision radiometric dating and high-resolution stable isotope proxy records of climate variability. Speleothems grow in caves when water reaches the unsaturated zone (Hendy, 1971; Schwarcz, 1986), but they do not grow in the water-depleted conditions of arid/hyper-arid deserts (Fleitmann et al., 2003; Holmgren et al., 1995; Vaks et al., 2003, 2006, 2007, 2010). Thus, speleothem deposition indicates positive effective precipitation (i.e. =precipitation–evaporation–runoff) during the rainy season, and enables us to precisely trace past humid episodes in the present-day desert region. Speleothems can be accurately dated by U–Th and U–Pb methods, using Thermal-Ionization Mass Spectrometry (TIMS) and Multi-Collector-Inductively-Coupled Mass Spectrometry (MC-ICP-MS) (Edwards et al., 1987; Woodhead et al., 2006; Walker et al., 2007). In Israel speleothem $\delta^{18}O$ values provide an effective proxy for the source of atmospheric precipitation (Frumkin et al., 1999; Bar-Matthews et al., 2003), whereas $\delta^{13}C$ values mainly provide information about changes of vegetation photosynthetic types above a cave (C3 – forest; C4 – steppe/semi-desert shrubs/grasses), which are indicative of relative wet–dry variations (Schwarcz, 1986).

Previous speleothem studies in the northern Saharan–Arabian region focused on the Negev Desert, Israel. These studies were based on 123 speleothems from 14 caves, located on a 300 km north–south transect, from the sub-humid Mediterranean climate in the north, to hyper-arid desert in the south, and included 344 U–Th age determinations. Most of the Negev Desert speleothems are older than 550 ka (the limit of the U–Th dating method). The younger speleothem layers are thin and their deposition was highly intermittent (Lisker et al., 2010; Vaks et al., 2003, 2006, 2007, 2010), and contrast with the massive young speleothems and continuous speleothem deposition in the Mediterranean climate zone further to the north (Bar-Matthews et al., 2003). No currently growing or Holocene speleothems are found south of present-day 300 mm rainfall isohyet. This shows that amount of atmospheric precipitation is the fundamental force driving the speleothem deposition in the region. Speleothem deposition in the central and southern Negev Desert during the Middle–Late Pleistocene was also very rare, occurring during short, mainly interglacial wet episodes. The four youngest clusters of speleothem growth episodes occurred at 350–310 ka, 310–290 ka, 225–190 ka and 142–109 ka, termed Negev Humid Periods (NHP) 4, 3, 2 and 1 respectively. Minor humid events between 350 and 550 ka have also been recorded. The NHP were most probably the result of stronger Mediterranean cyclones contemporaneous with an intensification of the African monsoon, bringing wetter conditions to both northern and southern Saharan–Arabian Desert, and possibly assisting the migrations of hominids and animals out of Africa (Vaks et al., 2007, 2010).

The major aim of this study is reconstruction of the timing of Pliocene–Pleistocene wet–dry cycles on northern margin of Saharan–Arabian Desert and their relation to the global climate change, using high-precision U–Pb dating of central/southern Negev Desert speleothems. The advantage of the U–Pb method is its ability to extend the utility of speleothems' dating beyond the 550 ka limit of the U–Th method (Woodhead et al., 2006; Walker et al., 2007; Polyak et al., 2008; Pickering et al., 2010). Additional aims are reconstruction of the history of dust supply and weathering patterns in the region using speleothem $^{87}Sr/^{86}Sr$ ratios, determination of the sources of atmospheric precipitation using speleothem $\delta^{18}O$, and identification of the first generation of vadose speleothems in order to determine when the tectonic uplift of the western shoulder of Dead Sea rift occurred.

## 2. Environment, climate and geology of the research area

Israel's present-day climate zoning incorporates a Mediterranean climate in northern/central Israel ( > 350 mm of rainfall/year) and the dry Negev Desert in the south. The northern Negev is characterized by mildly arid steppe/semi-desert (350–150 mm/a), whereas the research area in the central and southern Negev is arid to hyper-arid desert with 150–30 mm of annual rainfall (Fig. 1). Summers, between May and September, are hot and dry as a result from the sinking air from subtropical highs. The major rainfall source is mid-latitude Atlantic–Mediterranean cyclones moving eastwards above the eastern Mediterranean Sea mainly between November and March (Dayan, 1986). The precipitation from the Atlantic–Mediterranean cyclones declines sharply to the south and more gradually to the east of the eastern Mediterranean Sea coast, because the sea is the source of the moisture and latent heat feeding the cyclones (Shay-El and Alpert, 1991; Enzel et al., 2008). Thus, the northern Sinai coastline forms the southern limit at which rain clouds usually form, and the latter are carried to the east by westerly winds leaving the southern region dry (Zangvil and Druian, 1990) (Fig. 1). The location of the Sinai and Nile delta coastline was shifting during the Pliocene and Pleistocene (Zilberman, 1991, 1992; Said, 1993; Avital, 2003), affecting the transport of Mediterranean rainfall to the Negev.

Studied karstic caves in the Negev are found within dolomites and limestones of Cretaceous (Cenomanian and Turonian) Judea Group (Supplementary Fig. 1). The caves were most probably formed between the Late Eocene and Miocene when the Judea Group was below the groundwater table (Frumkin and Fischhendler, 2005). Tectonic development of the region since the Late Miocene included subsidence of the Dead Sea Rift valley's floor and uplift of its shoulders, including the Negev. As a result, the caves were uplifted above the groundwater table during two major tectonic phases: (1) in the Late Miocene–Pliocene (Picard, 1943; Garfunkel and Horowitz, 1966; Garfunkel, 1970, 1978, 1988; Steinitz and Bartov, 1991; Zilberman, 1991), and (2) during the Early Pleistocene (Zilberman, 1991; Avni, 1991, 1997;