Ministry of Energy
Geological Survey of Israel

Yamin plain: present-day and paleo climate conditions

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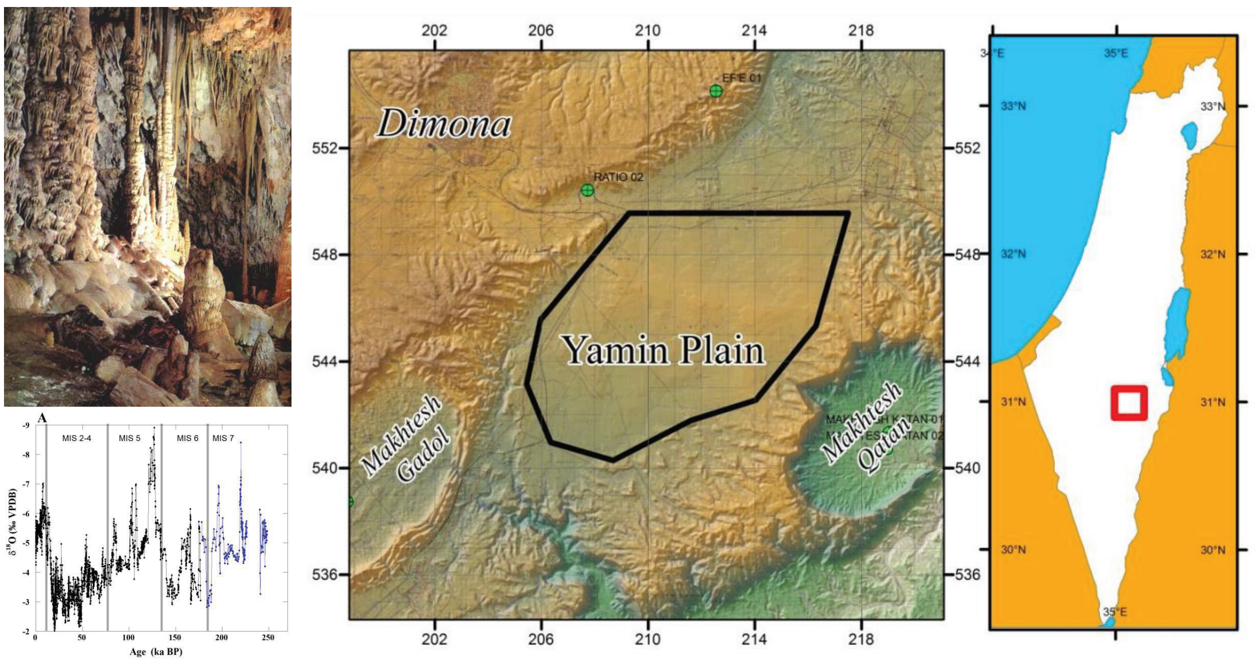

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YAMIN PLAIN: PRESENT-DAY and PALEO CLIMATE CONDITIONS

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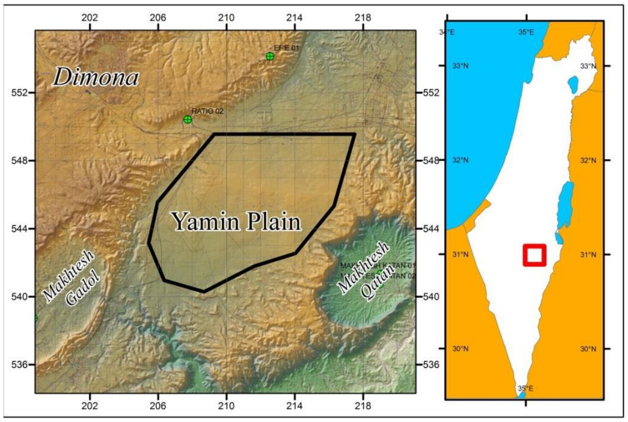
The goals of this report is to assess the suitability from climatic point of view of Yamin Plain (YP) to host a disposal site.

1. Yamin Plain

Yamin Plain (YP) is located in the northeast of the Negev Desert in Israel, in an arid climate. YP cover an area of about 150 km^2 (Figs. 1a, 1b), the topography is mainly of flat plain located between the two erosional craters (Makhtesh Qatan and Makhtesh Gadol), ranging from a peak elevation of 472 m above sea level (a.s.l.) to an elevation of around 390 m a.s.l. (Dody et al., 2017). Geologically, the YP is located in an asymmetric syncline, which is part of the Syrian Arch system (Krenkel, 1924; Salomon, 1987), and was intensively studied by Calvo et al (2018, 2019). Figure 1b shows slope (in degree units) in the vicinity of YP. The average annual precipitation is <100 mm/yr (Fig. 1b), while the potential evaporation amounts to 2600 mm. Rain falls during the autumn, winter, and spring seasons (October through May), comprising an average of 15 rainy days per year (Dody et al., 2017).
The location of the Greater Confinement Disposal (GCD) facility site was selected because of its high degree of waste containment potential. Characteristics of the site include arid climate and no surface water streams; Deep unsaturated zone with depth to groundwater of ~235 m; Deep structural basin filled with alluvium (sand and gravel); Remote location with low population density; Government owned land (Calvo et al., 2019).



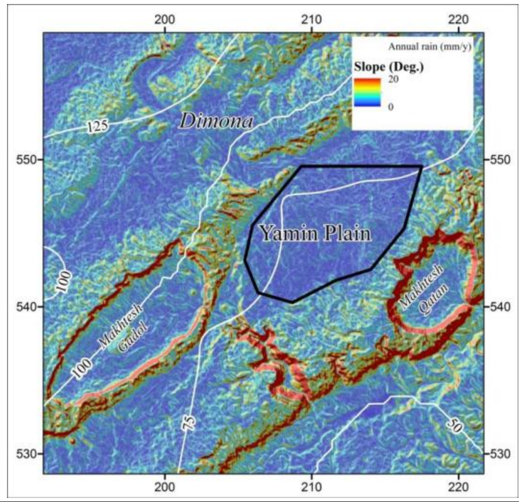


Figure 1a: *The location of Yamin Plain in the NE Negev (ITM coordinates). (From Calvo et al., 2018).*
Figure 1b*: Topographic slope of the Yamin Plain area in a 30 m pixel-size DEM (ITM coordinates). Contours of annual rainfall (mm/y) are also presented. (From Calvo et al., 2018).*

2. Present-day Climate and Rainfall system in Israel and its relation to YP

The Eastern Mediterranean (EM) - Levant region (Fig. 2) lies at the geographical meeting point of Eurasia, Africa, the Mediterranean Sea, and the Indian Ocean. The region is located along the Eastern Mediterranean Sea (EMS), which defines the Mediterranean climate zones. Away from the climatic influence of the EMS, the region rapidly becomes a desert. The EMS is the major moisture source for the precipitation. When passing over the land, the supply of moisture and latent heat becomes dramatically reduced to the south, and more gradually to the east (Shay-El and Alpert, 1991; Enzel et al., 2008). Thus, the northern Sinai coastline defines the southern limit at which rain clouds can form, and the latter are carried to the east by westerly winds, whereas the south remains dry (Zangvil and Druian, 1990). This results in the steepest rainfall gradient anywhere with Mediterranean climate in the world (Enzel et al. 2008). As a result, the present-day climatic belts are divided into the Mediterranean climate region in central and northern Israel north of the 350 mm isohyets (Fig. 3).

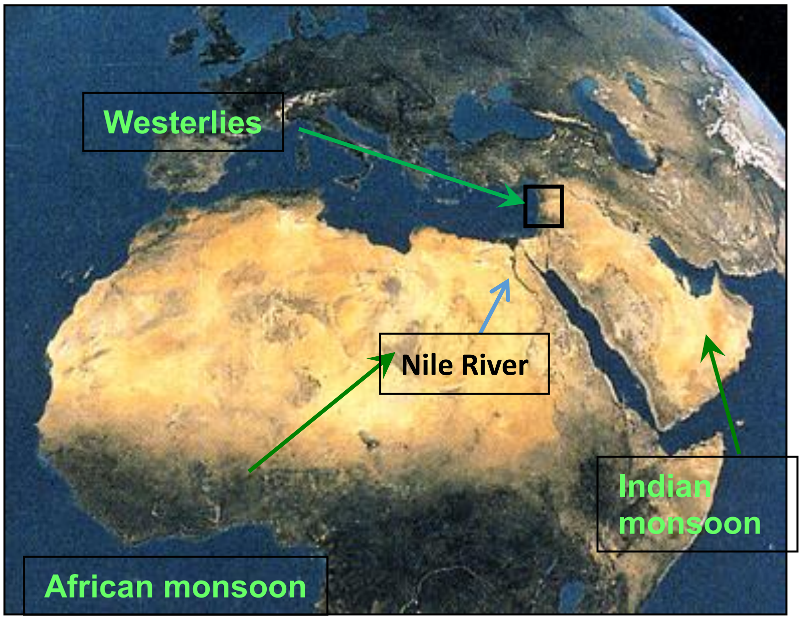


Figure 2. *Location and synoptic system: At the boundary between high - to-mid latitude and tropical-subtropical climate systems. The Mediterranean Sea moderate the climate. Most rainfall fronts originate in the NE Atlantic Ocean, pass over Europe and extract moisture from the EM Sea.*

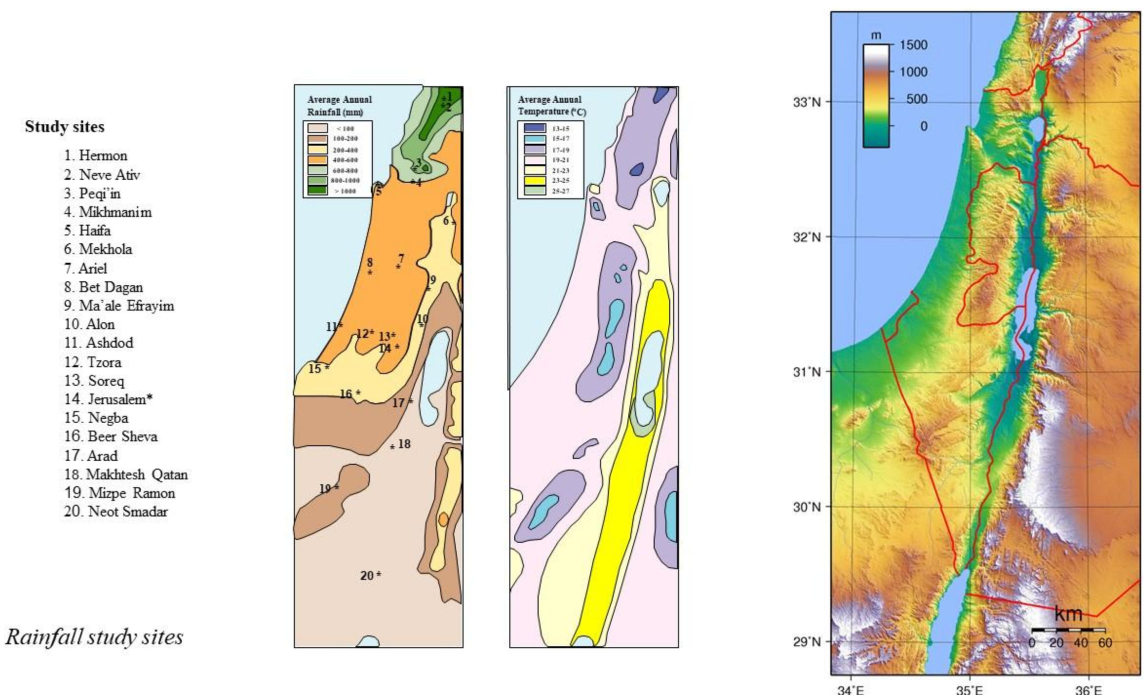


Figure 3. *Map showing the average annual rainfall and temperatures. The numbers indicate the study sites. YP is located between the "rain shadow" Desert and the Central Negev Desert climatic region.*

The desert region is divided into four regions (Fig. 4) (Vaks et al., 2006, 2010; Bar-Matthews et al., 2017): (1) **The 'rain shadow' desert** on the eastern flank of the Central Mountain Ridge of Israel. It defines a 15–30 km wide north–south strip along the Dead Sea and the Jordan Valley. (2) The **mildly arid steppe/semi-desert northern Negev**: a 40 km wide belt between the 150 and 350 mm isohyets. The northern Negev is the southern boundary of the Mediterranean climate zone. (3) The **arid central Negev** (or Negev Highlands) with 50–150 mm yr^{-1}. The vegetation is mixed between Mediterranean C3 type and C4 Sahara–Arabian Desert flora (4) The **hyperarid (25–50 mmyr−1) southern Negev**, Sinai, and southern Jordan. South of the 150 mm isohyet, in the central and southern Negev Desert. The vegetation is mainly of C4 Sahara–Arabian Desert flora (Vogel et al. 1986; Danin 1988).

At present, three types of trajectories characterize the rainfall pattern (Affek et al., 2023). In the first type, the precipitation is derived from mid-latitude Atlantic–Mediterranean cyclones (Dayan 1986; Ziv, 2006). The air mass arrives from Europe and passes over the Eastern Mediterranean Sea prior to reaching the Israeli coast. The second trajectory type is the North Africa trajectory, in which air mass moisture is derived mainly from the tropical Atlantic Ocean, pass over the southern part of the Mediterranean Sea, thus approaching the region from the south-southwest mainly from Egypt (e.g. Kahana et al. 2002). The third trajectory is the African trajectory that is characterized by air masses passing over land in Africa or over the Red Sea.
The northern Negev receives most winter precipitation from mid-latitude cyclones; the southern Negev receives its rainfall in sporadic short thunderstorms frequently associated with synoptic systems bringing moisture from the tropical Atlantic Ocean and from convective rainfall by the active Red Sea Trough (e.g., Kahana et al., 2002). These systems are common in the beginning and the end of the rainy season, approaching the region from the south-southwest (Kahana et al., 2002), and rarely affecting the northern Negev). Rainfall is usually in ∼2–3 high-intensity showers (~20–30 mm/hr) during the late fall or winter. The showers are localized, scattered, and short-lived, thus having limited effect on the regional mean rainfall (Sharon, 1972). The scattered high-intensity short-lived and localized showers have limited effects on soils and most of the water is not available for soil leaching (Amit et al., 2010).

Yamin Plain is located in the intersection between the mildly arid steppe/semi-desert northern Negev, the **arid central Negev and the 'rain shadow' desert**

Our understanding of the past climate is mainly based on climatic archives: mainly speleothems, Dead Sea lakes levels and soil formation.

Sharp transition from humid to hyper arid climate on North-East and South-West transect. The studied caves cover the various climatic regions

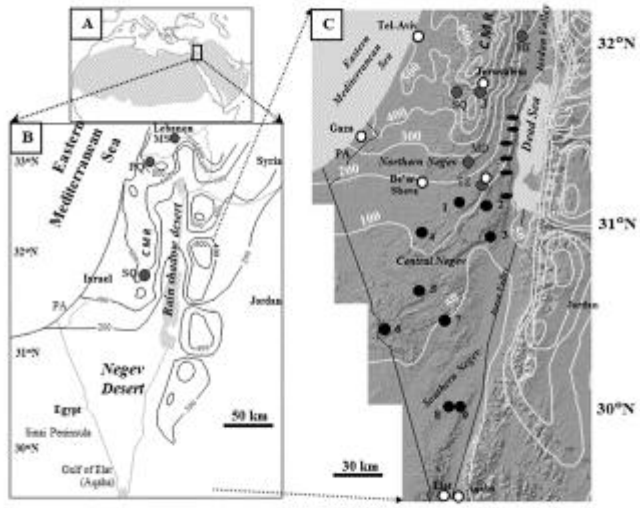


Figure 4. *Geographical location of the caves study area in the Negev Desert, annual precipitation and sample sites (from Vaks et al., 2017). (A) Map indicating the extent of the Saharan-Arabian Desert (shaded grey area). The rectangle marks the research area; (B) Annual rainfall map of Israel and adjacent lands: Palestinian Authority in Gaza (PA), north-eastern Egypt, western Jordan, south-western Syria, and southern Lebanon. Isohyets are indicated by black lines. Peqi'in Cave (PQ) (Bar-Matthews et al., 2003) located in northern Israel is marked. The dotted rectangle (enlargement in C) indicates the location of the desert caves studied in this research. (C) Map showing the relief (Hall, 1997), precipitation and location of the studied caves. The isohyets are marked by white lines and studied caves by black circles and numbers as following: 1 - Hol-Zakh Cave, 2 - Izzim Cave, 3 - Makhtesh-ha-Qatan Cave, 4 - Ashalim Cave, 5 - Even-Sid minicaves, 6 - Ma'ale-ha-Meyshar Cave, 7 - Wadi-Lotz Cave; Southern Negev: 8 - Shizafon mini-caves and 9 - Ktora Cracks. Other caves from other parts of Israel that were subject for previous studies (e.g. Bar-Matthews et al., 1997, 2003; Frumkin et al., 1999; Vaks et al., 2003, 2006); are marked by grey circles and abbreviations as follows: Central Israel: SQ Soreq Cave and Jerusalem Cave; Northern Negev: MD Ma'ale-Dragot and TZ Tzavoa Cave. The rain sampling stations at Be'er-Sheva, Arad, Makhtesh-ha-Qatan, Mitzpe- Ramon and Neot Smadar, are indicated by white circles.*

3. Speleothems

Formation of speleothems, most commonly composed of vadose-zone calcite, is linked to large-scale ocean–atmosphere–land hydroclimate processes. Their growth is associated with rainwater absorbing CO_2 formed in the soil as a result of biological activity, to form carbonic acid. Dissolution of soil carbonate and the host rock occur through downward migration of the carbonated waters. On reaching the open space of the cave, the solutions are supersaturated in CO_2 with respect to the cave atmosphere, and calcium carbonate deposition occurs as a result of CO_2 degassing.

Speleothems grow in caves when water penetrates into the unsaturated zone and surface vegetation is present to supply the CO_2 necessary for limestone dissolution (Fig. 5) (Hendy, 1971; Schwarcz, 1986). Speleothems may grow continuously in caves when water reaches the unsaturated zone and do not grow in arid/hyperarid deserts (e.g. Holmgren et al., 1995; Fleitmann et al. 2003a,b; Vaks et al. 2003, 2007, 2010) or where water is frozen and vegetation is scarce (e.g. Ayalon et al. 2013; Vaks et al. 2013). Thus, speleothem deposition is an indication that an annual season of positive effective precipitation (i.e. precipitation - (evaporation + runoff)) has occurred above the cave.

Speleothems potentially provide one of the most valuable paleoclimate, paleoenvironment and paleohydrology archives in this region (e.g. Bar-Matthews et al. 2000, 2003; Vaks et al. 2003, 2007, 2010; Frumkin et al. 2011), because their growth depends on water availability (rainfall), and the potential for high-resolution geochemical and stable isotope records. They can be accurately dated by the uranium–thorium isotopic method, (covering the last ~300,000 years) and with U-Pb methods (covering several million years). Thus, it is possible to accurately determine their growth and non-growth (hiatus) periods as indicators of water availability on land.

Together with the isotopic compositions of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) of each dated laminae, e.g., Bar-Matthews et al., 2000, 2003, 2017; Frumkin et al., 2011; Vaks et al., 2003, 2007, 2010; Fleitmann et al., 2011; Verheyden et al., 2017)

$\delta^{18}O$ and $\delta^{13}C$ isotope profiles of speleothem calcite are the most thoroughly investigated continental climate proxies (e.g., Hendy, 1971; Schwarcz, 1986; Bar-Matthews et al., 1996, 2017, 2019). The **$\delta^{18}O$ values** of speleothems ($\delta^{18}O_{Cc}$) depend on the isotopic composition of the water from which they were deposited and on the ambient temperature at the time of formation. Factors controlling water $\delta^{18}O$ include $\delta^{18}O$ values of the source of clouds (the sea surface), the atmospheric and hydrological evolution of rainfall such as temperature, distance from the marine source, altitude, rainfall amount, and seasonality of rainfall (e.g. Dansgaard 1964; Merlivat & Jouzel 1979; Gat 1996; Frumkin et al. 1999; Bar-Matthews et al. 2000, 2003; McDermott 2004). Thus, speleothem $\delta^{18}O_{Cc}$ records the global, regional, and local environmental conditions through sea surface conditions and climatic controls on the origin and amount of rainfall and temperature. Thus, we can use the speleothem $\delta^{18}O$ to determine either (1) the past temperature if we have an independent estimate of the past oxygen isotope composition of the water or (2) the past water $\delta^{18}O$ if we have an independent estimate of the past temperature. The past water $\delta^{18}O$ can be obtained from the isotopic composition of fossil waters that were trapped as fluid inclusions in the speleothems' calcite (Matthews et al., 2000, 2021, 2022; Dennis et al., 2001; McGarry et al., 2004; Levy et al., 2023).

The **$\delta^{13}C$ values** of calcite speleothems reflect mainly the type of vegetation in the vicinity of the cave, primarily reflecting the vegetation type, because the water percolating through the soil above the cave carries this information regarding the vegetation type. Enrichment in the $^{13}C_{Cc}$ usually reflects an increased contribution of C4 plants to soil CO_2, but the value is also a function of water-rock interaction and degassing processes (e.g. Bar-Matthews et al. 1996; Genty et al. 2001; Dreybrodt & Deininger 2014).

More advanced isotopic technique enable to calculate paleo cave temperature using clumped isotopes (D47) (Affek et al., 2008, 2022) and the isotopic composition (oxygen and hydrogen) of the original cave water inclusions locked in the speleothems can be analyzed and paleo rain water isotopic composition and paleo cave temperature can be reconstructed (Matthews et al., 2000; McGarry et a, 2004; Levy et al., 2023). All these advanced techniques make it possible to reconstruct the regional paleoclimate (The relatively large number of studies made on speleothems from caves in the EM-Levant region, allow us to achieve a deep insight into the climate of the land region; covering almost the entire climatic transect from the relatively wet EM region receiving >800mm annual rainfall, to the extremely dry region of Northeast Africa.

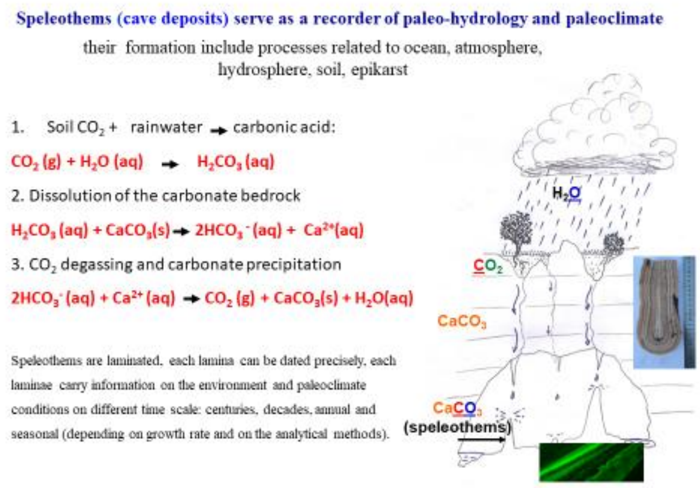


Figure 5. *Karst processes and Speleothems formation*

The studied caves are located along N-S and W-E transects of the EMS-Levant region. The N-S transects (Figs. 3, 4) starts from Mt. Lebanon and Mt Hermon in the northern Levant with present-day annual rainfall of more than 800 mm, across northern and central Israel with annual rainfall ranging from ~800 mm to ~500 mm, through the northern Negev Desert with annual rainfall of ~300 mm to the central and southern Negev Desert with ~100 to less than 50 mm annual rainfall respectively. This latter region links the Levant with North Africa and defines the northeastern corner of the Sahara Desert. The W-E transect is based on speleothems from caves located both on the western flanks and the "rain shadow" desert on the eastern side of the Central Mountain Ridge (CMR) of Israel, along the Dead Sea Basin (DSB), with present-day annual rainfall varying from ~500 mm in the northern segment, to less than 50 mm in the southern segment (Bar-Matthews et al., 2019, Fig. 4).

4. Climate conditions

4.1. Glacial and Interglacial conditions in central and northern Israel

Speleothems deposition ***in northern and central Israel was continuous during both glacials and interglacials*** (Ayalon et al., 1998, 1999, 2002; Bar-Matthews et al., 1997, 1998, 2000, 2003;

Frumkin et al., 1999; Figs. 6, 7). This continuity implies that water was always available in the unsaturated zone, and annual rainfall during interglacial was always more than ~300 mm and during glacials more than ~250 mm (Vaks et al., 2006, 2010; Keinan et al., 2019; Bar-Matthews et al., 2019).

The large oscillations in $\delta^{18}O$ and $\delta^{13}C$ values (Fig. 6) indicate climatic changes, and that the $\delta^{18}O$ record of speleothems displays a well-defined orbital modulation of glacial and interglacial marine isotope stages (MIS) and show good correlations with the EMS records, pointing to strong sea land links (Bar-Matthews et al., 2003).

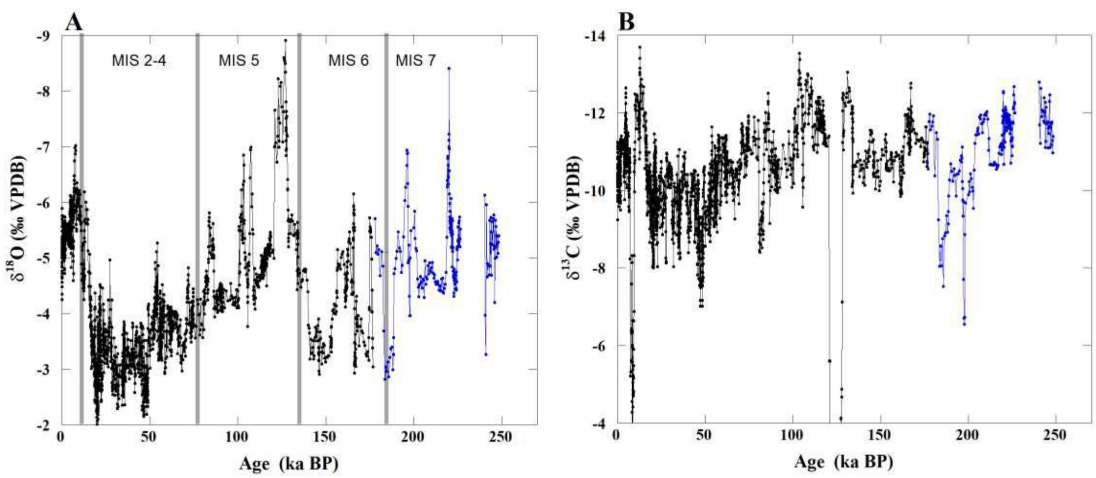


Fig. 6. *Eastern Mediterranean Central and Northern Israel of the last 230 ka (Soreq and Peqi'in caves) oxygen and carbon isotopic record. The large isotopic fluctuations are indicative of major climatic changes. Continuous speleothems depositions during several glacial-interglacial cycles, indicates that water was always available in the unsaturated zone. Annual precipitation during warm interglacials (MIS1, 5) and cold glacials (MIS 2-4, 6) was higher than a limiting threshold for speleothems growth. About 300 mm for interglacials, ~ 250 mm for glacial periods.*

The climatic record indicates relatively drier and cooler glacials with average temperatures of 10-16°C (McGarry et al., 2004; Affek et al., 2008; Matthews et al., 2021) but extreme wet peaks and warm temperatures during interglacials, mainly MIS 5e between 128-120 ka. Based on the isotopic composition and calculated temperatures during the previous glacial MIS 6 (185-135 ka BP) and the last glacial MI4-2 temperatures were colder by cold ~4-8 degree relative to present-day (Matthews et al., 2000; McGarry et al., 2004; Affek et al., 2008; Matthews et al, 2020).

Similar ranges of temperatures were calculated also for the EMS Surface Temperatures (SST) (Emeis et al., 1998, 2000, 2003; Essallami et al., 2007; Almogi-Labin et al., 2009).

Different conditions occurred during interglacials with the lowest $\delta^{18}O$ values during peak interglacial between 128 and 120 ka BP (MIS 5e), between 109-100 ka BP (MIS 5c) between 86 and 83 ka BP (MIS 5a) and during early Holocene, indicating relatively warmer and wetter conditions. The very low $\delta^{18}O$ values coincide with the timing of the deposition of organic rich sapropel layers that were deposited during cycles of extreme wet periods with enhanced rainfall over the Mediterranean basin (Kallel et al., 1997a, b). Based on evidence from the EMS and the speleothems record, deluge period characterized these periods, mainly during MIS5e and early Holocene in central and northern Israel. These periods are characterized by increased frequency of rain events, and large amounts of freshwater input from North African Monsoon (Rodríguez-Sanz et al., 2017), that also resulted in flooding originated from the Nile River flow and from freshwater originating in the central Saharan mountain ranges (e.g., Scrivner et al., 2004; Osborne et al., 2008, 2010; Rodríguez-Sanz et al., 2017. Winter climate modelling of the interglacial insolation maxima indicated a major change from strong seasonality at ~125 ka (Torfstein and Enzel, 2017) with strong Mediterranean storm tracks, to weaker seasonality at 115 ka BP (Kutzbach et al., 2014). The enhanced winter contribution of rainfall was suggested to track from Tropical Africa via tropical plumes as far north as the southern watershed of the DSB (Ziv et al., 2006; Kutzbach et al., 2014). The very short penetration of southern sourced, possibly of monsoon origin, might reached the DSB (Torfstein et al., 2015; Kiro et al., 2020) mainly due to flooding (Kiro et al., 2020) and occasionally reached as far as central Israel (Orland et al., 2019). Calculated temperatures for interglacial are similar to present-day and possibly ~2 degree higher during peak interglacial MIS 5e.

4.2. Glacial-Interglacial conditions in the Negev Desert

Formation of speleothems was intermittent in the more arid regions of Israel. In the semi-desert regions, speleothems do not grow today, but deposition occurred there mainly during the two last glacial periods (Vaks et al., 2003, 2006, 2010, 2017). In the central Negev, speleothems deposition did not occur during glacial but some growth intermittently occurs during peak interglacials (Vaks et al., 2010) (Fig. 7).

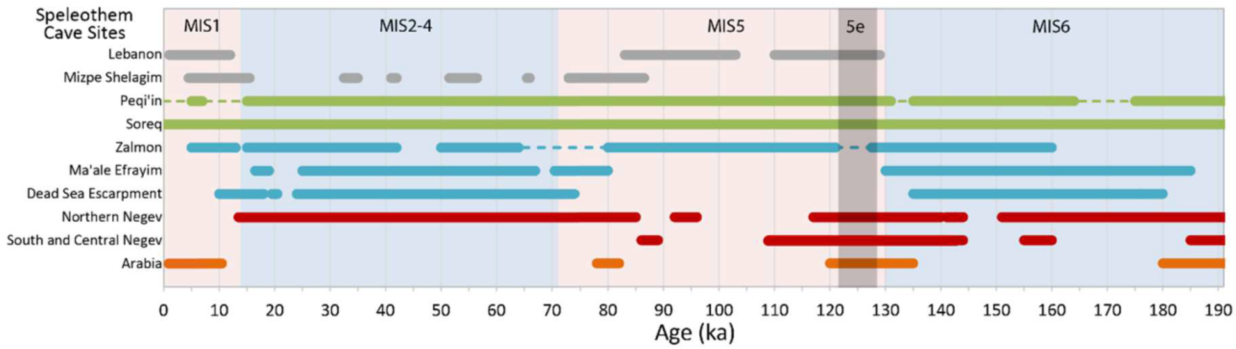


Figure 7. *Periods of speleothems growth from various caves in Israel (Keinan et al., 2019). Light blue/pink fields represent glacial/interglacial periods (Lisiecki and Raymo, 2005).*

In the northern Negev Desert, speleothems were mainly deposited during glacial intervals, with some deposition during peak interglacials (Fig. 7). Deposition during glacial periods suggests that the water balance in the Northern Negev Desert was more positive compared to part of the interglacials and present-day. This observation is taken to indicate that the desert border migrated ~30 km southward from its present-day position (Vaks et al., 2006, their Fig. 6; Bar-Matthews et al., 2017). Comparison between the $\delta^{18}O$ and $\delta^{13}C$ values of the northern Negev Desert speleothems with central Israel speleothems show similar trend, but the absolute $\delta^{18}O$ values of the former are significantly lower and $\delta^{13}C$ values are higher (Fig. 8). The lower $\delta^{18}O$ values of the Northern Negev speleothems most probably reflect Rayleigh distillation processes resulting from longer southward travel distance of rainfall (Vaks et al., 2006; Bar-Matthews et al., 2017) from Mediterranean origin. The higher $\delta^{13}C$ values in the northern Negev indicate that even during periods of increased northern Negev rainfall, the amounts were not enough to allow expansion of C3 type vegetation (Bar- Matthews et al., 2017). Thus, although speleothems were deposited during last glacial, the average amount of rainfall was lower compared to central and northern Israel.

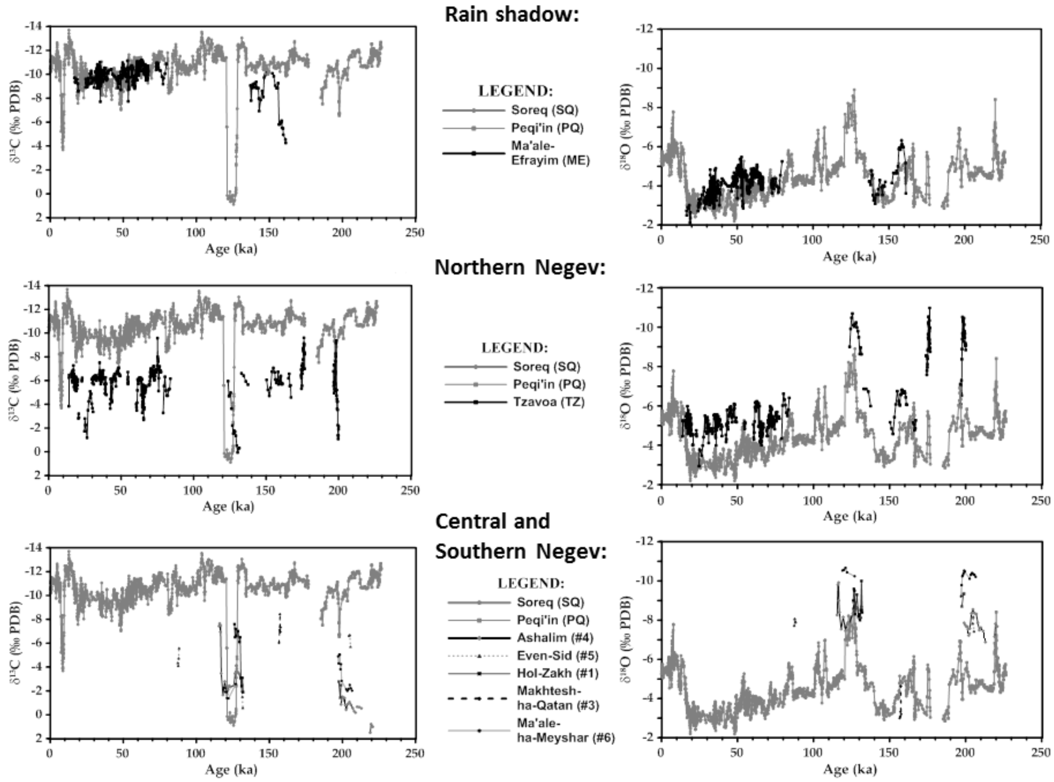


Fig. 8. *The $\delta^{18}O$ and $\delta^{13}C$ records of speleothems from central segment of the DSB (ME Cave), Northern Negev (Tzavoa TZ cave – Vaks et al., 2006) and Central and Southern Negev caves (Vaks et al., 2010) superimposed on the $\delta^{18}O$ and $\delta^{13}C$ records of the Soreq and Peqi`in caves speleothems (Bar-Matthews et al., 2017).*

4.3 Glacial conditions in the Central and Southern Negev Desert

A different picture emerges from central and southern Negev Desert speleothems, compared to the Northern Negev Desert. In this part of the Negev Desert, which is the north-eastern extension of the large Saharo-Arabian Desert, no speleothems deposition occurred during last glacial, and only minor deposition occurred during the previous glacial MIS 6 (Fig. 8). Thus, while rainfall penetrated the northern Negev during glacial periods, the central and southern Negev remained dry. ***This bears important implications to lack of significant rainfall in central and southern Negev during glacial intervals.*** This picture differs in the Dead Sea Basin as will be shown below.

4.4 Glacial conditions in the Dead Sea Basin

Before exploring the information derived from speleothems in this region, it is important to note that the very detailed study of Lake Lisan, the precursor of the Dead Sea, show that its highest stand occurred during the last glacial. It is argued that the existence of the larger Lake Lisan during glacial period compared with the Holocene Dead Sea requires significantly more rainfall (e.g., Zak 1967; Begin et al., 1974; Bartov et al., 2003; Enzel et al., 2008; Kolodny et al., 2005). Begin et al (2004) suggested that an additional southern rainfall source was more active during the Last Glacial, although this model has been not supported by additional evidence. The lake reached its highest stand and areal extent between ~27 ka BP and 23ka BP (Bartov et al., 2002, 2003, 2006, 2007; Haase-Schramm et al., 2004). However, this time interval is one for which a sediment core from the south-western shore of the Sea of Galilee shows that the predominant vegetation in northern Israel was steppe vegetation with grasses together and other herbs and dwarf shrubs, suggesting semi-arid conditions (Miebach et al., 2017). Thus, there is an apparent conflict between the pollen data, which call for relatively dry conditions during last glacial on one hand, and the high lake levels on the other hand, apparently pointing to much wetter conditions.

This raises the question of how the speleothems record from this relatively arid region responds to this duality. Growth and non-growth patterns of speleothems present a picture of differences between the northern, central and southern segments of the DSB. In the northern section of the DSB, speleothems continuously deposited during glacial and interglacials, as evident from Zalmon Cave speleothems (Fig. 8), where present-day annual rainfall is ~500 mm (Keinan et al. 2019). Their $\delta^{13}C$ values range for most of the time interval between -9 and -12‰, suggesting dominance of C3 type vegetation, similar to speleothems from central and northern Israel. However, their $\delta^{18}O$ values during the last glacial are lower by ~1-2‰ compared to central Israel caves (Keinan et al., 2019). The offset to lower $\delta^{18}O$ values during glacials is interpreted to reflect two factors: warmer temperatures coupled with increased rainfall amounts in the northern DSB relative to central Israel. The latter could be the result of the funneling of storm tracks from the Mediterranean Sea directly eastward across the Levant toward the northern DSB area (Keinan et al., 2019). Farther south along the DSB where annual average amount of rainfall is below 250 mm (ME cave, Fig. 3), and no present-day speleothems deposition, speleothems were mainly deposited during glacial periods, with only minor deposition during interglacial (Fig. 7). As with the northern Negev Desert, speleothems deposition during the last glacial suggests higher water availability in the central segment of the DSB relative to interglacials. However, unlike the northern Negev Desert speleothems, there is strong match between the $\delta^{18}O$ and $\delta^{13}C$ values of ME and Soreq Cave speleothems (Fig. 8), despite their being located 60 km apart, on the different sides of the CMR, and under very different present-day climates. This similarity indicates that during last glacial, the climate and vegetation were similar on both sides of the CMR, and rainfall that originated from the EMS source reached further east across the CMR (Vaks et al. 2003; Bar-Matthews et al., 2017). The similarity in climate and vegetation during glacials implies that the rainfall belt migrated at least 60 km farther east during last glacial and the amount of rainfall in both sides of the CMR was of the same EMS source (Goldsmith et al., 2017) and with probably similar temperatures (McGarry et al., 2004). Farther south, along the southern segment of the DSB, where annual rainfall is ~150-50 mm, speleothems deposition was very limited during last glacial with only very thin laminae, but their presence in this arid region during last glacial, indicates that more water was available relative to present (Lisker et al., 2010). We therefore suggest that the high Lake Lisan stand during last glacial, mainly between 27 and 23 ka BP is not necessarily a good indicator for rainfall amount but better indicator for water balance. During last glacial, climatic conditions were much colder with average annual temperatures dropping to ~10^{o}C (McGarry et al., 2004; Matthews et al., 2020; Affek et al., 2023). The colder conditions, and lower evaporation/precipitation ratio (Lisker et al., 2010; Vaks et al., 2003) in combination with short warm intervals that induced significant snow melting in the northern Levant during last glacial (Ayalon et al., 2013) would have drained large amounts of water into the DSB and recharged the ground water. All these most probably resulted in higher lake stand. Thus, the `apparent` contradiction between `wet` Dead Sea region, evident from the high Lake Lisan Stand (e.g. Torfstein et al., 2015), during most of last glacial on one hand, and a `drier Mediterranean` based on the isotopic composition of the speleothems (high $\delta^{18}O$ values, Fig. 8), the EMS marine records, and the pollen records (Langutt et al., 2011; 2018., Miebach et al, 2017; Chen and Litt, 2018) on the other hand, does not necessarily require great increased in annual rainfall. It can be viewed as a different response of the lake system (Leng and Marshall, 2004; Roberts et al., 2008) to the combined effects of lower temperature, higher precipitation/evaporation ratio and additional water supply from the rainfall penetration farther east, and from snow melting from the northern Levant and possibly the high mountain area in Jordan.

4.5. Interglacial conditions in the Central and Southern Negev and the sources of rainfall to the southern and eastern Levant

One of the major questions is if these peak interglacials periods, recorded in the EMS and in speleothems from central and northern Israel are recorded also in the arid desert

The review that emerges from central and southern Negev Desert speleothems (Vaks et al., 2010) is that in this part of the Negev, which is the north-eastern extension of the large Saharo-Arabian hyperarid desert condition started at ~ 1.0Ma (Vaks et al., 2010; Amit et al., 2006; Enzel et al., 2008). The region experienced short pluvial periods during interglacials. This is based on the episodic deposition of speleothems with very thin laminae in dispersed sites (Fig. 9). The ages of their outermost layers show that deposition occurred mostly during interglacials. These periods of speleothems deposition in the Negev Desert have been referred to as Negev Humid Periods (NHP) and reflect intervals when rainfall amount was high enough to allow water to infiltrate the cave (Vaks et al, 2010; Bar-Matthews, 2014). Evidence for wet peak interglacials, mainly MIS 5e in the Negev Desert, come from the timing of depositional periods of speleothems (Figs. 7, 8, 9) and from fossil corals in the elevated reef terraces along the Gulf of Aqaba which were extensively altered to calcite (Lazar and Stein 2011; Yehudai et al., 2017). There is also evidence for wet conditions from freshwater deposits in the Arava Valley, Israel (Livnat and Kronfeld, 1985), and further south in Egypt from fossil groundwater carbonate spring deposits in oases in the Western Desert (Sultan et al., 1997) and secondary uranium in ores and carbonates, which indicate extreme ground water movement during Egyptian Sahara pluvial periods (Osmond and Dabous, 2004). High speleothems $\delta^{13}C$ values (Fig. 8) indicate that vegetation cover was not well established during these NHPs (Vaks et al., 2010; Bar-Matthews et al., 2017). Thus, it was proposed that these NHP`s were clusters of short wet events during otherwise long droughts, sufficient to deposit a thin layer of carbonate in caves. This proposal is supported by the lack of calcic soil horizons in the southern Negev, which imply that these episodic wet events were neither intense nor prolonged (Amit et al., 2006). There are also evidence from the relationships between lake-level changes and water and salt budgets in the Dead Sea during peak MIS 5e in for increasing floods and rainfall from southern source into the DSB (Torfstein et al., 2015; Kiro et al., 2020).

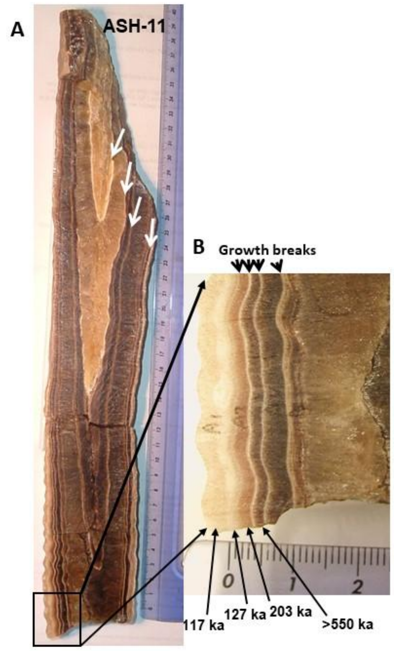


Fig. 9. *Stalactite ASH-11 from Ashalim Cave (from Vaks et al., 2017). A. The Basal, Intermediate, and the Young Member (composed of 4 thin layers); see enlargement in part (B) with U–Th ages. Numerous fine white layers divide between the thicker dark calcite layers; white arrows mark growth breaks.*

Waldmann et al. (2010) and Torfstein et al. (2015) argue for enhanced rainfall associated with the African monsoon with mid subtropical latitude climate systems, Vaks et al. (2010) argue for increase intensity of EM cyclones that resulted in penetration of rainfall farther south. The latter argument was based on the reduced frequency of depositional episodes and thickness of individual speleothems laminae southwards (Fig. 9), implying a decrease in rainfall from north to south similar to the present- day precipitation gradient (Vaks et al. 2010).

Pluvial intervals recorded along the north-south transects from the Levant to southern Arabia (Fig. 10) may shed light on the origin of moisture. As in the Negev Desert, the most intensive speleothems deposition in Southern Arabia (Fig. 10), occurs during peak interglacials.

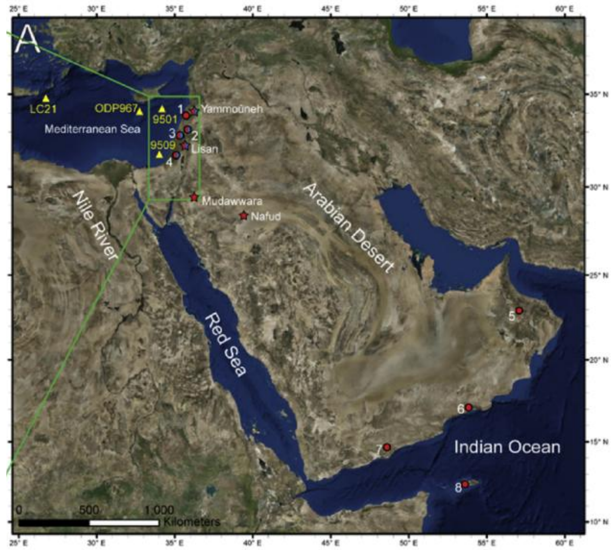


Fig. 10. Regional map with locations of the Levant study sites described in the text. Caves are shown as filled circles, marine drilled core sites as yellow triangles, and lakes as stars. Study sites are color-coded: blue – "wet" during glacial periods, red – "wet" during interglacial periods. The following caves are numbered: 1-Jeita and Kanaan Caves (Cheng et al., 2015; Nehme et al., 2015; Verheyden et al., 2017) 2-Mizpe Shelagim Cave (Ayalon et al., 2013), 3-Peqi'in (Bar-Matthews et al., 2003) and Zalmon Caves (Keinan et al., 2019), 4-Soreq (e.g. Bar-Matthews et al., 1997) and Jerusalem Caves (Frumkin et al., 1999), 5-Hoti Cave (e.g., Burns et al, 1998), 6-Qunf and Defore Caves (Fleitmann et al., 2007), 7-Mukallah Cave (Fleitmann et al., 2011), 8-Dimarshim Cave (Fleitmann et al., 2007).

Fleitmann et al (2011) argue that MIS 5e was the wettest interval with the main rain events being the African-Indian monsoon system. Rosenberg et al. (2013) show that pluvial periods in the Nafud Desert, Northern Arabia are in phase with southern Negev speleothems (Vaks et al., 2010) and southern Arabia speleothems (Fleitmann et al 2011). This temporal connection indicates intensive hydrological cycles over the entire Arabian Peninsula, but how far north the monsoonal storm track could reach is not clear. Whereas in southern Arabia the strengthening of the Indian monsoon was attributed to its intensification, the northern limit of the monsoonal migration is unknown, since currently, there is no current evidence for speleothems deposition in central Arabia (Fleitmann et al., 2003; Rosenberg et al., 2013). The ability of monsoon-related southern-derived rains to directly impact the Negev Desert and the Dead Sea watershed is not trivial, considering the relatively high latitude of the DSB and Southern and central Negev Desert caves and the distance from tropical Africa. However, recent general circulation models (e.g., Herold and Lochmann, 2009) show significant northern excursions of summer monsoon rainfall, suggesting that the influence of the African monsoon could have reached as far north as the northern Arabian Peninsula. Other model results indicate that the enhanced winter contribution from tropical Africa via tropical plumes could have also affected the southern watershed of the Dead Sea (Kutzbach et al., 2014). Orland et al. (2019), based on model simulations, argue for enhanced precipitation from southern sources for short time intervals during MIS 5e as far as central Israel.

Amit et al. (2006) presented results of analyses of gypsic-saline Reg soils that developed on flat alluvial surfaces throughout the southern and eastern Negev, showing that their distribution pattern has not altered for at least a few hundred thousand years. They identified controls on the rainfall distribution over southern Israel, and propose that regional hydroclimatic and physiographic settings led to hyperaridity in the southern Negev (Figs. 11, 12).

The fact that only gypsum-saline soils are found on middle Pleistocene to recent alluvial surfaces in the southern Negev implies that episodes of increased annual rainfall (<80 mm/yr) did not change the landscape of the hyperarid region, at least since the middle Pleistocene (Amit et al., 2006). Only in Pliocene sediments, calcic paleosols have been identified in the currently hyperarid region. This implies that <80 mm/yr of precipitation characterized this region during most of the Quaternary and the same pattern of aridity existed during at least two glacial-interglacial cycles.

It may be argued that soils may not be sensitive to short wet episodes (of ~2000 yr) Soil modeling indicate that decades- to centuries-long episodes of increased rainfall in an arid region will easily produce a detectable calcic soil horizon (McDonald et al., 1996). Although 2000 yr episodes of increased rainfall and resulting runoff (Greenbaum, 1986) would have incised and eroded the highly developed desert pavement of Pleistocene surfaces, no traces of such processes are evident on the well-paved Pleistocene surfaces in the Elat-Aqaba area. In addition, no dissolution of salts was observed in the soils (Amit and Yaalon, 1996) and no desert loess accumulation occurred at, 80 mm annual rainfall (Yaalon and Dan, 1974). Amit et al. (2006, 2010) claimed that permanent Quaternary hyperaridity in the Negev Desert resulted from regional tectonics blocking Mediterranean frontal systems. Although various episodes of wet Quaternary climates have been suggested in studies of the Negev Desert, they demonstrate that Reg soils, developed on flat alluvial surfaces and sensitive to minor changes in precipitation, indicate that the southern Negev has been permanently hyperarid at least since the middle Pleistocene.

Thus, the scattered high-intensity short-lived and localized showers have limited effects on soils and most of the water is not available for soil leaching. As a result, the very top soils in the southern Negev accumulate only soluble salts that prevent even occasional vegetation growth on the alluvial surfaces.

Under current climate conditions in the Negev Desert, calcic soils are widespread in areas with rainfall >80 mm yr-1. The fact that the hyperarid (<50 mm yr-1) southern Negev lacks any calcic horizons indicates that it never experienced an average rainfall of ≥80 mm yr-1 during the middle-late Pleistocene, whereas the northern Negev was wetter. They explain this Negev dichotomy by the main physical features controlling rainfall over the Negev, i.e., the southward-decreasing depth of the atmospheric boundary layer with distance from the Mediterranean, and the altitude of the central Negev Highland (1000 m). The interaction between these two features often prevents the passage of rain clouds into the southern Negev. The Holocene and Pleistocene gypsic-salic soil distribution across the Negev closely matches the current circumstances.
The lack of vegetation on such surfaces indicates the absence of decades or centuries of intense rainfall episodes capable of leaching the top soil and enhance vegetation growth and secondary calcium carbonate deposition.

This implies that ***the Negev Humid Periods (NHP)*** and especially during wet peak interglacials (mainly MIS 5e) may have resulted in clusters of short wet events during otherwise long droughts, but these episodic wet events were neither intense nor prolonged and climatic conditions remained arid in central and southern Negev, and in the southern DSB.

Thus, hyperacidity has prevailed over the southern Negev since the last stages of the uplift of the central Negev Highland in the late Pliocene early Pleistocene.

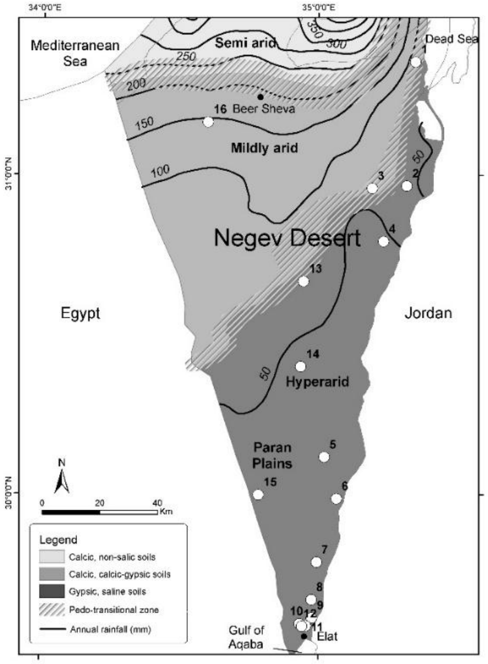


Figure 11. *Climatic zones of the Negev, Israel including isohyets and characteristic soils (from Amit et al., 2010).*

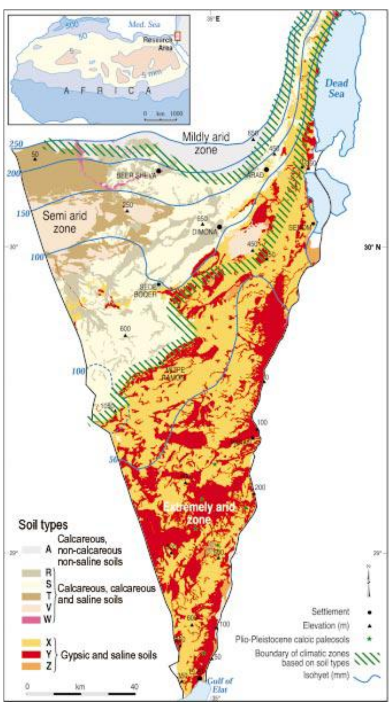


Figure 12. *Compiled soil association map of Negev Desert and annual rainfall distribution. Inset shows location of Negev relative to larger desert belt of Northern Hemisphere and Mediterranean Sea (Amit et al., 2010, after Dan et al., 1976).*

5. Conclusions

While Northern and Central Israel received rainfall during glacials and interglacials, the rainfall pattern in the Negev Desert and the DSB was different. Rainfall penetrated the northern Negev and the DSB during glacial periods, while the central and southern Negev remained dry. The NHP during peaks interglacial, may have resulted in clusters of short wet events during otherwise long droughts, but these episodic wet events were neither intense nor prolonged enough for calcic soils to develop.

Therefore, we can conclude that climatic conditions remained arid in ***Yamin Plain*** at least during the last ***200,000-250,000 years, time periods that cove several glacials and interglacials cycles. We anticipate that arid conditions will continue to prevail in Yamin Plain region, with possible increase in intensive floods, but there is no evidence that these flooding events will have significant impact on the water level.***

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