ABSTRACT
Although various episodes of wet Quaternary climates have been suggested in studies of the Negev Desert, here we 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. The wetter episodes were restricted to the northern Negev, currently mildly arid. Gypsic-saline Reg soils that developed on stable surfaces during >200 k.y. in the southern Negev are cumulative and polygenetic, but none exhibits even the weakest development of calcic horizons. Under current climate conditions in the Negev, 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. This Negev dichotomy is explained 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. We suggest that hyperaridity has prevailed over the southern Negev since the last stages of the uplift of the central Negev Highland in the late Pliocene–early Pleistocene.

INTRODUCTION
The Negev Desert (~10,000 km$^2$ at 29°–31°N), part of the larger Saharo-Arabian desert belt, is south of the semi-arid Mediterranean climatic region (Fig. 1). Although surrounding the Negev, Sinai, and northern Arabia is currently among the driest places on Earth; ~75% of the area is hyperarid (<80 mm yr$^{-1}$) of which 50% receives ≤50 mm yr$^{-1}$ (Fig. 1). Earlier studies suggested that the Negev experienced much wetter climatic episodes during the Quaternary (e.g., Horowitz, 1979; Magaritz, 1986; Goodfriend and Magaritz, 1988; Goodfriend, 1999), based on data from the semi-arid northern Negev: the question remains whether that applies to the southern Negev.

Here we present results of analyses of gypsic-saline Reg soils that developed on flat alluvial surfaces throughout the southern and eastern Negev. We analyzed the spatial distribution of late Holocene to recent rainfall-conditioned salic and calcic soils, compared them with present-day rainfall, and show that their distribution pattern has not altered for at least a few hundred thousand years. We identify controls on the rainfall distribution over southern Israel, and propose that regional hydroclimatic and physiographic settings led to hyperaridity in the southern Negev despite the dramatic climatic variations recorded by speleothems (Bar-Matthews et al., 1997) and lake levels (Bartov et al., 2002) 200–300 km to the north.

METHODS AND RESULTS
Diagnostic soil horizons developed on stable alluvial surfaces are excellent proxies for average regional climate (Yaalon, 1971; Birkeland, 1999). In hyperarid regions, soils are indicative of climate only if they formed in response to direct rain without additional water contribution from adjacent areas and slopes (Yair and Berkowitz, 1989) or ephemeral channels (Amit et al., 2006). Therefore, we avoided soils with any slope or catenary relationship and refer only to soils developed on stable, relatively flat surfaces that cover >25% of the Negev. Data from soil chronosequences from the Negev and Sinai (Dan et al., 1982; Gerson et al., 1985; Amit and Gerson, 1986; Amit et al., 1993; Amit and Yaalon, 1996) were summarized and supplemented by observations of hundreds of individual soils outside these sequences. The ages of the alluvial surfaces were determined by optically stimulated luminescence (OSL) methods (Porter et al., 1997, 2006). Parts of these surfaces are beyond the OSL age range, and are at least a few hundred thousand years old based on either their association with early to middle Pleistocene sedimentary units or their being older than middle Pleistocene human artifacts (Gerson et al., 1985; Dan et al., 1982; Ginat et al., 2002).

Using a geographic information system (GIS), we compiled data from earlier studies and our own soil data in the Negev in a map of soil associations (after Dan et al., 1976) based on diagnostic horizons (Fig. 1). Soil samples were treated by standard methods (Dan et al., 1964; Soil Survey Staff, 1999). Chemical and physical properties were determined according to laboratory procedures (Amit et al., 1993, 2000).

Figure 2 shows the southeasternmost extent of excessive annual rainfall (>100%) in northern and central Israel for each of the 7 wettest rain seasons of the last 23 for which such data were published (Israel Meteorological Service, 1981–2003). South of each line, rain from Mediterranean systems was considerably more restricted.

PLEISTOCENE–HOLOCENE SOILS IN THE NEGEV AS RELATED TO RAINFALL
Rainfall strongly affects the formation, characteristics, and depths of soil horizons in arid regions; therefore, we superimposed the soil data on the mean annual rainfall map to test and illustrate the case. Figure 1 shows that, except for a few transitional exceptions, the majority of soils related to extremely arid climates plot below the <80 mm yr$^{-1}$ isohyet delineating the southern and eastern Negev. The eastern Negev includes gypsic and salic-petrosalic soil horizons (groups X, Y, Z) at depths of 10–30 and 80–120 cm, respectively, regardless of the age of the alluvial surfaces on which these soils developed (Amit et al., 1993). However, no calcic soil horizons have been found on any of these surfaces. The semiarid zone (80–250 mm yr$^{-1}$) exhibits a transition from gypsic-salic soils to saline-calccic and calcic soils (groups R, S, T, V, W). The mildly arid zone (>250 mm yr$^{-1}$) is devoid of salic horizons, whereas calcic and noncalcic soils (group A in Fig. 1) are abundant. On middle Pleistocene–Holocene allu-
In IN THE SOUTHERN LEVANT, IN THE NEGEV DURING WET YEARS, the rainfall distribution for some of the wettest rain seasons in the southern Levant is shown in Figure 2. The 100% lines reflect the extent of advected excessive Mediterranean rainfall southeastward. That line, along with the rain shadow of the mountain backbone of central Israel (1200–1400 m above the Dead Sea), roughly reflects the shape of the southeastern corner of the Mediterranean. Figure 2 shows that excessive rainfall extends farther south during wet years. However, even in extreme cases, including the wettest 1991–1992 season with >5 σ above the 157 yr mean (552 mm) in Jerusalem, and the 1982–1983 season with almost 3 σ above the mean, excessive cyclonic rainfall never extended beyond the Negev Highland. Record rainfall may occur in the southern Negev during an active Red Sea Trough (Kahan et al., 2002), but mostly in the form of localized intense convective storms with limited effect on the regional mean (Sharon, 1972).

**DISCUSSION**

The fact that only gypsic-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⁻¹) did not affect the hyperarid region, at least since the middle Pleistocene. Hence, studies in the southern Negev indicating wetter conditions during the late Quaternary (e.g., Goodfird, 1999) may apply to the northern Negev, but should not be extended to the entire Negev. For example, isotopic compositions of calcic soils in these studies are all from the semiarid northern Negev (Fig. 1), where calcic soils are also currently forming (e.g., Magaritz, 1986; Goodfird, 1999). In contrast, the southern Negev is hyperarid to such an extent that no contribution of vegetation (either C3 or C4) to the 13 C composition of calcic nodules or that of land snails was detected in the soils (Amit et al., 2006). It follows that, in the Negev, calcic and gypsic-saline soils form where annual precipitation is 100–250 mm and <80 mm, respectively, as reflected in Figure 1. Moreover, calcic paleosols have been identified in the currently hyperarid region only in Pliocene sediments, which implies that <80 mm yr⁻¹ of precipitation characterized this region during most of the Quaternary. The same pattern of aridity in that area during at least two glacial-interglacial cycles (since marine oxygen isotope stage 7) is also evident from the δ13 C and δ18 O composition of secondary calcite veins (Avigour et al., 1992), speleothems (Vaks et al., 2003), and calcic nodules in fluvial pedogenic units (Amit et al., 2006).

During the last two glacial-interglacial cycles, the Saharo-Arabian hyperarid environment has prevailed in the southern and eastern Negev, and the southeastern limit has been maintained even during wetter periods in the northern Negev. This reflects a local physical blocking of significantly more moisture to the southern and eastern Negev, negating an early Holocene humid phase with Mediterranean moisture advected as far as the Gulf of Elat–Aqaba (Fig. 1) (Arz et al., 2003). It may be argued that soils may not be sensitive to short wet episodes (of ~2 k.y.) suggested for the early Holocene in this region (Arz et al., 2003). However, soil modeling efforts 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 2 k.y. 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).

CALCIC SOIL HORIZONS IN THE EXTREMELY ARID PARTS OF THE NEGEV

To form a calcic horizon, an elevated $p$CO$_2$ is needed to dissolve carbonate within a soil solution. The source of this elevated $p$CO$_2$ is root zone respiration and/or microbiological activity (e.g., Wright and Tucker, 1991); this causes the C3-C4 isotopic signal found in secondary calcites in soils relative to atmospheric CO$_2$ signal (Cerling and Quade, 1993). At present, vegetation covers alluvial surfaces in the Negev only in areas receiving >80 mm yr$^{-1}$, and in the hyperarid zone (<80 mm) only in niches where rock outcrops contribute additional runoff (Yair and Berkowicz, 1989).

Calcic horizons in the hyperarid zone are associated only with soils developed on Pleistocene–Pliocene alluvial surfaces (Fig. 1) and there are none in more recent deposits. Ginat et al. (2002) found calcic paleosols in several Pliocene–Pleistocene alluvial units that reach a maximum stage III, whereas alluvial units of similar age in the northern Negev reach stage VI (Gile et al. 1981; Amit et al., 2000).

These weakly developed calcic paleosols in the hyperarid Negev may indicate that even during early Quaternary episodes when calcic horizons developed in that region, their formation was restricted by scarcity of rainfall and vegetation. More than twice the modern rainfall is needed in Elat (30 mm/yr at present) to reach 80 mm, the minimum for calcic soils to form.

CAUSES OF PERMANENT ARIDITY

Two issues must be addressed relating to the observations presented here: (1) Why was there no significant rainfall in the southern and eastern Negev after the middle Pleistocene? (2) What enabled increased rainfall in that region to produce calcic horizons during the preceding time?

Generally, Mediterranean moisture and cloud systems move inland in an east and northeast direction, thus affecting central and northern Israel (Sharon, 1978). Southeastward advection toward the Negev is much less frequent, hence the abrupt decrease in rainfall approaching the latitude of the Sinai-Egyptian shoreline and farther south. Notably, on the northeastern boundary of the hyperarid soil groups, the physical features controlling the recent regional rainfall distribution are related to the distance (southeastward) from the Mediterranean and the elevated physiography of the Negev Highland and its northeastern extension. Along with the abrupt transition to the drier subtropical region, the depth of the atmospheric boundary layer (ABL), within which precipitating clouds develop, tends to decrease from 1800–2000 m (above sea level) near the coast to ~1400 m in the Negev Highland, to only 400–600 m above the ground (Dayan et al., 2002). Such shallow capping, frequent on rainy days (B. Ziv, 2005, personal commun.), will suppress precipitation processes. Thus, even when Mediterranean moisture and clouds move southeastward, precipitation is often disrupted over the highlands after the ABL has been considerably depleted by precipitation over the northern Negev, and even more by the orographic effect over the ridge. While rainfall over the northern Negev and the highlands is still related to the frequency of Mediterranean systems, the central Negev ridges considerably reduce rainfall from systems affecting the southern and eastern parts of the Negev (Enzel et al., 2004).

Convective rainfall from active Red Sea trough events contributes more to the annual rainfall in these regions than to the north (e.g., Kahana et al., 2002). Resulting high-intensity showers (>20–30 mm/hr) are mostly scattered, short lived, and localized, and have limited effects on the regional mean rainfall (Sharon, 1972): 15%–25% in the southeastern and 10%–15% in the northern Negev (Sharon and Kutiel, 1986; Morin et al., 1998).

Atmospheric features interacting with local topography determine the present-day abrupt transition to the hyperarid part of the Negev: these findings are best verified by the fact that at present, even during the very wettest years, the area southeast of the Negev Highlands remains dry (Fig. 1).

AGE OF HYPERARIDITY OF THE SOUTHERN NEGEV

Because the distance from the Mediterranean is critical to local climate, the historical location of the coast should be considered. The maximum drop in sea level occurred during the last glacial maximum (LGM) (Fig. 2). Based on current bathymetry, and the ~120 m lower global LGM sea level, the northern Sinai coast was 60–70 km to the north of its current position at the LGM. During most of the last and earlier glacial the coastlines were somewhere between that of the LGM and the modern coast. This probably increased the distance to the Mediterranean during each of the glacial epochs. Furthermore, the resulting reduction in ABL depth over the same unchanged topography would further reduce moisture advection into the southeastern Negev. Thus, even if the frequency of storms affecting the southern Levant increased, causing wetter conditions, the net impact on the southeastern Negev rainfall was still minimal, leaving it within the hyperarid realm.

As the Negev Highlands currently block rainfall in the southeastern Negev, the timing of its emplacement at current altitudes should be considered. The Pliocene Mediterranean coast was ~50 km south of its current location and is ~110 m above the highest known global Pliocene sea level (Fig. 2) (Zilberman, 1986; Greenbaum et al., 2000). This indicates a regional uplift of at least the northwestern and eastern Negev, probably associated with the contemporaneous arching of the mountainous backbone of Israel and the Negev Highlands.

The Negev Highland gained most of its elevation (500–800 m) during the late Miocene–early Pliocene (Begin and Zilberman, 1997), and rose another 100–200 m during the Pliocene–Pleistocene to its present elevation (Avni, 1998; Ginat, 1996). This late Cenozoic uplift resulted from a short-wave arching of the backbone of Israel attributed to the Dead Sea transform activity and intensive sediment deposition in the Dead Sea Rift to the east and on the Mediterranean Sea shelf to the west (Picard, 1951; Begin and Zilberman, 1997; Ginat, 1996; Avni, 1998).

Both the lower Pliocene topography and the shorter distance from the coast imply that the Negev Highlands were less of a barrier to Mediterranean rainfall in the past. Under such physiography and hydroclimatology, pre-Quaternary alluvial surfaces in the southeastern Negev received more rainfall that could have enhanced vegetation cover and root zone respiration, and the formation of the observed weak Pliocene–Pleistocene calcic horizons.

In conclusion, these results highlight the importance of considering the detailed regional tectonic, physiographic, and atmospheric features explaining detected climate variations in space and time. The interaction between local factors may cause a region to be significantly less sensitive to synoptic-scale climates recorded nearby, implying that climate changes near desert margins require more extensive in-depth scrutiny of local physical features, and should not be simply attributed to nearby areas.

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