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The role of rare rainstorms in the formation of calcic soil horizons on alluvial surfaces in extreme deserts

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A B S T R A C T

Soils in similar geomorphic settings in hyperarid deserts (<50 mm yr^{-1}) should have similar characteristics because a negative moisture balance controls their development. However, Reg soils in the hyperarid southern Negev and Namib deserts are distinctly different. Soils developed on stable alluvial surfaces with only direct input of rainfall and dust depend heavily on rainfall characteristics. Annual rainfall amount can be similar (15–30 mm), but storm duration can drastically alter Reg soil properties in deserts. The cooler fall/winter and dry hot summers of the southern Negev Desert with a predominance brief (≤1 day) rainstorms result in gypsic-saline soils without any calcic soil horizon. Although the Namib Desert receives only 50–60% of the southern Negev annual rainfall, its rainstorm duration is commonly 2–4 days. This improves leaching of the top soil under even lower annual rainfall amount and results in weeks-long grass cover. The long-term cumulative effect of these rare rain-grass relationships produces a calcic-gypsic-saline soil. The development of these different kinds of desert soils highlights the importance of daily to seasonal rainfall characteristics in influencing soil-moisture regime in deserts, and has important implications for the use of key desert soil properties as proxies in paleoclimatology.

Introduction

Soils of hyperarid deserts (<50 mm yr^{-1}) in similar geomorphic settings should have similar characteristics, as the main controlling factors for their development are an extremely negative moisture balance and atmospheric dust input (e.g., Bao et al., 2001; Ewing et al., 2006; Amit et al., 2006; Quade et al., 2007). In the southern Negev Desert and in parts of Sinai and northern Arabia deserts, stable Quaternary alluvial surfaces that have received only direct rainfall and dust input are characterized by Reg soils with diagnostic gypsic (By) and salic (Bz) soil horizons at depths of 10–30 and 80–120 cm, respectively (Dan et al., 1982; Amit et al., 2006; Matmon et al., 2009). These diagnostic gypsic and salic Reg soil horizons are characteristic of extremely arid climates (<80 mm yr^{-1}) and are ubiquitous in the Negev in areas having precipitation of 25–50 mm yr^{-1} or even less. No calcic soil horizons typical of arid environments (e.g., Gile, 1975; McFadden and Tinsely, 1985) are found on any of these surfaces.

In the Negev Desert calcic horizons are widespread in soils developed in the arid-semi-arid (100–250 mm yr^{-1}) central and northern Negev Desert (Dan et al., 1964; Magaritz, 1986; Goodfriend and Magaritz, 1988; Amit et al., 2006). This indicates that if soils have calcic horizons they were not developed under hyperarid conditions (Dan and Yaalon, 1982; Birkeland, 1999; Amit et al., 2006). These observations and inferences raise a question: can we apply the total annual rainfall threshold of ~80 mm yr^{-1} to distinguish soil characteristics in other deserts in the world? Answering this question requires the identification of potential causes for the differences in soil properties in different deserts. This study compares soil properties to rainfall patterns in the Namib and southern Negev deserts and is a step toward a resolution of this question. Both deserts currently have large areas experiencing precipitation of 50 mm yr^{-1} or less and have been hyperarid throughout the Quaternary (Heine, 1998; Brook et al., 1999; Bao et al., 2001; Lancaster, 2002; Amit et al., 2006). The study will contribute to a better understanding of climatic controls over soil-formation process in extreme environments.

In both deserts, we attempt to characterize the soils formed at the edge of moisture availability and to identify parameters that may explain similarities and dissimilarities between them. Amit et al. (2006) argued that soils are indicators of the cumulative effect of climate only if they formed in response to direct rain and dust input. Therefore, we use diagnostic horizons of Reg soils developed on stable, relatively flat alluvial surfaces, which are excellent proxies for regional-scale climate conditions (e.g., Yaalon, 1971; Birkeland, 1999) and avoided soil from sites that potentially could have received runoff from adjacent slopes

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(Yair and Berkowicz, 1989) or had any relationship with ephemeral channels (Amit et al., 2007).

We show that key properties of soils that develop on stable alluvial surfaces in a sustained hyperarid climate depend predominantly on the long-term cumulative effect of the characteristics of individual rainstorms over thousands of years and not simply on the average annual rainfall. The differences in the soil properties of these similar desert settings highlight subtle differences in the moisture regimes in hyperarid deserts that can result in very different pedogenic features that when simplistically overlooked can lead to misinterpretation of soils of the past.

Climates of the Namib and the Negev deserts

Namib Desert

Namibia lies along the southwestern coast of Africa with the north-flowing cold Benguela current producing the coastal Namib Desert (Fig. 1). The dry climate of Namibia is the outcome of the blocking by the Southern Hemisphere subtropical high-pressure zone (e.g., Mendelsohn et al., 2002). Shifts to the south of this zone in the austral summer reduce this blocking effect and allow southward movement of moist tropical air. The rare summer rainstorms in the central Namib Desert are in part incursions of moisture from the Intertropical Convergence Zone (ITCZ) under the influence of the Angola Low centered just north of Namibia (Nicholson, 2000; Mendelsohn et al., 2002). In the Namib Desert, the moist air converges in the zone of low pressure to produce non-localized, longer-duration rains (e.g., Tyson, 1986; Nicholson, 2000).

Another source for rare summer rainfall in the Namib Desert is trans-Kalahari moisture, advected from the Indian Ocean. The decrease in the Benguela upwelling associated with weakening of the coastal high-pressure inversion allows Indian Ocean air masses to reach and produce rainfall in the western Namib Desert (Brook et al., 2007). The direction of the relative long-distance transport of moisture to the Namib Desert by these systems determine the spatial distribution of rainfall and the low total annual rainfall amounts (Mendelsohn et al., 2002).

Rainstorms occur in the Namib Desert during the summer, between January and April, with total seasonal rainfall ranging from only 1–5 mm along the Atlantic Ocean coast increasing to ~85 mm along the eastern limits of the Namib Desert (Fig. 2) (Lancaster, 1984; Lovegrove, 1993; Lancaster, 2002). Temperatures are moderate relative to other desert regions, reflecting the influence of the cold Benguela current. Mean annual daily maximum temperatures range from 17 °C at the coast to 28°–33 °C inland, while minimum daily temperatures average 13°–16 °C throughout the region. The mean annual evaporation in the central Namib is > 2000 mm with relative humidity < 20% during the least humid months and 50–60% in the most humid months (Mendelsohn et al., 2002).

Negev Desert

The Negev Desert, at the northern edge of the large Saharo-Arabian desert belt, is located south of the semiarid Mediterranean climatic zone (Fig. 3). The area encompassing the Negev, Sinai, and northern Arabia is currently among the driest places on Earth: in 75% of the area the precipitation averages <80 mm yr^{-1} and half of that area is hyperarid (<50 mm yr^{-1}) (Fig. 3). Mean annual rainfall in the southern Negev Desert is 25–30 mm yr^{-1}. The synoptic-scale system responsible for most of the annual precipitation in the Negev Desert is an eastern Mediterranean extratropical cyclone, the Cyprus Low (Sharon and Kutiel, 1986; Alpert et al., 1990). The southern boundary of the winter rains during wettest winters is usually associated with the continuation to the east of the northern Sinai coastline, commonly located 10–20 km to its south (Enzel et al., 2008).

Convective rainfall by the active Red Sea Trough contributes a higher proportion of the annual rainfall in the southern Negev than in the northern Negev (e.g., Kahana et al., 2002). 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): 15%–25% and 10%–15% in the southern and northern Negev, respectively (Sharon and Kutiel, 1986; Morin et al., 1998). Thus the eastern Mediterranean extratropical cyclone, the Cyprus Low rainfall is probably responsible for most of the moisture available for soil development in the hyperarid parts of the Negev Desert during most of the Quaternary (Amit et al., 2006).

In general, summers in the Negev Desert are extremely hot and winters are cold (Atlas of Israel, 1985). Soil surface temperature in the

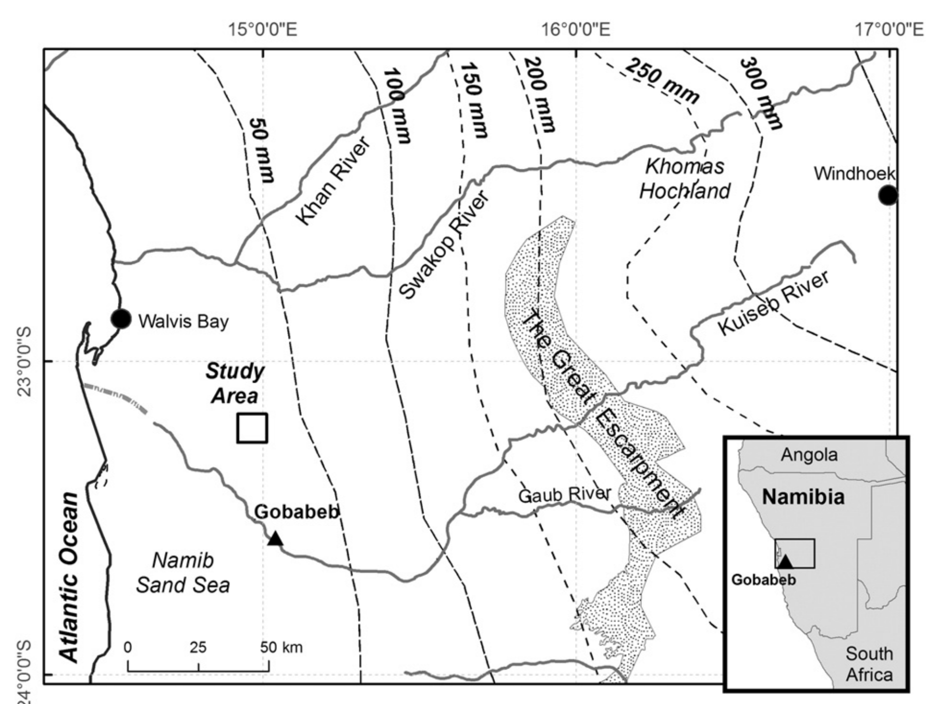

Figure 1. Location map and mean annual rainfall over the central Namib Desert.