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Particle-size fractionation of eolian sand along the Sinai–Negev erg of Egypt and Israel

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ABSTRACT

Eolian sand fractions along the west-east transport system of the northern Sinai Peninsula–northwestern Negev erg of Egypt and Israel were analyzed in this study with regard to source, dune geomorphology, eolian transport, and paleoclimate. The studied erg is composed of active linear (seif) dunes in northern Sinai (western part), and stabilized vegetated linear dunes in the NW Negev dune field (eastern part). Linear seif dunes differ from vegetated linear dunes in their vegetation cover, linearity, internal structure, and dynamics. Sand samples were analyzed for sand-grain morphology and particle-size distribution. Although both dune types are continuous landforms with similar orientations and sand-grain roundness values, the linear dunes of Sinai are coarser grained than the Negev vegetated linear dunes. The vegetated linear dunes have a variable but higher proportion of very fine sand (50–125 µm) content and a varying but lower sand fining ratio (defined as the ratio of fine sand percentage to very fine sand percentage). From these observations, we infer that fractionation of sand occurred along the studied eolian transport path during periods of enhanced windiness. Very fine sands are suggested to have been transported by saltation and low suspension from source deposits and sand sheets. We suggest that a significant proportion of the very fine sand fraction of Nile Delta sands has been transported downwind through northern Sinai during the late Pleistocene, especially when linear dunes reached the NW Negev due to last-glacial period windiness and probably larger sediment supply. Generally decreasing wind velocities and increasing precipitation along the west-east dune transport path enhanced vegetative cover in the northern Negev and enabled deposition of the very fine sand component within the dunes and probably further downwind. Our results suggest that particle-size distribution can elucidate much about erg history over time scales of a glacial-interglacial cycle, especially in cases where the sand provenance is of a single dominant source.

INTRODUCTION

Particle-Size Changes in Eolian Deposits

Particle-size distributions of dune sands are an important factor in understanding the morphology and dynamic processes of dunes (e.g., Bagnold, 1937; Tsoar, 1986; Lancaster, 1995; Pye and Tsoar, 2009). Theoretical and empirical studies have shown that particle-size distributions of eolian sand deposits change along their transport paths (McLaren, 1981; McLaren and Bowles, 1985). Some dune fields, composed mainly of parabolic dunes, are reported to undergo a gradual and slight decrease in particle-size means with downwind distance, interpreted to be partially due to winnowing of coarse sands (Muhs et al., 1999; Muhs and Holliday, 2001). Particle-size distribution modes have been mapped at various scales for active linear dune bodies, but significant trends have not been identified (Lancaster, 1995, and references within).

Particle-size fractionation acts on sediment in transport that undergoes selective deposition due to decreasing energy of the transporting process. As the transport energy decreases, coarser sediment has a greater probability of being deposited than finer particle sizes (McLaren, 1981). Particle-size fractionation of sand and silt has been shown for different arid environments, mainly with regard to accreting soils and eolian mantles that are formed by a mixture of suspended and saltating particles (McTainsh, 1984; Holliday, 1989). The process of fractionation of sand-grain fractions along transport paths has been reported for finer-grained eolian deposits and soils in the central United States (Olson et al., 1997) and northern Africa (McTainsh, 1984) but has not been fully described for dunes. At a smaller temporal and spatial scale, sand plumes of several hundred meters extending downwind of an abandoned sandy agricultural field in the Mojave Desert were found to exhibit fractionation, with smaller effective particle sizes toward the toe of the plume (Okin and Painter, 2004).

Particle-size-distribution changes in sand along a transport path of mobilized dunes can result from eolian abrasion of sand grains due to grain collision and erosion of the substrate underlying the dunes, as well as winnowing out of coarser eolian particle sizes. The relative importance of these different processes is still unclear for most dune bodies. Theoretically, given a particular amount of wind power, the particle-size distribution of loose source sediment, which includes sand, silt, and clay, should be differentiated (fractionated) along the transport pathway as different particle-size fractions have different threshold values for entrainment and transport. Silt and clay particles (<50 µm), carried primarily in suspension (Tsoar and Pye, 1987), should attain transport distances well beyond the region of sand and dune mobilization (Pye and Tsoar, 1987; Pye, 1995) in accordance to the duration and velocity of the winds.

Very Fine Sand

Unimodal particle-size distributions of 125–250 µm modes (fine sand) are common in active dune sands, as this particle size is optimal for transport by saltation. However, the transport dynamics of very fine sand are different than fine sand. Very fine sand, being dynamically transitional between saltation and low, modified suspension in strong storms (Bagnold, 1941; Chepil, 1951; Pye and Tsoar, 1987; Xu et al., 2007), makes this size fraction potentially and more uniquely sensitive to current and past changes in wind velocities. Very fine sand

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transport by suspension over longer distances is inferred from small amounts of very fine sand, interpreted to be eolian, found in offshore cores of the Mediterranean Sea (Hamann et al., 2008; Mulitza et al., 2010), on Mediterranean islands (Sevink and Kummer, 1984), and off the North African coast (McGee et al., 2013). The very fine sand fraction, defined here as the range of 50–125 µm, is a slight extension of the Krumbein phi (ϕ) scale for the very fine sand fraction of 63–125 µm, and includes the tail of (coarse) silt (50–63 µm). The 50 µm cutoff is in accordance with the lower cutoff of the U.S. Department of Agriculture (USDA) fine sand fraction definition and the fact that typical loess usually has particles <50 µm (Smalley and Vita-Finzi, 1968; Junge, 1979, and references within; Pye, 1995). The very fine sand fraction centers around 80–100 µm, being the particle-size range that has the lowest critical drag velocity needed to initiate particle mobilization (Bagnold, 1941; Chepil, 1951; Pye and Tsoar, 1987). Impact threshold velocities for fine particles are much lower than fluid threshold shear velocities (Pye and Tsoar, 2009). Thus, even modest wind velocities in an active dune field can keep very fine sand and coarse silt particles in motion, such that cumulative transport distances could amount to hundreds of kilometers (Muhs et al., 2008). These factors can cause particle-size fractionation of sand. Nevertheless, the scale in time and space of very fine sand transport and deposition is highly variable.

Recent studies in mid- and low-latitude dune fields report substantial but differing amounts of very fine sand, silts, and clays, mainly in stable vegetated linear dunes, though the significance of the very fine sand fraction is not discussed. Following the recent success of improved methods for coring dry dune sands (Munyikwa et al., 2011) and the proliferation of laser diffraction techniques to measure particle-size distributions, particle-size analysis along the full profile of linear dunes has been reported (e.g., Stone and Thomas, 2008; Fitzsimmons et al., 2009). Particle-size distributions of full dune profiles in the Strzelecki and Tirari Deserts of central Australia showed abundant fine sands and silts, although silt-sized material is most likely to have been deposited as secondary long-range–transported dust (Fitzsimmons et al., 2009). Stone and Thomas (2008) showed that Kalahari dune sand particle sizes have modes mainly within the 150–500 µm range, while some cores show "coarse silty fine sand layers" at their basal parts. However, the very fine sand fraction has not been analyzed in light of the different dune-building dynamics, namely, those between active sinuous-shaped linear dunes and vegetated linear dunes.

Study Outline and Goals

The study area, the northern Sinai Peninsula–northwestern Negev erg (Sinai-Negev erg), straddles the Egypt-Israel border (Figs. 1 and 2). The studied erg is composed of active linear (seif) dunes in northern Sinai (western part) and stabilized vegetated linear dunes in the NW Negev dune field (eastern part) of Israel. The Sinai dune sands are the immediate source of the Negev dunes.

The Sinai-Negev erg is an ideal "field laboratory" to study eolian particle-size trends along a sand transport system for several reasons. The erg is relatively small, confined, and young (Roskin et al., 2011a). The eastern part of the Nile Delta is artificially separated from the overlapping northwestern section of the northern Sinai dune field by the Suez Canal. While the past source deposits of the Sinai sands are not distinctly identified, the Nile Delta is the only reasonable candidate for the past source since the sands of the delta and the erg are similar mineralogically, and both are geochemically mature, suggesting a sedimentological link between them (Muhs et al., 2013). The erg lies to the north and downslope of a series of ridges and highlands of mainly carbonate strata, which reduce possibilities of additional sources of quartz grains to the erg as initially suggested by Crouvi et al. (2008) and studied by Muhs et al. (2013). Along the central and main sand transport corridor of the erg, sand-grain redness intensity attributed to reddish iron-oxide coatings does not vary significantly (Roskin et al., 2012), further suggesting a lack of additional and secondary sand sources.

By analyzing particle-size distributions and grain morphologies of northern Sinai sands and sands from optically stimulated luminescence (OSL) dated dune profiles of the NW Negev (from Roskin et al., 2011a), we identify progressive sedimentological changes in particle-size fractions along sand and dune transport corridors. We further explore spatial sedimentological trends in an effort to understand the source, transport modes, and formational controls of dunes and downwind eolian deposits in the northern Negev. Specifically, we test the hypothesis of sand particle-size fractionation and fining down the transport pathway of linear dunes, and the association with past regional paleoclimates and paleoclimate change.

STUDY AREA

Northern Sinai Dune Field

The northern Sinai dune field runs between hyperarid conditions in the southwest to arid conditions in its northeast corner (Abou Rayan et al., 2001; Mohamed, 2012). At Gebel Maghara in the west, mean annual rainfall is ~50 mm (Ahmed, 2010), and, along the Mediterranean coast, annual averages are 67 mm at Port Said (Tsoar, 1995), 104 mm at El-Arish, and 200 mm at Rafah (Abdel Galil et al., 2000) (Fig. 1B). The northern Sinai dune field east of the Nile Delta is spatially continuous over substantial areas, with dune heights exceeding 30 m (Gad, 2004). The Sinai sands are mainly sparsely vegetated to bare and uncrusted seif linear dunes (Tsoar, 1989; Abdel Galil et al., 2000; Rabie et al., 2000), and complex braided linear dunes (Tsoar, 1989, 1995) (Figs. 3A and 3B). Complex braided linear dunes characterized by low heights, compared with the active linear dunes, are mainly found to the east of Wadi Al-Arish, where the annual rainfall is somewhat higher (Fig. 1B). Other than in southwest Sinai, where dune crests extend to the east-southeast (Tsoar et al., 2004), the dunes extend in a general west-east orientation west of the Egypt-Israel border. This observation is important in ascertaining the past direction and upwind Nile Delta source of the sands.

Current annual seif dune elongation rates are in accordance with wind data. Strong southeastern eolian sand transport drift potentials (DP; defined by Fryberger, 1979) (DP = 1139) were calculated for the years 1987–1993 from meteorological data from the Port Said airfield, Egypt, at the northeast edge of the Nile Delta (Fig. 1B). The measured winds had annual monthly averages of 7.4–10 m/s between the years 1989 and 1999 (Roskin et al., 2011a, and references within). These winds may explain the occurrence of nonvegetated linear dunes in the western part of the Sinai dune field south of Port Said, which are currently elongating to the SSE by several meters per year (Tsoar et al., 2004). Maximum dune migration rates of 27.3 m/yr have recently been reported in the southwestern part of the dune field (Hermas et al., 2012). Wind data from central and eastern parts of northern Sinai also indicate that wind power decreases to the east toward the Negev. Annual elongation rates, usually in the range of 2–15 m (Misak and Draz, 1997; Tsoar, 1989; Tsoar et al., 2004), generally decrease from west to east. Nevertheless, limited sand is transported into the NW Negev dune field (Allgaier, 2008). These data and the continuous availability of sand supply imply that today the dynamics of Sinai sand movement are controlled chiefly by wind strength.

Minor sources of eolian sediments in the dune field environs are coastal dunes and Wadi Al-Arish (Fig. 1A). A 2–4-km-wide strip of transverse and parabolic dunes along the Sinai coast is partially separated from the inland

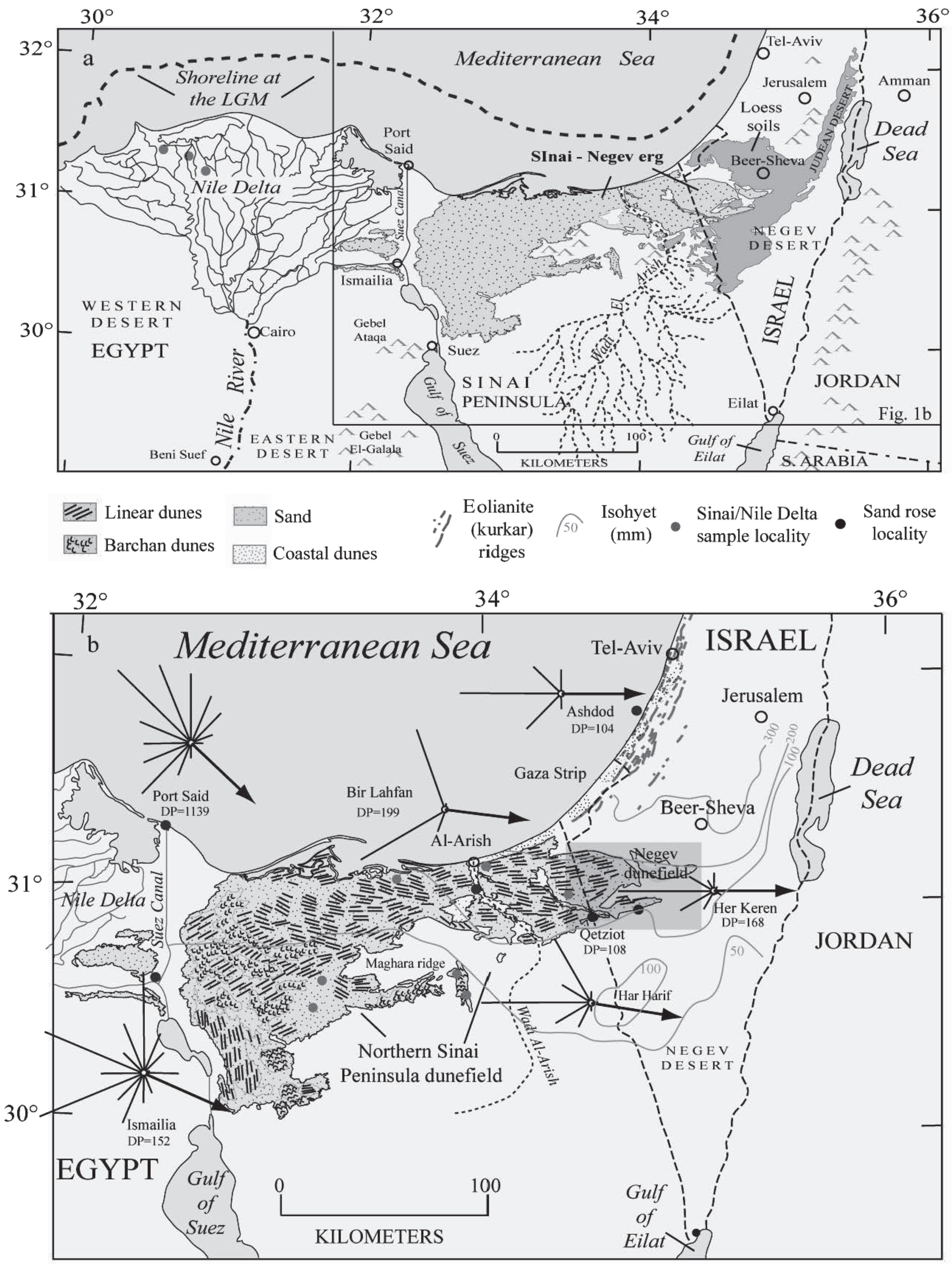

Figure 1. The study region and area. (A) The distribution of major eolian deposits in the Nile Delta, northern Sinai Peninsula, and in the central and northern Negev Desert, Israel. Note that the eastern parts of the Nile Delta are also covered by sand and dunes (modified after Muhs et al., 2013). (B) Principal dune forms of the Sinai-Negev erg and coastal sands of Israel and (current) sand wind roses. Generalized annual rainfall isohyets for the Sinai Peninsula are after Abou Rayan et al. (2001) and Milewski et al. (2009). The gray-shaded eastern part of the erg is the northwestern Negev dune field, enlarged in Figure 2. The sampling sites are described in Table 1 (modified after Muhs et al., 2013). LGM—Last Glacial Maximum.

Sinai dunes. The coastal dunes exhibit a lighter color and a coarser grain size then the inland dunes of Sinai (Tsoar, 1976). These dunes, as with the coastal dunes of Israel (Levin et al., 2006, and references within), are associated with a historical incursion ca. 1 ka. Wadi Al-Arish (Fig. 1B), the only wadi that dissects the Sinai dune field, has been found to be a negligible source for quartz dune sand (Muhs et al., 2013).

Northwestern Negev Dune Field

The NW Negev dune field (30°N, 34°E) covers ~1300 km^2, is of a triangular shape, and, at its eastern apex, attains a maximum breadth of 55 km. The Negev dune field is classified into three dune encroachment (incursion) corridors that differ in length, dune morphology and spacing, and sand transport rates (Roskin et al., 2011a) (Fig. 1B). The dune field runs along a desert fringe between the climatic zones of the Mediterranean Levant and the subtropical desert. The dune field, situated along the southern part of the wintertime cyclonic tracks of the Mediterranean Cyprus Low, receives ~150 mm of annual rainfall in the north but only 80 mm in the south (Fig. 1B). The current wind power of the Negev is lower than that of Sinai, as indicated in the sand wind roses (Fig. 1B). Winds typically encountered today do not cause

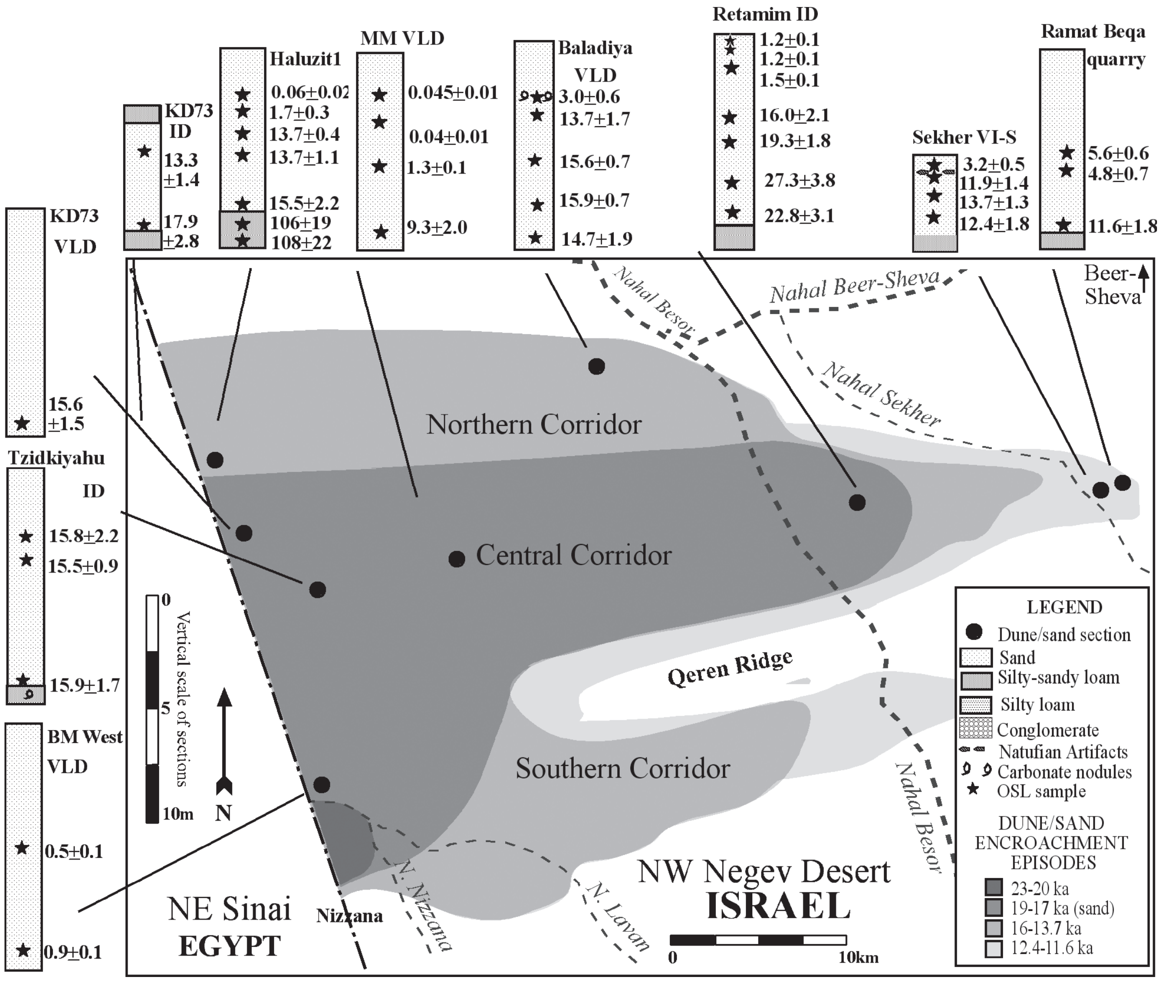

Figure 2. Northwestern Negev dune field development stages, dune encroachment corridors, and optically stimulated luminescence (OSL)–dated logs analyzed for particle-size distribution. Ages are in ka (modified from Roskin et al., 2011a). VLD—vegetated linear dune; ID—interdune.

substantial vegetated linear dune elongation nor do they rework the dune crest beneath depths of ~3 m (Roskin et al., 2011a).

In contrast to the Sinai dunes, the NW Negev dune field is dominated by stable vegetated linear dunes, the vegetation cover of which consists of vascular shrubs, with surface cover ranging from 5% to 17% (Tsoar and Möller, 1986; Allgaier, 2008; Siegal et al., 2013). This vegetation provides minute amounts of organic material to the upper parts of the dune section (Blume et al., 1995), which are negligible for particle-size distribution analysis. The dune flanks are currently stabilized by biogenic soil crusts (Danin et al., 1989; Kidron et al., 2009), although some dune crests are active. Similar to a majority of the Sinai linear dunes, the dunes have long axes oriented in a general west-east direction (Ben-David, 2003).

The NW Negev dune field is flanked by late Quaternary loess deposits. The traditional views linking northern Negev loess sources solely to dust entrained from the distant upwind Sahara Desert (Yaalon and Dan, 1974; Yaalon, 1987; Ganor et al., 1991) and more proximal Wadi Al-Arish and Sinai floodplain deposits (Ginzburg and Yaalon, 1963; Yaalon and Dan, 1974; Ganor et al., 1991; Hunt, 1991) have recently been modified. Crouvi et al. (2008, 2009), Enzel et al. (2010), and Amit et al. (2011) proposed that the coarse silt quartz fraction in the loess is derived from eolian abrasion of quartz sand grains during the mobilization of dunes in the Sinai and Negev. Negev loess is reported to be enriched in K-feldspar, plagioclase, and calcite, relative to quartz, when compared to these minerals in the Negev dunes. These relations may indicate that these relatively soft minerals underwent eolian abrasion along the Sinai-Negev erg system and could be at least a partial source for loess in Israel (Muhs et al., 2013).

Paleoclimate of the Sinai-Negev Erg

The paleoclimate that enabled the Negev dune field development has traditionally been interpreted to be the result of past aridity (Goring-Morris and Goldberg, 1990; Magaritz and Enzel, 1990; Hunt, 1991; Harrison and Yair, 1998). Elsewhere, active inland desert dunes have also been interpreted to be indicators of arid conditions (Sarnthein, 1978; Hesse and Simpson, 2006), and this paradigm is in accordance with the assumption that dune mobilization thresholds are defined in part by a decrease in effective precipitation. In many parts of North America, dunes are active in hyperarid environments where wind strength is low, while vegetated dunes are stable in semiarid environments where wind strength is high (Muhs and Holliday, 1995). Recent modeling shows, however, that dune activity is controlled dominantly by wind power, and dunes can be mobilized even

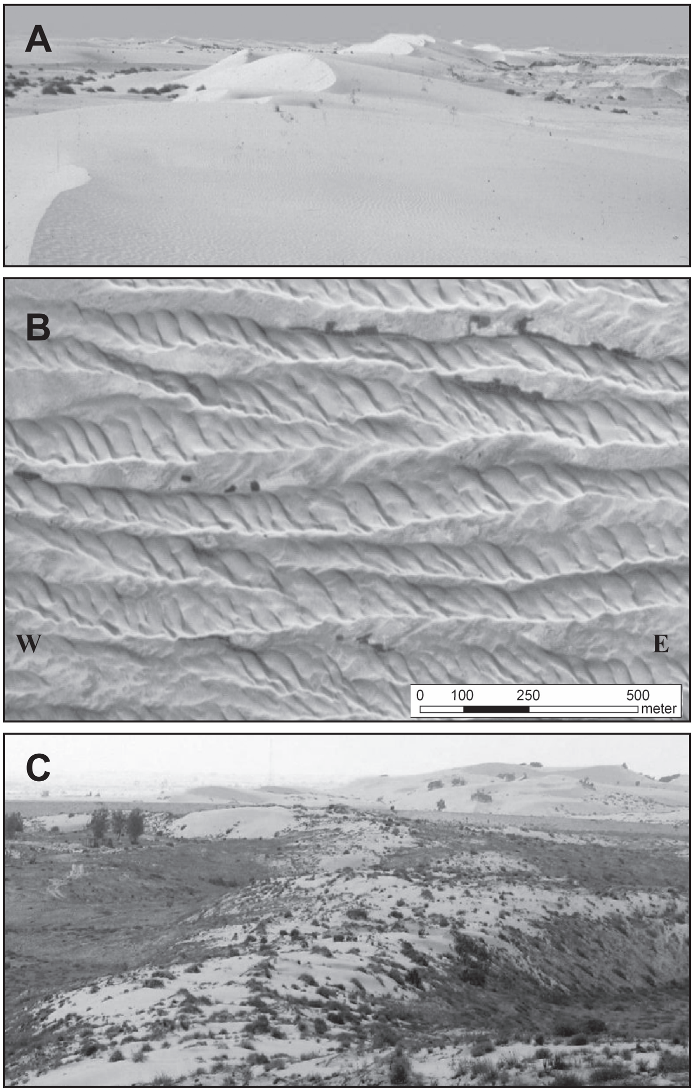

Figure 3. Linear dune types of the Sinai-Negev erg from west to east. (A) Active linear seif dune in the central part of the Sinai dune field (courtesy of Haim Tsoar). (B) Active braided (raked) devegetated linear dune in northeastern Sinai (from Roskin et al., 2011b). Note the west-east dune elongation direction and corresponding dominant paleowind orientation during the late Pleistocene. Modern reactivations of superimposed northeast-facing dunelets are in accordance with current dominant southwesterly winter storm winds. (C) A stabilized vegetated linear dune (VLD) at the BM site of the NW Negev dune field (Fig. 2) by the border with Egypt. An active braided dune can be made out beyond the border.

in humid climates in at least some regions when stripped from vegetation (Tsoar, 2005, 2013; Yizhaq et al., 2009).

Although there is evidence for measurable sand movement in northern Sinai at present, there must have been times in the past when sand advanced at substantially higher rates through the action of powerful winds. If these winds occurred in the past, they could have been the driving mechanism behind transport of both deltaic and coastal sand inland into northwest Sinai. Under proposed scenarios of last-glacial synoptic climatology, it is likely that there were higher-velocity, more frequent, west-to-east winds over the area now occupied by the Sinai-Negev erg, possibly due to more frequent eastern Mediterranean cyclonic systems (Enzel et al., 2008). However, as stated by Kocurek (1991), there is still no reliable means to calculate paleowind speeds. Nevertheless, with an abundant sand supply from the Nile Delta, high-velocity winds would have produced optimal conditions for initiation and growth of the Sinai-Negev erg during the last glacial period (Roskin et al., 2011a, 2011b).

Particle-Size Distributions of the Sinai and Negev Sands

The particle-size distributions of the sands of the Sinai-Negev erg have not been analyzed in a detailed, or in a regional context, or systematically along the transport direction of the erg's sand. The particle-size distribution of northern Sinai dune sands, usually performed for single sites by dry sieving, are reported to have unimodal peaks in the range of 125–250 µm, typical for mobilized linear dunes (Tsoar, 1976, 1978; Goldberg, 1977; Sneh and Weissbrod, 1983; Misak and Draz, 1997). Elsewhere in Sinai, the 125–500 µm fraction has been reported for barchan-dominated dunes and sand ramp deposits by Gebel (Mountain ridge in Arabic) Maghara and Lagama (Goldberg, 1977) and linear dunes south of the city of Al-Arish (Misak and Draz, 1997) (Fig. 1B). No distinct difference in sand particle size was found between the dune crests and flanks (Sneh and Weissbrod, 1983), and the sands displayed meager amounts, e.g., (~5%) of silts and clays (Gad, 2004).

For the NW Negev dune field, diverse particle-size distributions are reported. Negev dune sands sampled from the surface are moderately rounded to well rounded and are reported to exhibit bimodal particle-size distributions, predominantly the 125–250 µm and 63–125 µm fractions. Negligible west-east downwind particle-size-change trends are interpreted to be due to either varying wind intensities or provenance (Hunt, 1991). Roskin et al. (2011a) conducted a comprehensive sampling program of full dune sections of the NW Negev dune field and used laser diffraction particle-size distribution analysis. These investigators reported the dune field to consist of sand to loamy sands, though detailed analysis of particle-size fractions was not conducted. In the southwestern part of the Negev dune field, silts and clays derived from the upper 1 m do not exceed 6%–7% (Tsoar and Möller, 1986; Blume et al., 1995, 2008) and have been reported to be near zero by Enzel et al. (2010).

METHODS

Sampling

In order to retrieve the longest available sand transport paths for the Negev, dune sections were sampled at the western and eastern ends of each dune encroachment corridor. The central corridor, composed of several geomorphic units, is the widest, longest, and thickest corridor in the Negev dune field and is the main conduit for northern Sinai sand (Fig. 2). Here, dune mineralogies were found to be less "contaminated" by local sand additions from sources (mainly carbonates) around the periphery of the dune field (Muhs et al., 2013). The northern corridor was also studied, because it has fewer geomorphic units (Roskin et al., 2011a), and, therefore, trends may be more easily preserved. Nine sites were sampled for this study. Approximately half of the sections were exposed, allowing precise sampling according to stratigraphy. In other cases, hand drilling was performed down to the dune base with Dormer Engineering hand augers (Dormer soil samplers [Australia], http://dormersoilsamplers.com/Dormer).

Northern Sinai sand samples were acquired from the Geological Survey of Israel (GSI) archives, courtesy of Dr. Amihai Sneh, who sampled them for the GSI during the late 1970s, since the northern Sinai dune field, being part of Egypt, is currently inaccessible. The samples were usually obtained from shallow depths of 0.2–0.4 m in representative dune-geomorphic settings throughout the northern Sinai dune field (Table 1). We do not suspect that this sampling constraint affected the results, since globally, as in northern Sinai (Sneh and Weissbrod, 1983), no significant trends in particle-size changes with regard to their location upon and within the active linear dune section have been established (e.g., Folk, 1971; Ahlbrandt, 1979; Livingstone, 1987; Pye and Tsoar, 2009). Representative late Pleistocene sand samples from cores of the middle and lower Nile Delta were collected by Jean-Daniel Stanley (see Stanley et al., 1996).

Sedimentology

Analysis of particle-size distributions for the Negev sands, composed of 100 particle-size band measurements within the range of 0.1 µm to 1924 µm, was carried out by laser diffraction (using a Malvern Mastersizer MS-2000) at the GSI, Jerusalem, using the GSI protocol for desert sediments. Samples were split into 5 g portions, sieved to <2 mm, and stirred for dispersion for 10 min in Na-hexametaphosphate solution, followed by ultrasonification for 30 s. Three replicate aliquots were initially run for each sample. Due to good reproducibility of the results, attributed to the sand particle-size of the samples, later runs used two aliquots for each sample. Each aliquot was subjected to three consecutive 5 s runs at a pump speed of 1800 rpm. The raw laser diffraction values were transformed into particle-size distribution using the Mie scattering model (optical parameters RI (refractive index) = 1.52; A (absorption) = 0.1). Particle-size distributions of the Sinai and Nile Delta sand samples, obtained later, were analyzed with a very similar particle range (0.09–1839 µm) and particle-size bands, and the same measurement protocol using the laser diffractometer of the Eolian Simulation Laboratory of Ben-Gurion University of the Negev (Fritsch ANALYSETTE 22 MicroTec Plus).

These two laser diffraction analyzers use the same laser wavelength (632.8 nm). We assumed that using the same protocols for both laser analyzers provides highly compatible results. Comparison of soil sediment particle-size distributions between different laser diffraction techniques and the sieve/hydrometer methods indicated discrepancies for silt and clay particle-size distributions while sand particle-size distributions were found to be in good agreement (Cheetham et al., 2008), and previous studies have jointly used both of these analyzers (Sun et al., 2002). In order to further validate the results between the particle-size distributions of the Fritsch and Malvern laser diffraction analyzers, 12 representative Negev sand samples were measured in both the Malvern and Fritsch analyzers. The chosen samples included a wide range of particle-size distributions in order to maximize possible differences between the two analyzers. The percent volume of particles per particle-size band for all of the samples for each analyzer was averaged. An equation of $y = 0.98x + 0.03$ ($r^2 = 0.89$) was calculated for the average percent volume of particles per each equivalent particle-size band of each analyzer. A paired *t*-test was conducted between the averaged particle-size bands of both analyzers. No significant difference was found between the two averages ($p < 1.00$; mean = 0.00004).

According to the dynamics of sand-grain fraction characteristics, we analyzed the particle-size distribution fractions at cutoffs of >250 µm (medium- to coarse-sized sand), 250–125 µm (fine sand), 50–125 µm (very fine sand), and <50 µm (silt and clay). The silt-plus-clay fraction represents particles that are transported in full suspension and are therefore assumed not to be relevant to dune mobilization processes. Following the hypothesis that the particle sizes gradually decrease downwind, due to eolian sedimentological mechanisms, we define here a sand fining ratio (R):

$$R = \frac{f_{FS}}{f_{VFS}}$$

where f_{FS} is the percentage of find sand fraction (125–250 µm), and f_{VFS} is the percentage of very find sand fraction (50–125 µm) in the measured sand samples.

Three frames of fine and very fine sand grains per sand sample were analyzed and photographed with a DeltaPaix Invenio3SII camera attached to a binocular stereomicroscope (Nikon SMZ800). Sand-grain roundness was assessed for each frame (~50 and 100 grains per fine and very fine sand samples, respectively) using the Powers (1953) grain roundness chart.

RESULTS

Sand-Grain Shape and Color

The very fine sand fraction and the fine sand fraction of the studied samples generally exhibit similar distributions of grain roundness characteristics (Fig. 4). Approximately 15%–25% of the grains are angular, ~80% are subangular and 5%, are subrounded (Fig. 5). Though the Negev fine sand samples exhibit a higher percentage (25%) of angular grains compared to the Sinai samples (15%), the grains are less angular than coarse loess quartz grains found downwind of the NW Negev dune field that were reported to be angular shaped (Enzel et al., 2010). Chipped grains and freshly exposed faces of grains were observed for grains in some of the samples. For both Sinai and Negev sands, the grains in the fine sand fraction usually had more prominent red coatings than grains in the very fine fraction. The Nile sand samples appeared darker than the Sinai and Negev sands, due to ~5% presence of dark (heavy) mineral grains. The heavy mineral component of the Nile sands may indicate that during earlier stages of transport, the heavier minerals were winnowed out, while lighter quartz grains were transported in a downwind direction, as found by Muhs and Holliday (2001) for the Muleshoe dune field in New Mexico and Texas.

Sand-Grain-Size Features

Nile Delta and Sinai dune sands have lower amounts of very fine sand (Fig. 6) and therefore generally higher average R values, 5.1 and 4.4, respectively, compared to the Negev ($R = 2.8$) (Table 2; Fig. 7). The Negev sands also have a wide range of modes of medium, fine, and very fine sand compared to the Sinai dune sands, which exhibit modes usually in the range of 200–300 µm (Fig. 8). Despite these dissimilarities, the groups have similar average fine silt and clay content (<10%) and very small amounts of average silt (<2.5%), which may represent small inputs of suspended eolian material.

On average, the Sinai sands have substantial fractions of medium sand (~33.4%) and fine sand (~45.5%) and contain small quantities of very fine sand (10.4%) (Table 2; Fig. 6).

TABLE 1. SITE DESCRIPTION OF PARTICLE-SIZE DISTRIBUTION FRACTIONS AND SAND FINING RATIO (*R*)

Site and sample no.	Physiography	Depth from surface (m)	Normalized depth (m)	% 250–1000 mm (medium sand)	% 125–250 mm (fine sand)	% 50–125 mm (very fine sand)	% 20–50 mm (coarse–medium silt)	% 0–20 mm (fine silt + clay)	Mode mm	Fine/very fine sand ratio (*R*)
NW Negev (DF-)										
Haluzit 1	VLD									
DF 802		2.9	0.4	6.5	38.1	40.8	3.2	11.4	123.1	0.93
DF 803		3.7	0.5	11.0	50.6	28.2	0.8	9.4	167.2	1.79
DF 804		4.5	0.6	5.2	54.0	31.3	0.5	9.1	144.9	1.73
DF 81		6.8	0.9	2.8	33.4	49.5	1.4	12.9	111.7	0.68
Baladiya	VLD									
DF-72		0.65	0.1	11.9	37.7	31.2	3.4	15.8	139.7	1.21
DF 74		1.75	0.1	9.1	45.9	33.0	0.5	11.4	150.4	1.39
DF 75		2.4	0.2	6.0	33.7	37.6	4.3	18.5	131.3	0.90
DF 76		3.2	0.3	18.2	39.6	27.1	2.2	12.9	171.7	1.46
DF -714		5.7	0.5	26.0	53.1	12.1	1.2	7.6	202.0	4.39
DF -719		9.8	0.8	13.2	38.2	31.9	2.7	14.0	150.0	1.20
DF -720		10.25	0.8	11.2	36.8	28.9	3.8	19.3	152.0	1.28
KD 73	VLD overlying sand deposit									
DF 690		1.5	0.1	23.8	43.1	22.6	3.2	7.3	183.0	1.91
DF 692		4.5	0.3	11.6	58.8	22.6	0.6	6.4	162.0	2.61
DF 695		9.2	0.6	31.9	51.8	10.3	1.0	5.0	213.0	5.02
DF 680		1	0.7	17.8	27.4	18.4	11.0	25.4	197.0	1.49
DF 681		2	0.7	24.4	41.4	18.8	4.5	10.9	195.0	2.20
DF 682		3	0.8	30.9	38.2	19.6	2.7	8.7	211.0	1.95
DF 683		4	0.9	64.2	28.0	3.7	0.6	3.5	324.0	7.62
DF 684		4.5	0.9	27.6	42.9	21.4	0.7	7.4	188.0	2.01
DF 685		6	1.0	42.4	34.8	9.7	2.7	10.4	265.0	3.58
Tzidkiyahu	VLD overlying sand deposit									
DF-550		1.2	0.0	20.8	49.7	20.0	2.4	7.1	185.0	2.49
DF 554		3.8	0.1	21.5	55.4	16.7	0.9	5.5	189.9	3.32
DF 557		7.2	0.2	24.2	64.0	7.1	0.9	3.8	203.4	9.01
DF-534		4.6	0.4	20.5	61.2	13.0	0.8	4.5	187.8	4.70
DF-537		7.8	0.5	29.9	46.3	15.3	2.7	5.9	207.5	3.02
DF-521		2.5	0.7	24.6	63.5	6.3	0.8	4.8	203.0	10.13
DF-524		4.5	0.7	27.3	58.7	6.7	1.8	5.5	201.0	8.80
DF-660		10.2	1.0	44.1	45.4	5.8	1.0	3.8	231.5	7.86
MM	VLD									
DF -13		2.6	0.3	18.6	53.3	19.9	0.6	7.5	175.7	2.67
DF -16		5.7	0.7	12.7	56.9	21.8	0.7	8.0	164.8	2.61
DF -17		7	0.9	7.9	47.2	32.8	0.7	11.4	147.2	1.44
Retamim	VLD overlying sand deposit									
DF -560		0.4	0.0	24.3	42.9	22.6	3.5	6.8	201.7	1.90
DF 561		1.5	0.1	23.3	43.8	23.3	1.9	7.7	205.7	1.88
DF -563		2.85	0.2	30.4	55.4	6.8	1.6	5.8	203.0	8.14
DF -565		4.6	0.3	40.5	52.9	1.4	0.9	4.3	243.0	37.61
DF -566		6.1	0.4	46.3	46.3	2.3	1.2	3.8	248.0	19.82
DF -568		7.85	0.5	38.6	51.7	1.4	2.3	5.9	232.0	37.22
DF 543		3.3	0.7	42.0	47.4	4.8	1.7	4.0	239.3	9.88

(*continued*)

TABLE 1. SITE DESCRIPTION OF PARTICLE-SIZE DISTRIBUTION FRACTIONS AND SAND FINING RATIO (*R*) (*continued*)

Site and sample no.	Physiography	Depth from surface (m)	Normalized depth (m)	% 250–1000 mm (medium sand)	% 125–250 mm (fine sand)	% 50–125 mm (very fine sand)	% 20–50 mm (coarse–medium silt)	% 0–20 mm (fine silt + clay)	Mode mm	Fine/very fine sand ratio (*R*)
Retamim (*continued*)										
DF 545		4.6	0.8	49.4	46.5	0.5	0.0	3.5	252.3	90.30
DF 548		6.65	0.9	18.0	58.1	14.0	1.0	8.9	186.7	4.16
DF-700		7.6	1.0	7.1	38.8	40.2	2.6	11.4	143.8	0.97
DF-701		7.65	1.0	31.2	56.2	4.2	1.3	7.2	218.0	13.37
Beqa	Sand infill of wadi									
DF-580		3.1	0.4	24.3	48.8	16.1	2.5	8.3	203.0	3.02
DF-579		4.3	0.5	19.3	47.8	19.5	3.4	10.0	188.3	2.45
DF-578		4.85	0.6	27.8	60.6	4.7	1.9	5.1	211.1	12.94
DF 577		4.9	0.6	31.8	44.1	11.3	4.0	8.8	224.6	3.92
DF 576		5.2	0.6	25.5	44.8	14.4	4.6	10.7	207.8	3.12
DF 575		8	1.0	6.2	37.4	39.7	4.5	12.2	132.2	0.94
BM West	VLD overlying sand deposit									
508		3.1	0.2	32.0	51.6	9.3	1.6	5.6	215.6	5.55
509		5.5	0.3	38.1	53.0	3.3	1.1	4.5	229.4	16.05
510		7.7	0.4	31.0	40.6	18.5	4.0	5.9	227.1	2.19
511		9.8	0.5	32.7	41.3	15.7	4.0	6.3	231.1	2.63
505		5	0.9	32.7	45.8	12.5	2.1	7.0	219.3	3.67
506		6.5	0.9	30.0	58.4	4.1	1.1	6.5	216.8	14.35
Sekher-VI	Archeological site									
NS-1		0.5	0.2	21.4	58.6	0.9	1.7	8.3	195.0	64.44
NS-2		0.75	0.2	19.7	62.8	11.0	1.5	5.9	188.0	5.70
NS-3		1.5	0.5	27.1	49.9	12.2	7.4	3.4	207.0	4.11
NS-4		2.65	0.8	20.5	65.9	5.4	1.2	7.0	199.0	12.23
Northern Sinai dunefield										
A-1	Bir Hasna Barchan dune	–		40.90	53.50	1.39	0.63	3.52	222.8	38.5
A-16	Wadi Kharadein reworked dune base sand	–		18.95	41.38	10.81	0.32	28.54	202.8	3.8
A-19	Wadi Ghazala LD	–		42.48	45.70	8.25	0.24	3.33	222.8	5.5
A-20	Wadi Ghazala (LD)	–		26.93	53.18	15.52	0.28	4.09	202.8	3.4
A-22	Gebel Hamir LD	–		29.69	50.40	12.05	0.43	7.42	222.8	4.2
A-24	Bardawil Sabkha (coastal) dune	–		81.83	12.83	0.18	0.00	5.16	472.0	71.3
A-25	Gebel Hamir LD	–		55.68	31.05	7.60	0.68	4.94	295.2	2.1
A-26	Bir Gafgafa LD	–		13.48	66.51	10.81	0.22	8.99	184.6	14.6
A-29	Bir Gafgafa LD	–		53.39	35.54	4.27	0.53	6.28	295.2	1.3
A-30	Al Arish LD	–		41.17	47.61	6.40	0.26	4.53	222.8	9.9
A-33	Al Arish LD	–		52.45	37.76	4.02	0.30	5.48	295.2	1.6
A-38	Bardawil Sabkha dune sand	–		45.97	37.39	11.39	0.51	4.73	168.1	2.7
A-46	Gebel Libni jncl. ripples sand sheet	–		28.15	46.49	14.68	1.17	9.52	222.8	4.8
Nile Delta										
S-86, W-1	3 km Kafr El Zaiyat	17		36.8	39.1	9.8	2.2	12.0	277.5	4.0
S-86, W-14		35		55.6	21.6	8.3	2.6	11.9	373.9	2.6
S-55, W-2	In Ez. El Saiyid Mansur	12		41.6	33.9	6.1	2.1	16.4	277.5	5.5
S-55, W-7		19		75.6	17.8	1.5	0.5	4.4	373.9	11.9
S-52, W-8	2 km NE Ras El Husan	24		22.0	52.3	13.2	2.5	9.9	227.5	4.0
S-52, W-19		40		46.4	30.5	6.6	2.4	14.0	306.5	4.6

Note: The Sinai samples were usually sampled from 0.2 to 0.4 m depths beneath the surface. VLD—vegetated linear dune; LD—linear dune.

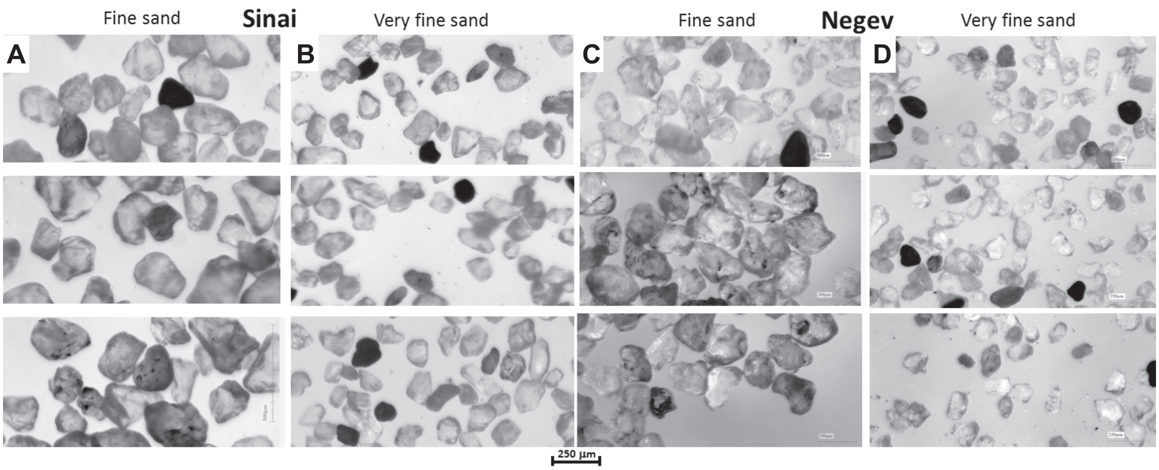

Figure 4. Sinai and Negev fine and very fine sand grains. (A) Fine sand of sample A-30 from a linear dune, near Al-Arish, northern Sinai (Fig. 1B). (B) Very fine sand of sample A-30. (C) Fine sand of sample DF-651 from a vegetated linear dune at the Tzidkiyahu site (Fig. 2), in the northwestern Negev dune field, Israel. (D) Very fine sand of sample DF-651.

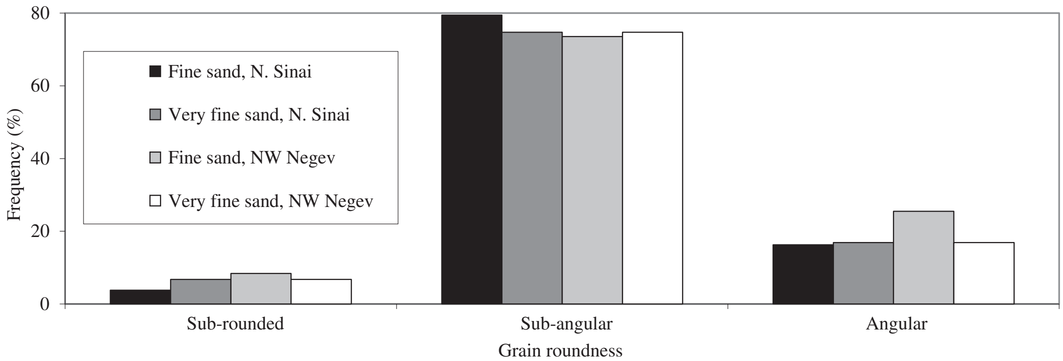

Figure 5. Sand-grain angularity for fine and very fine sand fraction of Negev and Sinai sands.

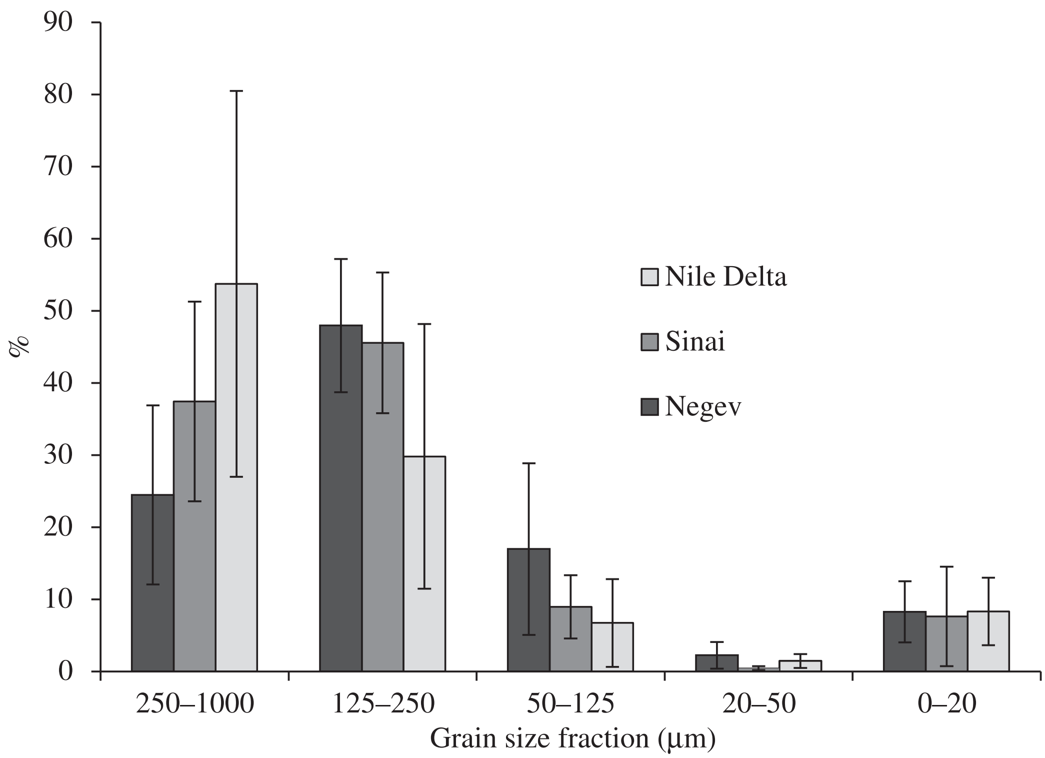

Figure 6. Grain-size fractions of the Nile Delta, northern Sinai, and NW Negev sands.

TABLE 2. PARTICLE-SIZE FRACTION RANGES AND AVERAGES FOR THE SAND SAMPLES

Region		% fine silt and clay (0–20 mm)	% silt (20–50 mm)	% very fine sand (50–125 mm)	% fine sand (125–250 mm)	% medium–coarse sand (250–1000 mm)	Mode (mm)	Average *R*	*N*	Comments
Negev	Range	3.5–19.3	0–7.4	0.5–49.5	46.5–65.9	2.8–49.4	111–252	2.8	58	
	Average: Std. dev.	8.9: 2.3	2.4: 1.8	17.5: 12.5	47.6: 9.7	23.6: 11.9	194: 36			
Sinai	Range	3.3–28.5	0.2–0.6	1.4–15.5	31.1–53.5	13.5–55.7	206–355	5.1	12	Coast dune sample A-24, with mode of 472 mm, was excluded from calculations.
	Average: Std. dev.	7.44: 7.2	0.4: 0.2	8.9: 4.4	45.5: 9.75	37.4: 13.9	255: 41			
Nile Delta	Range	4.4–16.4	5.0–18.4	1.5–13.2	17.8–52.3	22–75.6	169–456	4.4	6	
	Average: Std. dev.	11.4: 4.1	2.1: 4.7	7.6: 3.9	32.6: 12.5	46.3: 18.2	315: 98			

Note: Further site data for the Nile Delta sands can be found in Stanley et al. (1996).

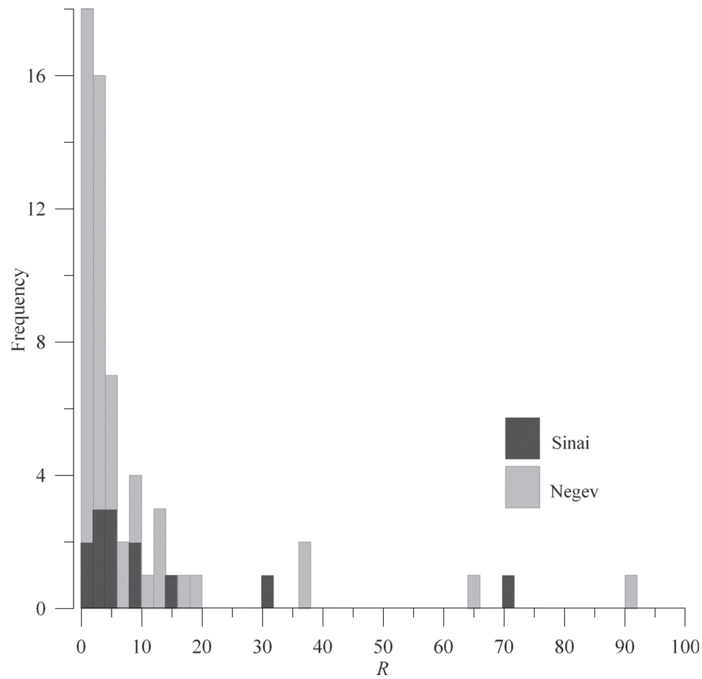

Figure 7. Sand fining ratio (*R*) of the northern Sinai and northwestern Negev sands.

Tsoar (1978) also found a particle-size distribution cutoff for particle sizes <125 µm for a seif linear dune west of Wadi Al-Arish, and Misak and Draz (1997) reported a dominantly fine sand composition for Sinai dune sand south of Al-Arish. The Sabhat (salt marsh in Arabic) Bardwil sample (A24) west of Al Arish (Fig. 1B), with a major mode of 472 µm and a minor mode ~200 µm (Table 1), is very different and thus is not included in the calculations. The sand is mainly part of the coarser-grained coastal dunes as described by Tsoar (1974, 1976), with partial westward contribution from the inland Sinai sand, similar to dune sand farther west on the Suez Gulf coast as described by Harris (1958). The coarse-grained coastal fraction is not found in the Sinai linear dunes that are farther from the coast and exemplifies the lack of substantial input from the coast southwards into the Sinai dune field. The high-peaked mode of sample A1 (Table 1), which has the least content of very fine sand, is from a (currently) active

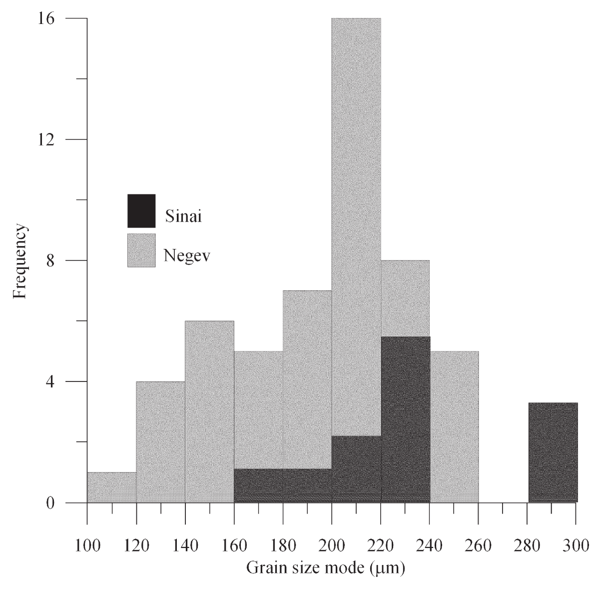

Figure 8. Particle-size mode frequency of the northern Sinai and NW Negev sands.

barchan dune. The barchans may be perceived as a field laboratory exemplifying how active dunes release the very fine sand fraction. The Sinai sands do not exhibit any west-east trend in fining of particle-size distribution modes or increase in the very fine sand fractions.

The Negev dune field sands have modes in the range of 100–260 μm. The abundant modes are 200–220 μm (Fig. 8), i.e., slightly finer than the northern Sinai sands. Nearly half of the Negev sands have finer-grained modes than the Sinai sands. On average, the Negev sands have substantial fractions of fine sand (~47%) and substantially larger amounts of very fine sand (~17%) compared to the Sinai sands (10.4%) (Table 2). Thirty out of the 58 Negev samples contain over 15.5% very fine sand compared to only one Sinai sample with 15.5% very fine sand. The Negev's central dune encroachment corridor has very fine sand contents in the wide range of 0.5%–40%. The two end sections of the northern corridor have very fine sand content in the range of 12%–50%.

A mixed analysis of variance (ANOVA) test using different grain-size fractions (μm) of 250–1000, 250–125, and 50–125 and different locations (Nile Delta, Sinai, Negev) as the independent variables was applied to the data. The analyses showed a main effect of grain-size fraction ($F[2,156] = 58.73$, $p < 0.001$) and a significant interaction between fraction and location ($F[4,156] = 14.51$, $p < 0.001$). To explore this interaction, *t*-tests comparing between the fractions from the different locations were conducted in order to validate the significance of grain-size fractions between regions (Fig. 6). Since the low number of analyzed samples for the Nile Delta and the Sinai do not fulfill statistical requirements for a parametric test, the data underwent a nonparametric Mann-Whitney test. Both *t*-tests and Mann-Whitney tests resulted in significant differences ($p < 0.05$) between all three fractions of the Nile Delta and the Negev sands and between the Nile Delta and Sinai medium sand fraction. Significant differences ($p < 0.05$) were found also between the Sinai and Negev sands, both for the very fine sand and the medium sand fraction. These results support the hypothesis that changes in grain-size fractions occur along the eolian transport system from the Nile Delta through northern Sinai to the NW Negev.

The statistical parameters of the regional sand groups tend to cluster. The Negev sands, predominantly positively skewed, are in good correlation with similar kurtosis values (Fig. 9A). The Sinai samples have slightly negative skewness values, with kurtosis values in most cases similar to the Negev sands. Both Sinai and Negev sands usually exhibit moderately good to poor sorting values (Fig. 9B).

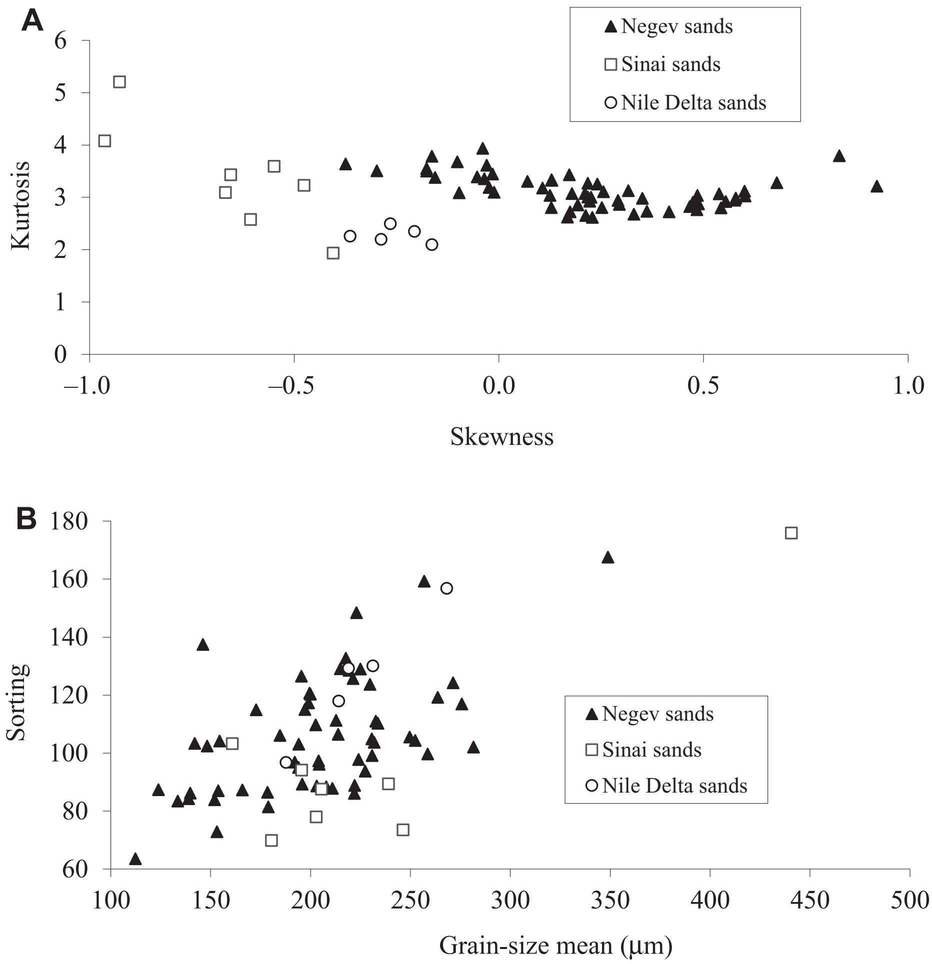

Figure 9. (A) Plot of kurtosis vs. skewness values of the sand samples. (B) Plot of sorting vs. mean particle-size values of the sand samples.

Particle-Size Variability in the NW Negev Dune Field

The northern dune encroachment corridor of the NW Negev dune field has both in the west and east mainly very fine sand with modes in the range of 100–140 μm, while in the central dune incursion corridor modes are coarser and more varied, in the range of 125–260 μm (Table 1; Fig. 2). In the central corridor, no trend in *R* values is apparent along the dune profiles, and each profile's *R* curve in relation to the normalized depth is different (Figs. 10A and 10B). The northern corridor end sections have a similar trend in particle-size changes, with the midprofile containing a lower very fine sand fraction (Fig. 10C). The eastern end of the Baladiya section is coarser grained than in the west.

In the central corridor, the lower parts of the dune sections have a noticeably broader *R* value and mode range of 125–325 μm. The upper parts of all of the central corridor sections have a relatively narrow particle-size mode range of 175–225 μm but a wide *R* range. The youngest section, MM, the lowest sample of which is dated to 9.3 ± 2.0 ka (Fig. 2), has a low *R* and the lowest mode values, and relatively high very fine sand contents (20%–33%; Table 1). Each dune section seems to have several size modes ranging between these values (Table 1). Beyond its upper active section and one basal unit (DF-700), which has exceptionally high very fine sand content (40%), the central part of the Retamim section has a relatively low very fine sand content.

Fining along the central corridor is not pronounced. For example, the Sekher VI section at the eastern end of the dune field, dated to ca. 12 and ca. 3 ka (Fig. 2), has the narrowest mode range of 189–205 μm (Fig. 11A; Table 1) and is not finer grained than the modes of the KD 73 section, 45 km to the west by the Egypt–Israel border, where, with the exception of two units, the

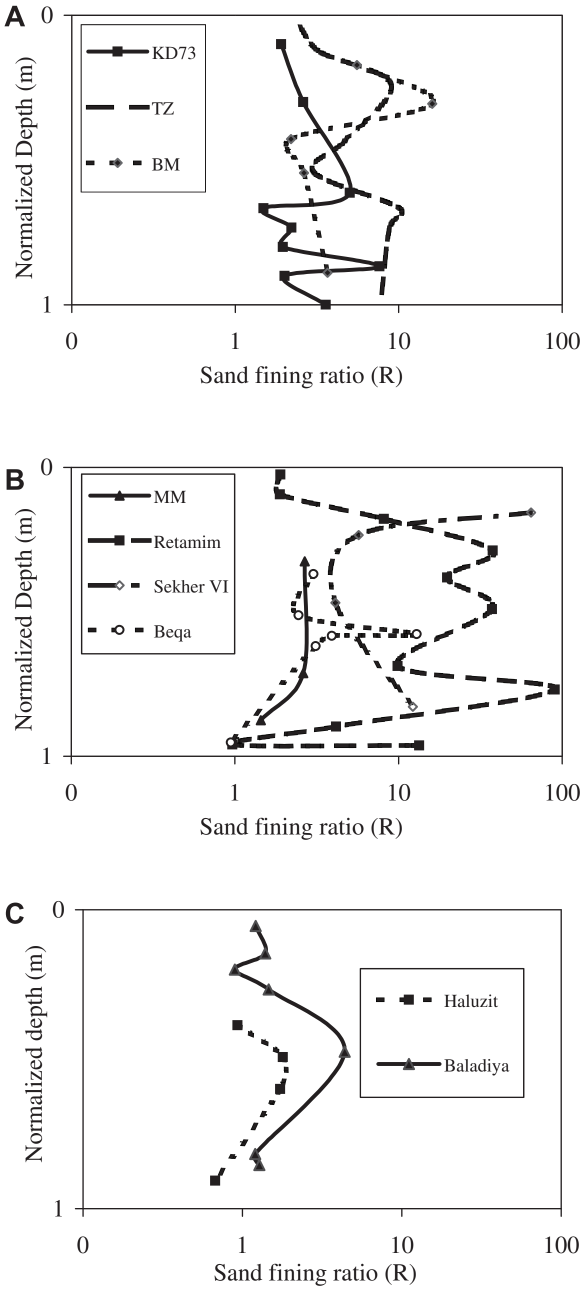

Figure 10. Sand fining ratio vs. normalized depth of dune and eolian sand sections per dune of: (A) the western part of the central dune encroachment corridor, (B) central and eastern part of the central dune encroachment corridor, and (C) northern dune encroachment corridor. For section location, see Fig. 2.

modes range from 162 to 211 µm. At the KD-73 vegetated linear dune section, sample DF-695, dated to 15.6 ± 1.5 ka (Roskin et al., 2011a), has a mode of 213 µm, and the adjacent DF-681 of the KD-73 interdune upper section, dated to 13.3 ± 1.4 ka, has a mode of 195 µm, similar to the Sekher sands deposited slightly later.

There are significant sedimentological variations for adjacent dune sections. The Beqa and Sekher VI sections, only 800 m apart at the far eastern end of the dune field (Fig. 2), exhibit different ranges in mode values and particle-size distribution curves (Figs. 11A and 11b). A similar discrepancy between Sekher sand particle-size distribution has been reported by Bacon et al. (2011). The 8-m-thick Beqa section infills a wadi, and its upper part has been reworked several times in the Holocene. The Sekher section is only 3 m thick, mantling a chalk ridge. The Beqa section particle-size distribution modes are in the range of 188–224 µm, other than the basal 2.5-m-thick grayish colored unit (sample DF-575) dated to 11.6 ± 1.8 ka. Sample DF-575, in the same age range as the lower Sekher sands, also has a distinct particle-size distribution curve and a mode of 132 µm.

Very Fine Sand Units in the NW Negev Sections

Several distinct units of very fine sand with mode peaks in the range 104–131 µm occur throughout the dune field (Fig. 11). These units, found mainly at the base of eolian sand sections, have different ages that span the full late Pleistocene age range of the NW Negev dune field sands.

The *R* profile generally reflects the particle-size distribution mode profile pattern but further highlights inherent sedimentological changes and processes (Fig. 11). These changes include an interchanging (zig-zag) pattern between units of the same section with fine sand dominance and negligible very fine sand units with substantial content of very fine sand (Fig. 10). As documented for the profiled particle-size distribution modes, no clear trend of very fine sand content occurs with depth, and therefore there is no connection between sand OSL age and changes in particle-size distribution. No sand fining occurs parallel to the downwind sand transport directions in the Negev dune encroachment corridors (Fig. 1B), which probably implies that the changes in particle-size distribution are more of a dynamic eolian character and also are probably not solely related to time-transgressive pedogenic breakdown of quartz grains with time.

DISCUSSION

Sedimentological Properties of the Sinai-Negev Erg Sands

The dominant subangular shape of the sand grains of the Sinai and Negev is consistent with most other arid inland dune sand grains, which range in the subrounded and subangular classes (Goudie and Watson, 1981). Similar sand-grain roundness distributions are also found for both fine and very fine sand fractions of desert dunes elsewhere (Khalaf and Gharib, 1985; El-Sayed, 1999, and references within). The limited amount of distinct freshly exposed surfaces and chipped grains observed does not indicate substantial grain-to-grain eolian abrasion. More angular grains were observed in the Negev fine sand samples compared to the Sinai samples (Fig. 5). On the contrary, the higher red-grain coatings of the fine sands suggest less abrasion, while the lighter color of the very fine sand may indicate that some of the grains are more likely to be products of eolian abrasion, a hypothesis that needs further testing.

Although the original and direct sand source characteristics of the Sinai-Negev erg are probably absent today, late Pleistocene sand of the Nile Delta that has been logged from beneath

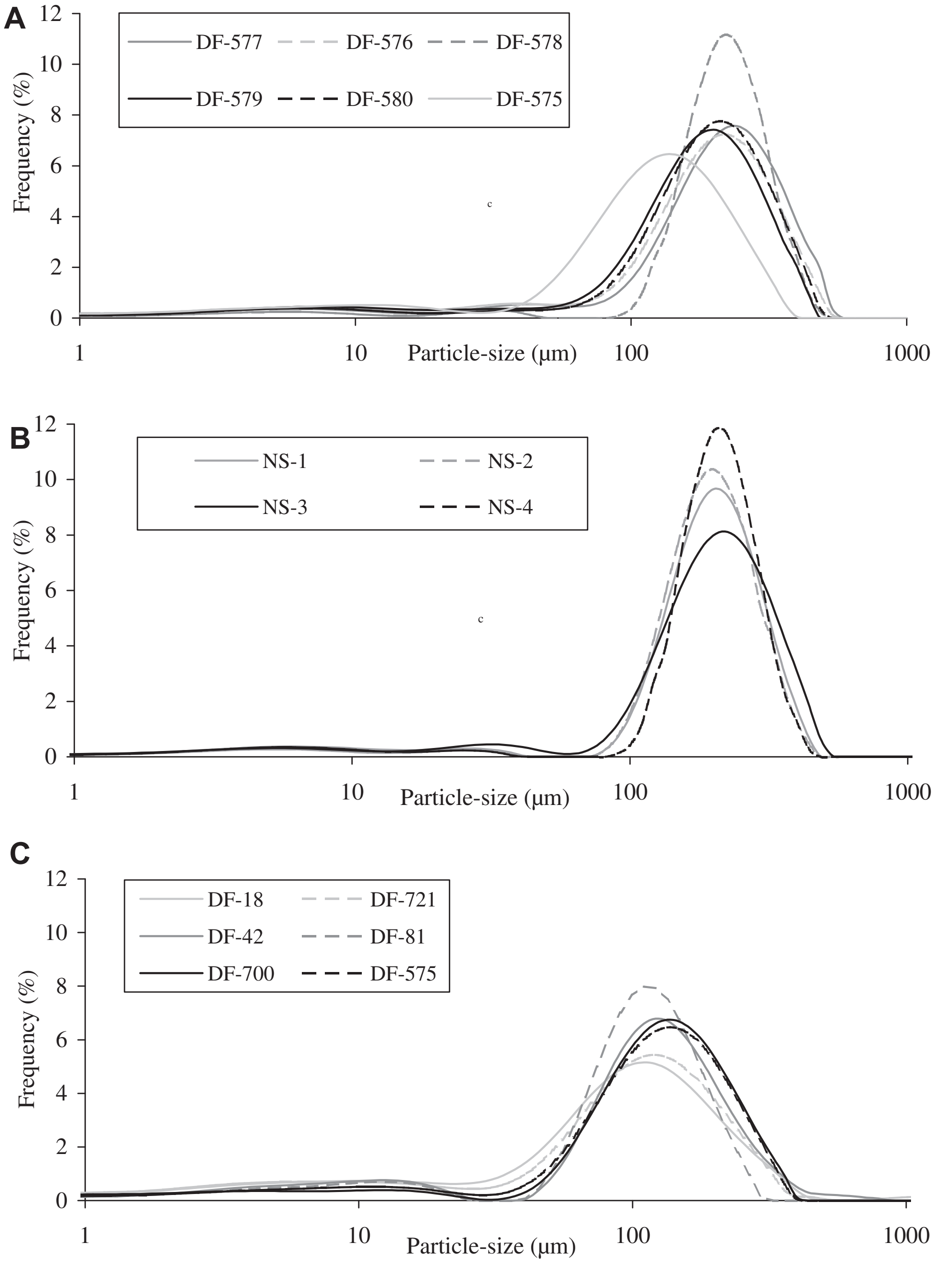

Figure 11. Exemplification of particle-size distribution variations between the adjacent Beqa (A) and Sekher VI (B) (exposed) sections, located at the eastern end of the NW Negev dune field. Each group has one sand sample with a particle-size distribution similar to the other section. The higher peaked curves are of the Sekher samples (other than NS-3) and include DF-578. Sample DF-575, marking the base of the Beqa section, is the outstanding finer-grained curve. (C) Negev sand samples with modes around 100 µm.

Holocene silts and clays (Stanley et al., 1996) may be a good candidate (Muhs et al., 2013). It seems that very fine sand was initially present in the delta, as were more abundant finer and larger sand particle sizes within the original dune sources (Fig. 6; Table 2). However, it cannot be concluded that the samples were fully preserved in the delta since deposition, as eolian processes, especially in the windy late Pleistocene, may have acted upon the deltaic sediment shortly following deposition, initiating winnowing. Several studies have reported that the various depositional settings of the Nile Delta have sediments with particle-size distributions ranging between medium-sized sand to fine silt, but they nearly always include very fine sand (Frihy and Stanley, 1987; Frihy et al., 1998; Stanley, 2002). Five different eolian microenvironments along the Suez Canal also showed different proportions of very fine sand content (Harris, 1958). Based on $^{87}Sr/^{86}Sr$ isotopic similarity, part of the Negev loess particles has been suggested to be of a Nile Delta origin (Vaks et al., 2013), particularly the coarse fraction (Haliva-Cohen et al., 2012).

While Frihy and Stanley (1987) showed the potential of identifying depositional environments of sands based on their sedimentological characteristics, specific identification of the Sinai-Negev erg source deposits and environments is quite complex. Late Pleistocene sands cored in the northeastern Nile Delta have been found to possess inherent mechanical abrasion features (Frihy and Stanley, 1987), while modern desert sands are more characterized by solution etching. Most of the sand grains located at the northern edge of the Nile Delta in a beach environment are rounded (Abd-Alla, 1991), but this may suggest that these sands and the beach sands of northern Sinai, which have undergone significant fluvial action, are not the source of the Sinai dunes, strengthening the assumption that the upper and central Nile Delta deposits located directly west of the erg are the source of the erg. Desert sand grains, usually of coarse and medium fractions, near the delta shore, are also rounded and contain v-shaped and crescent-like pits of 10–20 µm. The pits are interpreted to be a result of eolian sand abrasion (Abd-Alla, 1991). Based on interpretation of scanning electron microscope (SEM) images, it seems that the pits are usually 10–20 µm in size, corresponding to fine silt sizes. This observation is in accordance with recent 125 µm sand grain-grain abrasion experiments that simulate 1000 km of transport, approximately four times the length of the Sinai-Negev erg. The experiment produced 18.6% ± 0.4% of the particles below 125 µm, with 9.0% ± 1.6% below 18 µm, while the sand-size distribution values remained similar (Merrison et al., 2010; Merrison, 2012). Based on the sand-grain chemical and mechanical features reported by Abd-Alla (1991), the Nile Delta sands may have often undergone multiple cycles of transport and deposition. Experiments of quartz silt production from abrasion of highly angular quartz sand grains found that after the first 16 h of a 224 h experiment, 40% of the total fine and coarse silts (not very fine sand) were produced (Wright et al., 1998). This is a fair analogue of eolian abrasion for first-cycle erosion. However, it seems that first-cycle erosion is not the predominant case of the study area. As earlier work suggests, interpretations of the origin of sands on the basis of grain surface features alone may be insufficient (Frihy and Stanley, 1987, and references within), which necessitates focusing on particle-size trends as an indicator of eolian transport processes.

Therefore, we build upon previous studies (Tsoar, 1990; Hunt, 1991; Amit et al., 2011; Roskin et al., 2012; Muhs et al., 2013) and infer that the very fine, fine, and larger sand fractions of the Sinai-Negev erg evolved from widespread source deposits in the Nile Delta that were exposed during the last glacial period (Stanley and Warne, 1993). This assumption for sand is similar to the genetic association of quartz silt grains between the Nile Delta and the Negev loess initially proposed by Smalley and Krinsley (1978). The variability of the Sinai and Negev sand-grain coatings within the fine and very fine sand fraction may also be attributed to different depositional environments in the delta, as suggested by Roskin et al. (2012), and may not necessarily be a sole result of eolian abrasion.

Fractionation of very fine sand occurred by the hypothesized Nile Delta source and continued in the northern Sinai sands. The coarser sand fractions were winnowed out, while very fine sand was often transported by saltation and low suspension in a general eastward direction beyond the Sinai dune field. Due to SW and NW dominant winds, as evidenced by the formation of seif dunes (Tsoar, 1989), the very fine sands were transported and dispersed to the east in a wide angle, which may account for their presence in the northern Negev loess deposits (Fig. 1B). The significantly higher coarse sand fractions in the Sinai samples compared to the Negev (Fig. 6; Table 2) and the presence of coarse-grained zibars at the base of linear seif dunes in northern Sinai (Tsoar, 1989), not found in the Negev, exemplify the fractionation process of finer sand from coarser sand. During times of high sand supply, the fine sands form active linear seif dunes, while very fine sand fractions are released from their source material to be partial constituents of vegetated linear dunes. Downwind fining (grading) of sands from the upper parts of active dunes in the Suez Canal area is reported for short distances (Harris, 1958). This trend can be inferred to be seen as a small-scale analogue for the whole Sinai-Negev erg.

Spatial and Temporal Distribution of Very Fine Sand

Sedimentation of very fine sand is found elsewhere in the Sinai and Negev. Very fine sand occurred in NW Negev paleosols already by the late middle Pleistocene (ca. 190 ka), early marine isotope stage (MIS) 6, long before the appearance of vegetated linear dunes. This observation indicates that small amounts of invading sand, including this fraction, reached the region from the west, probably from Nile Delta sediments (Amit et al., 2011). Separately OSL-dated fine sand (125–150 µm) and very fine sand (88–125 µm) of correlating sand (sheet) units at ~1.5 m depths within the Qerem Shalom paleosol section, along the Egypt-Israel border, between the Negev dune field and Gaza Strip, are of very similar ages (13.4 ± 1.7 ka, 14.5 ± 2.3 ka, respectively) (Zilberman et al., 2007) and date to the main late Pleistocene Negev dune incursion from the west (after Roskin et al., 2011a, 2011b). This suggests a genetic synchronicity of very fine and fine sand deposition that originated from the west along the Nile Delta–Sinai–Negev eolian transport system, during and prior to dune encroachment.

The different very fine sand contents present in several sandy to loamy paleosol units, dated between ca. 200 ka and ca. 30 ka and underlying the younger NW Negev dunes, also imply that small quantities of fine sand along with very fine sand reached the Negev prior to the dune encroachment. The variability is attributed to the relative paucity of sediment supply or weaker winds (Roskin et al., 2011a, 2013c). Downwind northern Negev loess deposits of similar age ranges, reported to usually have particle-size distributions (Crouvi et al., 2008) that are finer than the NW Negev paleosols, may also imply a fractionation mechanism along the Nile Delta–Sinai–Negev transport system prior to the Negev dune encroachment. A jump in the very fine sand content from 10%–20% to 20%–50% at Qerem Shalom around 190 ka marks the onset of an increased eolian transport system of very fine sand that ended with the onset of the Holocene. Amit et al. (2011) reported a significant input of coarse silts and very fine sand with a 70 µm mode minimally OSL dated to ca. 180 ka in reg soils of the southern Negev Desert (by the border with Egyptian Sinai). This input was suggested to be connected to the exposure of sandy Nile Delta sediments during a period of glacially eustatically lowered sea level. Amit et al. (2011) further suggested a genetic connection between the coarse silt formation and transport, and dune mobilization in northern Sinai. Therefore, since transport of very fine sand requires lower wind power than the fine sand that characterizes linear dunes, the assumption of Amit et al. (2011) does not necessarily imply that dunes were mobilized at the time, especially at the intensities inferred for the NW Negev during the late Pleistocene. However, further study of the NW Negev paleosols is required to validate this hypothesis.

Despite the current paucity of very fine sand in the active Sinai dunes, late Pleistocene falling (Mushabi) dune sands in an erosional basin of Gebel Maghara (Fig. 1B) were found to contain significant amounts of very fine sand (Goldberg, 1977). The basin may have been a favorable trap for finer grain sizes that overtopped the basin's ridge as climbing dunes. This is supported by empirical field investigations of a 20° slope of a climbing dune, where, under a wind shear velocity of 30 cm/s, grains of 130 µm diameter were found to saltate to the crest while coarser grains did not (Tsoar et al., 1996; White and Tsoar, 1998). This setting may be analogous to the depositional environment of the ~100 µm quartz grain mode deposits on the Qeren ridge gully slopes slightly above the elevation of adjacent dunes in the NW Negev (Enzel et al., 2010), regardless of their formation processes.

The high variability of the *R* and the very fine sand contents in NW Negev dune sections, not identified between the samples of northern Sinai, suggests fluctuating rates of transport and deposition in the northern Negev after 23 ka. This variability implies that the fractionation process and consequent deposition of very fine sand usually occurred in short and highly windy events. The sand component of 62–185 µm has been found to be the component with the biggest standard deviation value and also the one with the highest degree of sensitivity, mainly controlled by source-to-sink distance (Guan et al., 2013). Several distinct dune units with an abundance of very fine sand are found throughout the dune field in basal units, such as at the Beqa section. These units, characterized by finer grain sizes, may mark the leading head of fractionized eolian encroachment. An upper unit of an interdune deposit (DF-18 of the MM section) exhibits 33% of very fine sand is dated to 9.8 ± 1.9 ka (Roskin et al., 2011a), similar to the time of upper Negev loess deposition at ca. 10 ka (Crouvi et al., 2009). This unit may represent the final stages of eolian deposition, when wind speeds were less proficient at mobilizing coarser fine-grained sand. Eolian erosion of the late Pleistocene paleosols that underlie the dunes (Roskin et al., 2011a) is also a possible closer and partial source for these very fine sand units, though further study is required to identify the relative contribution of the dune substrate to downwind sediments. Evidence for this is hand sample DF-685 (17.9 ± 2.8 ka) at the base of the KD-73 section, which had ~3% of sand-sized silt pellets. As the equivalent (OSL) dose of the sample was strongly biased and the age error relatively large, we attributed the pellets to the underlying paleosols dated to ca. 45 ± 13 ka (Roskin et al., 2011a). The reasons behind temporal and spatial variance of very fine sand deposition along the 25–45 km Negev dune field transect may explain why a regional particle-size fining trend is not identified in the Negev.

Marine and terrestrial very fine sand deposits in the Levant region provide further supportive data for suspension of very fine sand during windy periods. Sharp increases of very fine sand and coarse silt contents, similar to earlier glacial times, are found in offshore Mediterranean cores during the Heinrich 1 stadial ca. 17–14 ka, a period of persistent higher wind velocities (Jullien et al., 2007; Hamann et al., 2008; Tjallingii et al., 2008; Costas et al., 2012; McGee et al., 2013), when the dunes encroached into the NW Negev (Roskin et al., 2011a). Sufficient amounts (several percent) of very fine sand available for luminescence dating in Quaternary terrestrial deposits found throughout Israel (N. Porat, 2012, personal commun.), such as in late Pleistocene fine-grained deposits infilling open fractures along the western Dead Sea escarpment (Roskin et al., 2013a), also attest to a more distal suspension of this fraction.

Regional Winnowing Mechanism

Our proposition for downwind fractionation of very fine sand fits eolian sand transport dynamics, the transport mechanism and distance of which are controlled by particle sizes (Pye and Tsoar, 2009). A fining with distance trend of eolian sediments between the Negev dunes and sandy loess soils was initially suggested by Ravikovich (1981), who also noted that the coarse silt (74–44 µm) and very fine sand fractions (144–74 µm) are transported significantly longer distances than coarser sand modes. Field experiments with the Negev dune sands found that sands with a mean particle diameter (MPD) of 130 µm have substantially higher sand emission fluxes than sands with an MPD of 180 µm (Bacon et al., 2011). Pye and Tsoar (1987) stated that today in typical wind storms, quartz particles larger than 50 µm are unlikely to be transported more than 60 km from their source, and most will be deposited within ~30 km. During the Last Glacial Maximum (LGM), the low-latitude regions like the study area may have had more frequent strong winds and higher wind speeds (Harrison et al., 2001; Jullien et al., 2007; Enzel et al., 2008; McGee et al., 2010, 2013). Thus, very fine sand could have been transported to greater distances by a combination of saltation and short-term suspension. Taking the Pye and Tsoar (1987) rates at a time scale of thousands of years means that very fine sand, if independently mobilized, could potentially be blown for hundreds to thousands of kilometers, beyond the Negev dune field and loess belt. While small quantities of very fine sand are present in marine cores and throughout Israel, it seems that the main bulk of late Pleistocene very fine sand is found in the NW Negev paleosols, vegetated linear dunes, and northern Negev loess deposits that are no farther than 400 km from the Nile Delta. This observation supports the hypothesis that extremely windy episodes triggered dune mobilizations in the NW Negev (Roskin et al., 2011b).

During times of dune mobilization in the Sinai and the Negev, deposition of very fine sand in the Negev vegetated linear dunes is suggested to be due to a decrease in transport energy and an increase in surface friction. For certain episodes during the late Pleistocene, such as during the Heinrich 1 and Younger Dryas, which caused rapid vegetated linear dune encroachment into the Negev (Roskin et al., 2011a, 2011b) and probably no earlier than the last glacial, the Sinai dunes as found by Goldberg (1977) were probably highly active at the same time and probably for some time before. When the linear dunes of the Sinai reached the Negev region, their extending noses included the saltating sand along with very fine sand that were transported via the dunes and earlier by low suspension (Fig. 12). Following reduction in wind speed and turbulence, vegetated linear dune vegetation cover may have increased, if there was a generally more humid late Pleistocene climate in the region (Baruch and Goring-Morris, 1997; Vaks et al., 2006). Vegetation increases the aerodynamic roughness of the surface, thereby extracting energy from the airflow and reducing shear stress at the surface (Pye and Tsoar, 1987), causing an exponential decrease in sand transport and inducing deposition of all of the sand fractions (Allgaier, 2008). Part of the very fine sand also continued to be transported farther east to form part of the upper sections of the primary northern Negev loess deposits. The very fine sand (74–125 µm) fraction comprises the coarse end of the particle-size distribution of these loess deposits east and south of the dune field (Crouvi et al., 2008; Haliva-Cohen et al., 2012). In these deposits, the coarse silt and very fine sand content increased ca. 30–35 ka and peaked at 20–14 ka (Crouvi et al., 2008).

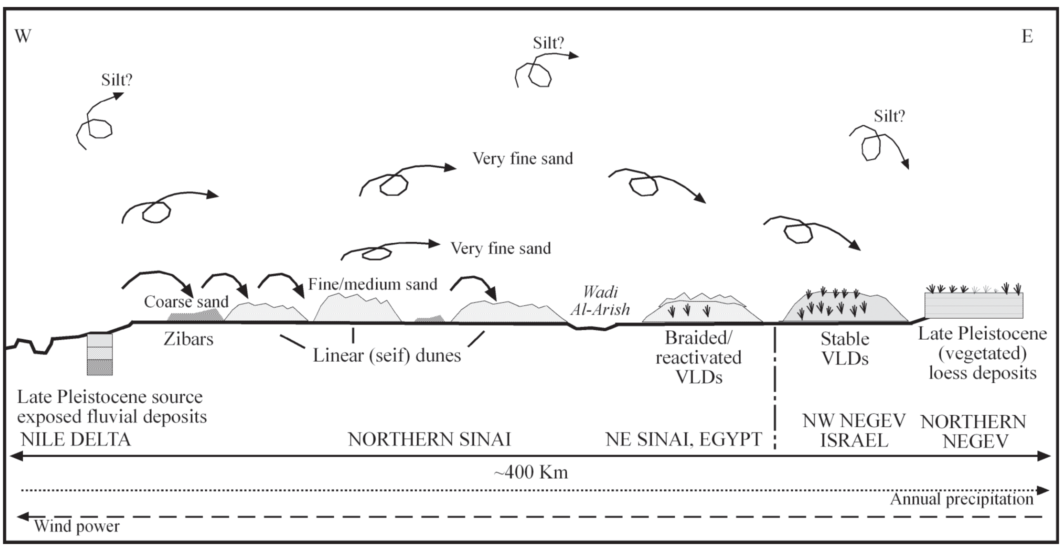

Figure 12. A conceptual model of eolian fractionation along an eolian transport system from the Nile Delta, through northern Sinai, and into the northern Negev Desert (Israel). The figure is modified from Figure 11c of Pye (1995), which proposes one of several alternative situations in which loess deposits may be formed. Along the Sinai sand transport path, the wind power decreases, and annual precipitation increases. Medium to coarse sand creeps in Sinai to form zibars, fine sand forms linear (seif) dunes, and fine and very fine sand saltates to the east to form vegetated linear dunes in times of large sand supply. Very fine sand is also suggested to be transported in low suspension to the east to be a partial component of loess deposits. Beyond the possibility of full suspension above the Sinai-Negev erg, in the past, deltaic silt may have also been deposited in dunes and later released with dune mobilizations, a hypothesis worth testing.

Postdepositional Translocation of Very Fine Sand and Silt

Allochthonous (postdepositional) input of very fine sand (after Goudie et al., 1993) into the Negev vegetated linear dunes during the Holocene seems unlikely. At the Qerem Shalom section, OSL-dated fine (125–150 µm) and very fine sand-grain fractions (88–125 µm) of a sample from a calcic paleosol, only 25 cm beneath the paleosol top, are dated to 55 ± 13 ka and 42 ± 5 ka, respectively. Though falling within errors, the younger very fine fraction has been interpreted to be postdepositional due to later dust fall (Zilberman et al., 2007). As the late Pleistocene sequence shows fluctuations of slow sand sheet accumulation and pedogenic stability in a hypothesized moister climate that probably supported more vegetation, incorporation of very fine sand into the upper part of the soil is possible. However, we suggest that this scenario is not likely for dunes.

Currently, rainfall and consequent percolation values in dunes along with wind intensities and corresponding dust fall do not support the idea that dust and very fine sand are translocated down the Negev dune profile in the presiding Holocene environment. The Negev dunes are also encrusted with a cynobactaeria type that collates fines deposited upon the dune surface, which severely limits translocation. The biological crust has been found to establish itself in 4–7 yr (Kidron et al., 2009, and references within), and Negev dunes have been proposed to have been stabilized by crusts for much of the Holocene (Roskin et al., 2011a, 2013b). Blume et al. (1995, 2008) demonstrated translocation of clays through the upper 1–2 m vegetated linear dune axis in some Negev dunes that are currently active, but Negev dunes have limited clay contents that do not show trends with depth (Table 2). Annual and seasonal rainfall infiltration studied in the SW dune field usually does not infiltrate the dune section to depths greater than 1–2 m (Yair, 2008). Water percolation down to 4 m in the Negev uncrusted vegetated linear dune axis profile only occurs in response to above-average rainfall exceeding 100 mm in 2 mo (Yair et al., 1997). Therefore, only in wetter conditions is percolation expected down the profile. The hypothesized wetter late Pleistocene (Baruch and Goring-Morris, 1997; Vaks et al., 2006; Tsoar, 2013) is in theory a favorable time period for deeper water penetration. However, Blume et al. (2008) stated that for the Nizzana sands, pore radii are in the range of 50–100 µm, and geometric mean radii in dune sands of 250 µm have been recently modeled and physically calculated not to exceed 43 µm (Glover and Walker, 2009). These conclusions physically bar the possibility of very fine sands and even coarse silt to percolate down-profile. The upper active crest of the vegetated linear dunes that are not constantly being resupplied from Sinai shows similar very fine sand contents to the rest of the profile. This does not seem to indicate that winnowing is occurring today, nor are very fine sands being incorporated into the section by local dune reactivation.

Climate Gradient, Winnowing, and Changing Linear Dune Types

The current difference between the active linear seif dune types of northern Sinai and the vegetated linear dunes of the NW Negev likely reflects past conditions that promoted winnowing of sand in Sinai and deposition of very fine sand in the Negev. Vegetated linear dunes, being of an accumulative nature (Roskin et al., 2011b; Telfer, 2011), were ideal candidates for deposition and preservation of such sediments. Based upon a climate gradient of rainfall (Mohamed, 2012) and wind intensities, and consequently dune types, across the Sinai-Negev erg from west to northeast (Fig. 1B), it seems, that as today, this gradient existed in the past. This gradient was probably characterized by higher rainfall and wind value ranges. In a similar fashion, Amit et al. (2006) proposed that the current climatic and rainfall gradient similarly existed in the late Pleistocene between the northern and southern Negev. Accordingly, dunes, as today, had less vegetative cover and were active in the west and more vegetated toward the east and northeast. In times of stability, dunes in the northern part of the Negev dune field were also probably covered with thicker stabilizing biogenic crusts, preserving the dune profile as occurs under the current climate (Almog and Yair, 2007).

Because of the pathways of cyclonic storms over the Mediterranean Sea, it is drier and windier in the west (Sinai) and wetter and less windy in the east (Negev): The rainfall gradient of the Sinai-Negev region (Fig. 1B) is in general agreement with a decrease in sand drift potential from west to east. Therefore, the southwestern part of the Sinai dune field, where precipitation is currently below 50 mm, has been often extremely arid and unvegetated throughout the late Pleistocene and Holocene, similar to the southern Negev at similar latitudes to the east (Amit et al., 2006). As winds are strong in western Sinai, the region has been probably continuously prone to eolian erosion throughout glacial and interglacial periods, which can explain the 190 k.y. of hypothesized activity. Drift potential values of northern Sinai generally decrease to the east, ranging from >1000 vector units (v.u.) at Port Said (Roskin et al., 2011a) to 200 v.u. at Bir Lahfan and 21–108 v.u. in the NW Negev (Tsoar et al., 2008) (Figs. 1A and 13). Assuming generally similar wind directions in the late Pleistocene (Ben-David, 2003; Enzel et al., 2008), if this gradient in wind power was enhanced in the late Pleistocene, it explains the encroachment of dunes from Sinai into the Negev and their consequent stabilization. The eastern end of the Negev dune field is not fronted by a topographic obstacle on its downwind side. Therefore, the eastern extent of the dunes was probably controlled by a decrease in windiness along with a thicker vegetation cover due to higher annual rainfall (~150 mm today). This decrease in wind speed may have also occurred following the Younger Dryas (Enzel et al., 2010), which is consistent with global data (Roskin et al., 2011b, and references within; Costas et al., 2012; McGee et al., 2013).

This sedimentological pattern is also apparent in the change of dune types along the Sinai-Negev erg transport path. In the western and central Sinai dune field, west of Wadi Al-Arish, there are linear dunes and barchans (Abdel-Galil et al., 2000; Tsoar et al., 2004). East of Wadi Al-Arish, complex-braided linear dunes (Tsoar, 1995), found to be currently less active than their linear seif dunes west of Wadi Al Arish (Misak and Draz, 1997; Abdel-Galil et al., 2000), extend into the Negev. Northern Sinai and the Negev are suggested to have experienced a long dry period during most of the seventeenth and eighteenth centuries, which resulted in the formation of these braided linear dunes. Prior to that, they may have been vegetated linear dunes (Tsoar, 1995). This change in dune types is in agreement with the general eastward increase in rainfall, which is relatively similar in northeastern Sinai and the NW Negev (Fig. 1b), enabling the dunes to support vegetation and develop into vegetated linear dunes by joint elongation and accretion (Roskin et al., 2011b).

CONCLUSIONS

This study presents a spatial analysis of particle-size distributions of radiocarbon-dated Nile Delta sands, northern Sinai dune field sands, and NW Negev vegetated linear dune sands, dated by OSL. Based on previous studies and the available samples for this work, the particle-size distributions of Sinai sands and their lower and less deviated very fine sand content in relation to the Negev sands leads to a conceptual eolian sedimentological model of particle-size fractionation of sand along the Sinai-Negev erg during the late Pleistocene (Fig. 12). Though they are continuous geographic sand deposits with similar orientations and sand-grain roundness values, a modern-day gradual decrease

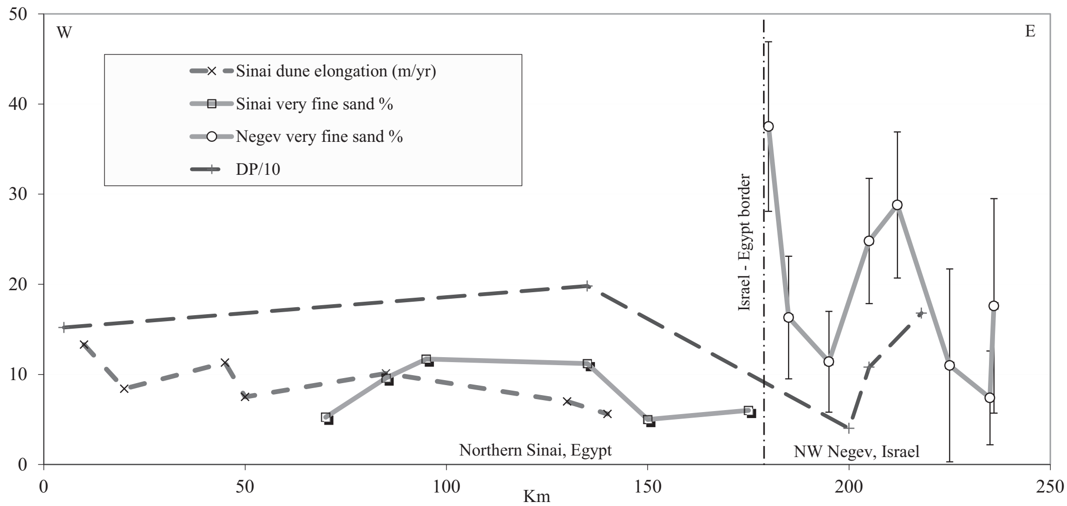

Figure 13. Climatic and very fine sand percentage, changes, and trends along the Sinai-Negev erg transport system. The very fine sand percentage of the Negev sections is the average of the full dune profile. The *y* axis represents different values as marked in the legend. DP—drift potential. The locations of the DP values are shown in Figure 1B. Very high DP values (DP = 1139) of Port Said near the northwestern corner of the Sinai-Negev erg are not presented.

in windiness and increase in precipitation in a general west-east orientation along the Sinai-Negev erg are suggested to reflect a similar but enhanced climate gradient in the past. This gradient is postulated to have controlled the proposed mechanism of sand fractionation and downwind deposition of very fine sand.

Intermittent periods of enhanced windiness in the late Pleistocene are suggested to have triggered fractionation of the fine and very fine sand fraction of the NW Negev sand source. The source of the sand is hypothesized to be solely confined to the Nile Delta and northwestern Sinai sand sheets. In periods of high sand supply, fine sand formed active linear dunes in the western and central parts of northern Sinai. Intermittent downwind transport of very fine sand via low suspension and rapid saltation along with saltating fine sand led to vegetated linear dune accretion and elongation in the Negev where vegetative cover was higher. Based on varying very fine sand components in paleosols beneath the Negev dunes, dominantly coastal sands north of the Negev dune field and in the northern Negev loess deposits, this conceptual model is suggested to have occurred in lower and variable intensities along the same eolian transport path, probably since the late middle Pleistocene (ca. 190 ka) around early MIS 6.

We find that particle-size distribution is a robust indicator of depositional modification of eolian dune sand along a transport system from a defined source and climatic gradient of an erg, which is further expressed by geomorphological differences of the linear dunes. Hopefully, in the future, when sediment sampling possibilities can be completed in the same systematic fashion in Egypt as they have been in Israel, a more comprehensive understanding of the eolian processes along the Sinai-Negev erg can be achieved.

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