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Origin of the Sinai-Negev erg, Egypt and Israel: mineralogical and geochemical evidence for the importance of the Nile and sea level history

Daniel R. Muhs
U.S. Geological Survey, dmuhs@usgs.gov

Joel Roskin
Ben-Gurion University of the Negev

Haim Tsoar
Ben-Gurion University of the Negev

Gary Skipp
U.S. Geological Survey, gskipp@usgs.gov

James Budahn
U.S. Geological Survey

See next page for additional authors

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Authors
Daniel R. Muhs, Joel Roskin, Haim Tsoar, Gary Skipp, James Budahn, Amihai Sneh, Naomi Porat, Jean-Daniel Stanley, Itzhak Katra, and Dan G. Blumberg

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Daniel R. Muhs [a], [*], Joel Roskin [b], Haim Tsoar [b], Gary Skipp [a], James R. Budahn [a], Amihai Sneh [c], Naomi Porat [c], Jean-Daniel Stanley [d], Itzhak Katra [b], Dan G. Blumberg [b]

[a] *U.S. Geological Survey, MS 980, Box 25046, Federal Center, Denver, CO 80225, USA*
[b] *Dept. of Geography and Environmental Development, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 84105, Israel*
[c] *Geological Survey of Israel, 30 Malkhe Israel St., Jerusalem 95501, Israel*
[d] *Geoarchaeology-Paleobiology Department, E-205 NMNH, MRC-121, Smithsonian Institution, Washington, DC 20013, USA*

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ABSTRACT

The Sinai–Negev erg occupies an area of 13,000 km^2 in the deserts of Egypt and Israel. Aeolian sand of this erg has been proposed to be derived from the Nile Delta, but empirical data supporting this view are lacking. An alternative source sediment is sand from the large Wadi El Arish drainage system in central and northern Sinai. Mineralogy of the Negev and Sinai dunes shows that they are high in quartz, with much smaller amounts of K-feldspar and plagioclase. Both Nile Delta sands and Sinai wadi sands, upstream of the dunes, also have high amounts of quartz relative to K-feldspar and plagioclase. However, Sinai wadi sands have abundant calcite, whereas Nile Delta sands have little or no calcite. Overall, the mineralogical data suggest that the dunes are derived dominantly from the Nile Delta, with Sinai wadi sands being a minor contributor. Geochemical data that proxy for both the light mineral fraction ($SiO_2/10–Al_2O_3 + Na_2O + K_2O–CaO$) and heavy mineral fraction ($Fe_2O_3–MgO–TiO_2$) also indicate a dominant Nile Delta source for the dunes. Thus, we report here the first empirical evidence that the Sinai–Negev dunes are derived dominantly from the Nile Delta. Linkage of the Sinai–Negev erg to the Nile Delta as a source is consistent with the distribution of OSL ages of Negev dunes in recent studies. Stratigraphic studies show that during the Last Glacial period, when dune incursions in the Sinai–Negev erg began, what is now the Nile Delta area was characterized by a broad, sandy, minimally vegetated plain, with seasonally dry anastomosing channels. Such conditions were ideal for providing a ready source of sand for aeolian transport under what were probably much stronger glacial-age winds. With the post-glacial rise in sea level, the Nile River began to aggrade. Post-glacial sedimentation has been dominated by fine-grained silts and clays. Thus, sea level, along with favorable climatic conditions, emerges as a major influence on the timing of dune activity in the Sinai–Negev erg, through its control on the supply of sand from the Nile Delta. The mineralogy of the Sinai–Negev dunes is also consistent with a proposed hypothesis that these sediments are an important source of loess in Israel.

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1. Introduction

Many of the world's largest ergs, or aeolian sand seas, are found over a vast area of the subtropical zones of the Sahara Desert of Africa and the Arabian Peninsula, with a total dunefield area well in excess of 3 million km^2 (Pye and Tsoar, 2009). Dunefields over this region have tremendous importance for paleoclimate studies, as the presence of dunes indicates strong winds or low precipitation (<100 mm) either at present or in the past, as well as an availability of source sediments and lack of stabilizing vegetation in the source area. Furthermore, the orientation of inactive dunes gives important clues for paleowind directions in the past. Thus, dune geomorphology constitutes one of the most robust, direct records of past atmospheric circulation, aridity, wind strength and paleohydrology.

The advent of optically stimulated luminescence (OSL) dating (see review in Singhvi and Porat, 2008) has revolutionized paleoclimatic studies of dunes, as the only requirement is the presence of quartz, which is rarely an issue with aeolian sand. Recent studies of the dunefields in the Sahara, the Sinai–Negev erg, and the Arabian Peninsula, with good OSL geochronology, have yielded important paleoclimatic information in Mauritania (Lancaster et al., 2002),

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[*] Corresponding author. Tel.: +1 303 236 7919.
E-mail address: dmuhs@usgs.gov (D.R. Muhs).

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Egypt and Sudan (Bubenzer et al., 2007), Israel (Roskin et al., 2011a, 2011b) and Arabia (Goudie et al., 2000; Preusser et al., 2002, 2005; Atkinson et al., 2011, 2012), as well as regional syntheses (Swezy, 2001; Glennie and Singhvi, 2002; Lancaster, 2007, 2008; Singhvi and Porat, 2008). One conclusion common to these studies is that dunes over a wide region were very active during the Last Glacial Maximum (LGM), but dune activity diminished at the close of the Last Glacial period, a concept articulated earlier by Sarnthein (1978). During the post-LGM period and in the late Holocene, dune activity resumed in many of these regions.

More than one forcing mechanism is possible for the shift from intense Last Glacial and post-glacial dune activity followed by early-to mid-Holocene dune stability in the Sahara and Arabian Peninsula. Increased moisture at the beginning of the Holocene could have been supplied by insolation-forced northward migration of the intertropical convergence zone, or ITCZ (Bernhardt et al., 2012). This has been referred to as the African Humid Period (~15 ka–5.5 ka) and is well established as a period of diminished dust accumulation in the early-to mid-Holocene, based on studies of marine cores off Africa in both the Atlantic (DeMenocal et al., 2000) and the Mediterranean (Hamann et al., 2008, 2009). During such a humid period, sand supplies to dunes in some parts of the region may have been cut off by the growth of Holocene lakes in basins that previously provided sediment (ultimately from fluvial sources) to active dunes (Lancaster, 2008). In coastal regions, such as the southern part of the Wahiba Sand Sea of Oman, sea level history may have played a role in diminishing sand supply by post-glacial sea level rise (Radies et al., 2004; Preusser et al., 2005). Whether sediment supplies to feed actively migrating dunes are a function of climate in the source area, regional hydrology, or sea level fluctuations requires identification of the source sediment of the dunefield, but few studies in the Sahara Desert or Arabian Peninsula have been undertaken to determine provenance of dune sands.

Sand dunes and their histories have significance in other aspects of sedimentation history and landscape evolution. Although abrasion of sand grains and size reduction due to ballistic impacts have been recognized for a long time as a possible source of loess and finer grained dust (see reviews in Muhs and Bettis, 2003; Muhs, 2013), there has been considerable emphasis on the importance of this process in subtropical deserts in recent years (Crouvi et al., 2008, 2010, 2012; Enzel et al., 2008, 2010; Amit et al., 2011). In these latter studies, the Sinai–Negev erg is proposed to be at least a partial source of loess in Israel, downwind of the dunefield.

In this study, we examine the composition of dune sands from the Negev Desert of Israel and the Sinai Desert of adjacent Egypt, situated between the vast deserts of the Sahara and Arabia (Fig. 1). As pointed out by Tsoar et al. (2008) these two dunefields (Sinai and Negev) are geomorphically part of the same sand sea; their division into two landscape entities is due solely to the political boundary that separates them. Studies by Goring-Morris and Goldberg (1990), using archeology and radiocarbon dating, and by Enzel et al. (2010) and Roskin et al. (2011a, 2011b), using OSL geochronology, show that dunes of the Sinai–Negev erg, like other dunefields in the Sahara Desert-Arabian Peninsula region, were active during the Last Glacial period, the post-glacial period and the latest Holocene, but show little evidence of activity during the early-to mid-Holocene.

Determination of the source of sand in the Sinai–Negev erg is a major goal of our study. To the best of our knowledge, one sediment source alone has been proposed for the Sinai–Negev erg, sand from the Nile Delta. Emery and Neev (1960) inferred a Nile source for the non-carbonate component of beach sands on the Mediterranean coast of Israel and Pomerancblum (1966) reported that continental shelf sands off this coast were Nile-derived as well. Nachmias (1969) reported a Nile source for Tertiary Saqiye Group sediments found in Israel. All these studies inferred Nile origins using heavy mineral analyses. Davis et al. (2012) propose that the Nile has been a major source for aeolian sediments in Israel for the past ~2.5 million years, based on cosmogenic isotope evidence from quartz. Nevertheless, identification of the Nile as a source for the Sinai–Negev erg sands seems to have been both a working assumption and an untested hypothesis (Neev et al., 1987; Goring-Morris and Goldberg, 1990; Pye and Tsoar, 2009; Amit et al., 2011; Roskin et al., 2011b, 2012). The best argument for a Nile Delta source is the simple lack of evidence for other likely sources (Tsoar et al., 2008). Nevertheless, the lack of an alternative source does not actually prove a Nile Delta source. Further, the inference of derivation of quartz-rich dunes from what seems at first glance to be an obvious Nile Delta source is problematic. Sneh and Weissbrod (1983) report that dune sand in Sinai is composed of ~95% or more quartz, and Roskin et al. (2011b) present preliminary data showing that dunes in the Negev part of the erg are also quartz-rich. However, recent petrographic and isotopic data show that Nile River sands are, at present, derived primarily from two major tributaries in the upper part of the drainage basin, the Blue Nile and Wadi Atbara. The White Nile contributes at most ~3% (Garzanti et al., 2006; Padoan et al., 2011). Both the Blue Nile and Wadi Atbara drain rocks of the Ethiopian Plateau that are dominated by Cenozoic basalts (Pik et al., 1998), rocks that do not contain quartz. Thus, in this study, we also examine the composition of probable late Pleistocene age, dune-sand-sized sediments of the Nile Delta.

Other possible quartz-rich sources for the Sinai–Negev erg are very limited. Areas in central Sinai within the Wadi El Arish drainage basin have bedrock dominated by Cretaceous or Eocene rocks. Although these rocks are composed mostly of carbonate facies, Bartov (1990) reports that sandstone facies are also present in two of the Cretaceous units. These rocks are situated in the upper drainage basin area of Wadi El Arish (Figs. 1 and 2) and thus provide a source that is upstream and upwind of much of the Sinai–Negev erg. Farther north, in north-central Sinai, Lower Cretaceous sandstones, now part of what is called the Kurnub Group (Bartov, 1990), were formerly referred to as "Nubian Sandstone." These rocks are downwind of many of the dunes in the erg, however, so at most they constitute a potential source for only part of the erg. To test the competing hypotheses of the Nile Delta versus local rocks in Sinai for the source of the Sinai–Negev erg, we conducted studies of the mineralogy of the dune sands and these possible source sediments.

Study of the Sinai–Negev erg mineralogy also allows us to test the hypothesis that abrasion of sand-sized particles is the source for loess in Israel that is found downwind of the Sinai–Negev erg (Fig. 1). Crouvi et al. (2008, 2010, 2012), Enzel et al. (2008, 2010), and Amit et al. (2011) have emphasized the importance of this dunefield in supplying silt-sized quartz, generated by aeolian abrasion of sand-sized quartz, to loess downwind. If reduction of sand-sized quartz to silt size by aeolian abrasion has occurred, then other minerals in the Sinai–Negev erg should also be affected by this process. Experimental work by Kuenen (1960) and Dutta et al. (1993) shows that aeolian abrasion and ballistic impacts can efficiently reduce sand-sized feldspars to silt sizes. Kuenen's (1960) studies show that both sand-sized feldspars and carbonate minerals abrade to finer sized particles much more quickly than does quartz. Thus, if dune sands of the Sinai–Negev erg provide some of the particles to the loess bodies downwind of the dunefield by aeolian abrasion of quartz, they should also contribute a proportionally greater amount of feldspar and calcite, because these latter minerals are less resistant to aeolian abrasion. The evidence for this should be a dunefield whose mineralogy is measurably more quartz-rich than that of the loess found downwind.

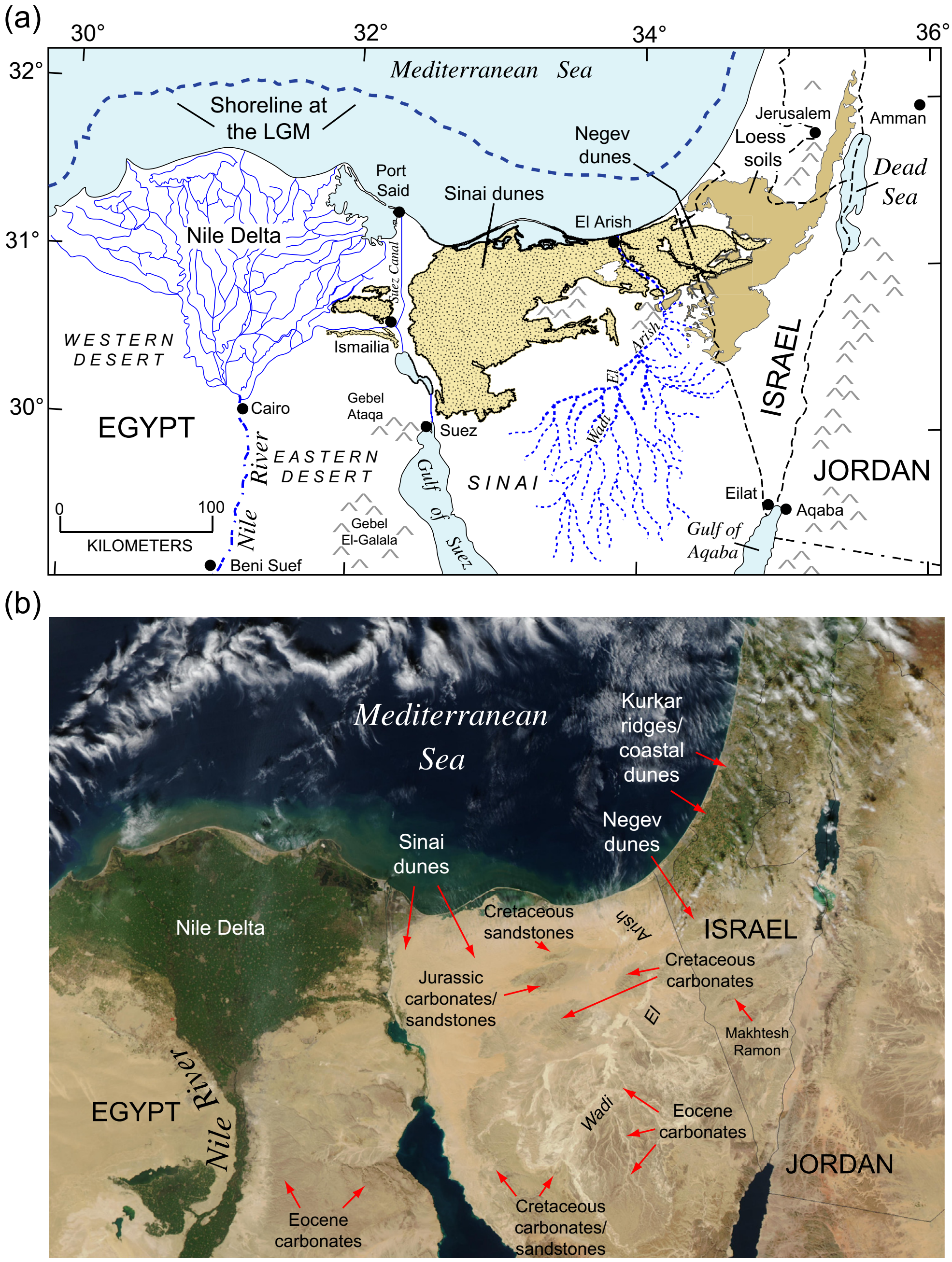


Fig. 1. (a) Map showing the distribution of aeolian sand in the Sinai–Negev erg (stipple pattern), loess and loess-derived soils (from Dan et al., 1976), location of the shoreline at the Last Glacial Maximum (LGM), and localities referred to in the text. Aeolian sand mapped by the authors from Landsat TM and ETM imagery. Location of the LGM shoreline is based on an estimated −130 m (relative to present) LGM paleo-sea level (Peltier and Fairbanks, 2006) and the paleogeography of the coast at this time from the International Bathymetric Chart of the Mediterranean (Intergovernmental Oceanographic Commission), available online at: http://www.ngdc.noaa.gov/mgg/ibcm/ibcm.html. (b) MODIS image from the Aqua satellite acquired on 6 February 2003. Also shown is the bedrock geology of the region, from Bartov (1990). MODIS image courtesy of Jeff Schmaltz, MODIS Rapid Response Team, NASA GSFC.

2. Study area: the Sinai–Negev erg

2.1. Geomorphology

The Sinai–Negev erg occupies a total area of ~13,000 km^2 (Roskin et al., 2011b), making it a moderate-sized sand sea compared to some of the larger ergs in the Sahara-Arabian Peninsula region. Although the Negev Desert portion of the Sinai–Negev erg has been studied in detail recently (Blumberg et al., 2004; Tsoar et al., 2008; Roskin et al., 2011a, 2011b), far less study has been made of the dunes in Sinai. We mapped the extent of the dunes and identified dune types in this region, using Landsat 5 TM imagery (band 1, blue) from 1984 to 1986 and Landsat 7 ETM imagery (band 8) from 1999, augmented by examination of SPOT imagery. The extent of aeolian sand in Sinai was mapped by identifying areas with: (1) typical dune geomorphic expression, such as linear or barchan forms; (2) high returns on black-and-white imagery in these spectral bands, indicating a dominance of highly reflective minerals such as quartz, with a minimal vegetation cover; and (3) evidence of a surficial cover that masks preexisting drainage. Our mapping (Fig. 2), although done independently, is in good agreement with previous mapping of

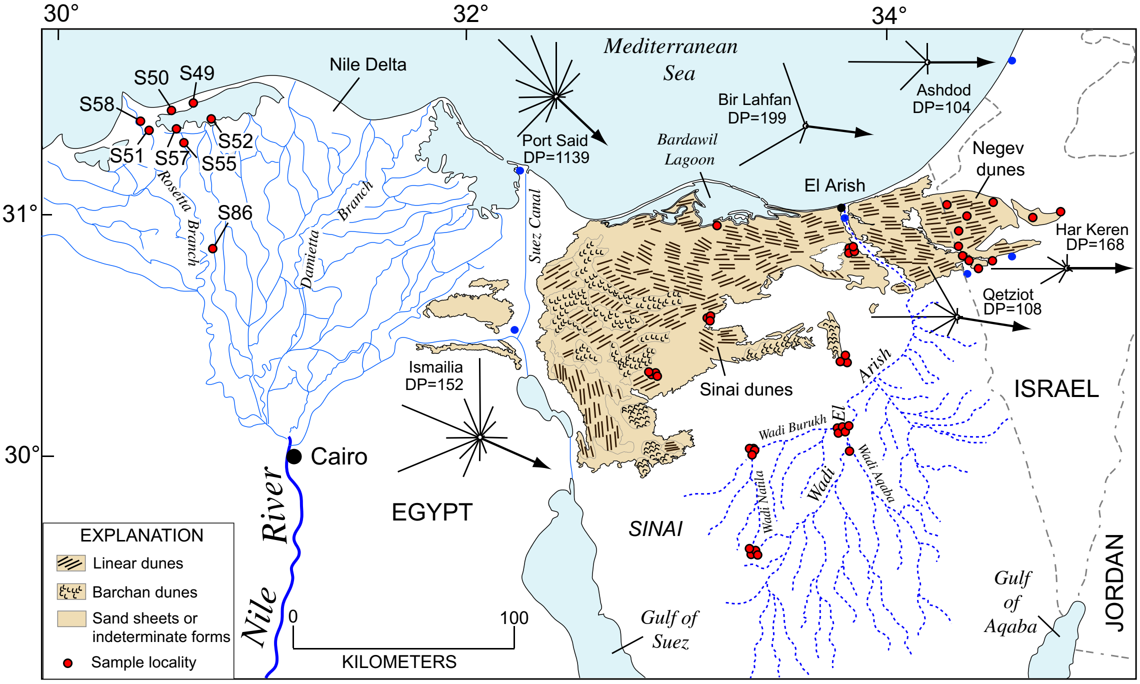


Fig. 2. Map showing the distribution of aeolian sand in the Sinai–Negev erg, along with principal dune forms (mapped by the authors, as in Fig. 1). Red circles are sample localities for Nile Delta cores (from Stanley et al., 1996), Sinai wadi sands, Sinai dune sands, and Negev dune sands. Also shown are sand roses (computed by the authors using methods in Fryberger and Dean, 1979) for various localities (shown as blue circles) in the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

aeolian sand in Sinai by Neev et al. (1982), Sneh and Weissbrod (1983) and Bartov (1990).

All investigators who have studied the Sinai–Negev erg have recognized that there are a number of different dune forms in this sand sea (Tsoar, 1974, 1984, 1989; Neev et al., 1982; Sneh and Weissbrod, 1983; Rubin et al., 2008; Tsoar et al., 2008; Roskin et al., 2011a, 2011b, 2012, in press; Hermas et al., 2012). By far the most common landforms are linear dunes (Fig. 3). In Sinai, these take the form of seif dunes, characterized by a sinuous dune crest that has steep slopes on both sides of the crest. Complex linear dunes are also present. Seif dunes in Sinai are mostly 2–5 km long (Tsoar, 1995), measured along their long axes, but we also observed

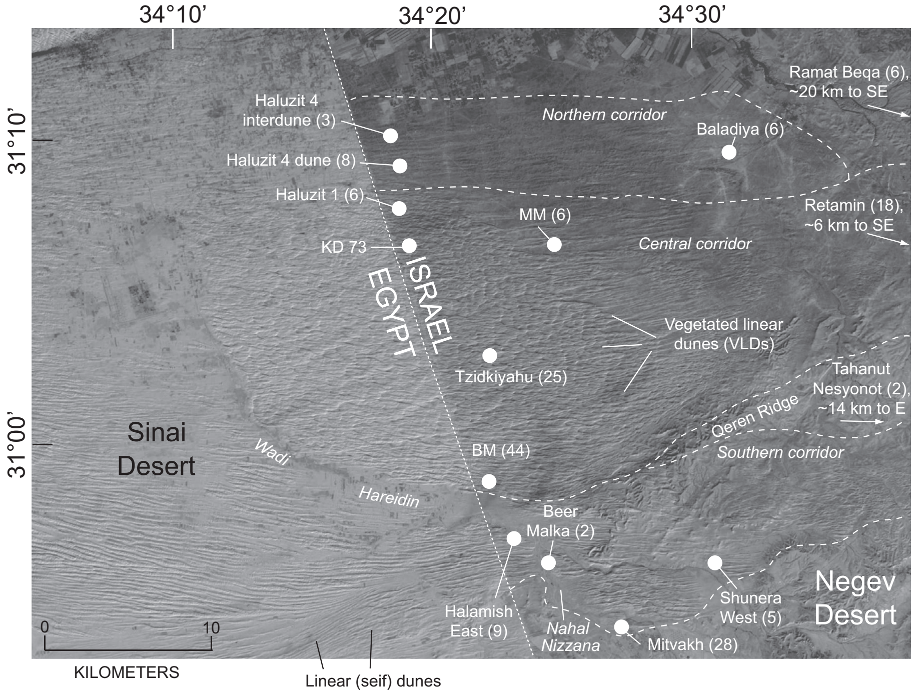


Fig. 3. Landsat TM image (Band 1, blue) of the Israel–Egypt border area, showing dune forms, contrast in degree of vegetation cover on each side of the border, dune incursion corridors (Roskin et al., 2011b) and sampling localities in the Negev dune field. Number in parentheses is number of samples analyzed at each locality.

dunes as long as 7–14 km, mostly in the southwestern part of the erg, where their long axes trend northwest-to-southeast (Fig. 2; see also Tsoar et al., 2004). Rubin et al. (2008) reexamined the dunes studied by Tsoar et al. (2004) and found lateral migration of seif dunes on the order of ∼13 m over a 26-year period. North of this region, but still in the western part of the erg, smaller seif dunes generally trend southwest-to-northeast. In the north-central part of Sinai, linear dunes are oriented northwest-to-southeast, although in some places they trend west-to-east (see also Tsoar, 1995). In northeastern Sinai, and continuing into the Negev Desert of Israel, the largest linear dunes have long axes that trend west-to-east, indicating a westerly paleowind. Superimposed on the largest linear dunes in this region, however, are younger "dunelets," or smaller dunes, with orientations that imply paleowinds from the southwest (Roskin et al., 2011a), similar to modern wind directions in the area.

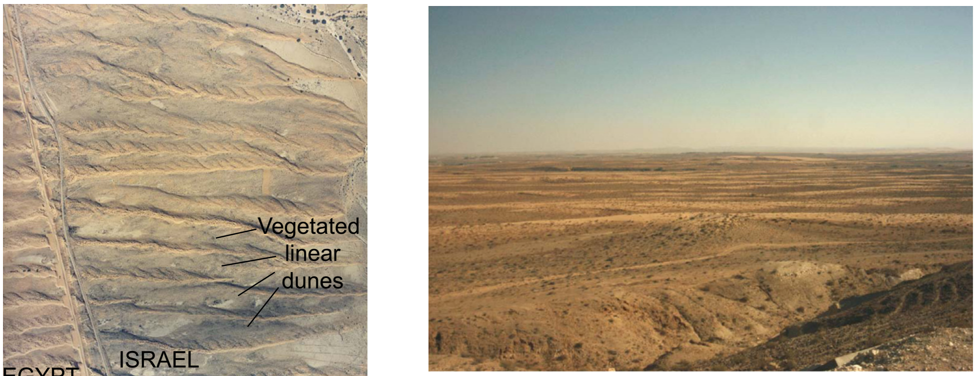
In a few regions of Sinai, the dominant landforms are barchan dunes. Most areas of barchans that we mapped are in western Sinai, although a few are also found in the southernmost part of the dunefield, to the north of Wadi Burukh and Wadi El Arish (Fig. 2). Measured from downwind arm to downwind arm, most barchans we observed are ∼400–800 m wide, although some are as much as ∼1000 m wide. In southwestern Sinai, barchans have arms that point to the southeast, consistent with the larger linear dunes found to the west of the barchans (Fig. 2). The same orientation is found with much smaller barchans in an isolated dune tract in the central part of the erg, where several of our samples were collected. Elsewhere in Sinai, barchans have arms that point to the northeast, again consistent with the orientations of linear dunes that are found near them. Tsoar (1984) showed that what were originally barchans are currently being modified into linear (seif) forms in the area south of the city of El Arish.

The dunes that dominate the Negev Desert portion of the Sinai–Negev erg are referred to as vegetated linear dunes, or VLDs (Tsoar et al., 2004, 2008). They differ from seif dunes not only because they are vegetated, but also because they do not have a meandering form. Furthermore, VLDs are characterized by blunt crest lines and round profiles. In the Negev Desert and elsewhere, VLDs sometimes converge into a Y-junction, discussed in more detail by Tsoar et al. (2004, 2008).

Dunes on opposite sides of the Egyptian–Israeli border in the Sinai–Negev erg show very different degrees of activity. On the Egyptian side, dunes in most of the erg are unvegetated and fully active (Figs. 3 and 4), so much so that they have been considered a hazard to farmland, roads, and infrastructure (Misak and Draz, 1997). Although interdune areas are often vegetated, the crests and sides of dunes in Sinai host little or no vegetation. In contrast, dunes on the Israeli side of the border, in the Negev Desert, are mostly inactive. Ripple marks, indicating some contemporary movement of sand, are apparent on some dune crests, but most dunes are stabilized by vegetation (Figs. 3 and 4). The stabilizing vegetation includes shrubs such as sage (*Artemisia monosperma*) and other low-growing vascular plants, but far more important is the presence of biological soil crusts. Tsoar and Karnieli (1996) showed a progressive increase in biological soil-crust cover on the Israeli side of the border, using Landsat MSS imagery from 1984 to 1989. The dramatic difference in degree of vegetation cover is visible on Landsat TM imagery (Fig. 3), MODIS imagery, and thermal imagery from NOAA-AVHRR 14 data (Qin et al., 2001). The contrast in degree of activity is apparently caused by Bedouin animal trampling and grazing of vegetation, which is intense on the Egyptian side and absent on the Israeli side (Tsoar, 2008).

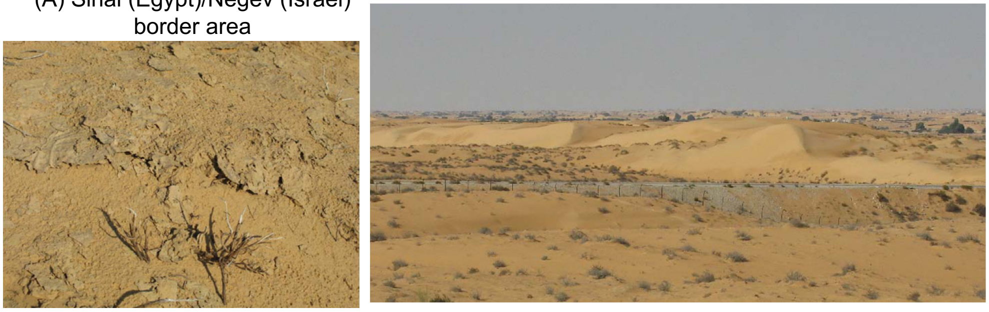
2.2. Stratigraphy and geochronology

Simple field observations yield important clues that the dunes in the Sinai–Negev erg may have a long geologic history. Examination of Landsat imagery shows that the southwest-to-northeast



(A) Sinai (Egypt)/Negev (Israel) border area

(B) Linear dunes, Negev Desert, Israel



(C) Soil crust on dune, Tzidkiyahu, Negev, Israel

(D) Active linear dunes, Sinai, Egypt (west of Halamish)

Fig. 4. Photographic gallery of typical vegetated or partially vegetated dune types in the Negev Desert of Israel [(A) and (B)], biologic soil crust that typically stabilizes these dunes [(C)], and unvegetated seif dune in the Sinai Desert of Egypt [(D)].

linear dunes found in the peninsula jutting into Bardawil Lagoon (Fig. 2) are “drowned” landforms. These dunes, some of which extend over most of the east–west extent of the peninsula, are surrounded by the lagoon on the west, east, and north sides of the peninsula and have no apparent source to the southwest. Thus, the presence of these southwest–northeast-trending dunes on a peninsula situated within a lagoon requires formation during a time when sea level was lower, most likely during the Last Glacial period. Orientations of both linear dunes and barchans in the southwestern part of the Sinai dunefield imply paleowinds from the north, which differs from the resultant drift directions (RDD) of the present, based on observations at Port Said and Ismailia, Egypt (Fig. 2). Roskin et al. (2011a) noted that the largest VLDs of the Negev have long axes that also indicate paleowinds that differ from the present winds. Collectively, these observations indicate that at least some of the dunes in the Sinai–Negev erg formed under conditions different from those of the present, or at least what is represented by the period of wind records.

Early studies suggest that much aeolian activity took place during the Last Glacial period. Goring-Morris and Goldberg (1990) observed the relation of dune deposits to archeology in both Sinai and the Negev and inferred a Last Glacial period of major aeolian sand sedimentation. Rendell et al. (1993) presented stratigraphic and thermoluminescence (TL) data that suggested dune incursions into the Negev Desert could have taken place during the latest Pleistocene, but inverted TL ages at two sites make these interpretations tenuous. Harrison and Yair (1998) reported that interdune depressions in the Negev portion of the erg have a stratigraphy (overbank silts with intercalated paleosols) that imply several thousands of years of alternating sediment accumulation and stability between the dunes during the Pleistocene. Finally, Enzel et al. (2010) showed that coarse, sandy, fluvially reworked loess in parts of the Negev Desert overlies aeolian sand. OSL ages of the basal portions of the loess are ~11 ka and the uppermost aeolian sand has an OSL age of ~13 ka. There is also evidence for Holocene dune activity. Tsoar and Goodfriend (1994) reported radiocarbon ages of aeolian sand in the Negev Desert indicating multiple dune incursions into this region in the Holocene.

Despite the inferences from these early studies, numerical age control of dunes in the Sinai–Negev erg has been generally lacking until the first systematic and widespread program of OSL geochronology was undertaken by Roskin et al. (2011a, 2011b). These stratigraphic and geochronologic studies provide a detailed history of the Negev portion of the erg. On a north–south transect (Fig. 3) from Haluzit to Nahal Nizzana (“Nahal” is wadi or drainage in Hebrew), the dunes are underlain by a distinctive, though probably eroded, paleosol developed in what Roskin et al. (2011b) infer may have been aeolian sheet sands (Fig. 5). This paleosol, although truncated, has abundant silt that Roskin et al. (2011b) interpret to have been added syndepositionally while pedogenesis was in progress. Analyses of the sand fractions from this paleosol yield OSL ages of 116 to 106 ka at two localities and ~30 ka at a third locality. Thus, the aeolian sand in which this paleosol developed could have been deposited as early as the latter part of the Last Interglacial period. Aeolian sand is found above the paleosol across a north–south distance of ~20 km or more in the Negev part of the erg (Fig. 5). Windblown sand, typically 5–25 m thick, is apparent in both VLDs and in interdune areas between the linear dunes. OSL ages show that dunes in the Negev portion of the erg began to accumulate as early as ~23 ka in the southwest corner of the dunefield. Following the LGM at ~21 ka (in calendar years), the dunes invaded the northwestern part of the Negev along three

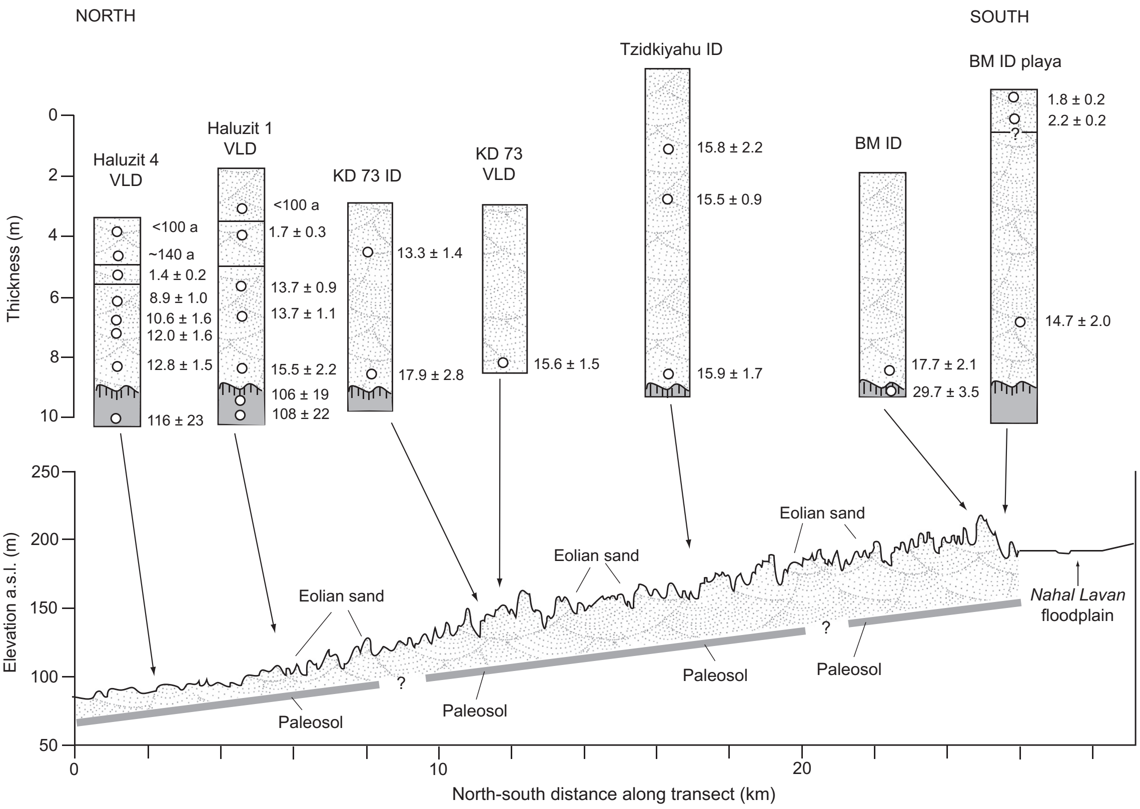


Fig. 5. North–south topographic profile from Haluzit, Israel to Nahal Lavan (see Fig. 3 for localities) showing Negev Desert dune topography, stratigraphy, and OSL ages in ka. Redrawn from Roskin et al. (2011b).

main west–east encroachment corridors (Fig. 3), during three periods. The main dune-encroachment period occurred between 18 and 11.5 ka (Roskin et al., 2011b), and thick aeolian sand deposits accumulated in the western Negev dunefield. Enzel et al. (2010) and Roskin et al. (2011a) suggested that dune elongation occurred in a windy climate during the Heinrich 1 and Younger Dryas cold events and further that the eastern dunefield developed mainly in the Younger Dryas. Additional incursions or remobilizations due to human impact have been dated to the late Holocene (∼2–0.8 ka) and modern times (<150 yrs), respectively (Roskin et al., 2011b, in press). Between these episodes, the dunes were usually quasi-stable and probably at least partially encrusted (Roskin et al., 2011b).

We examined the sediments in one dune exposure in some detail, at a locality called Mitvakh along the southwestern margin of the Negev portion of the dunefield (Figs. 3 and 6). Here, ∼7 m of dune sand are exposed and augering by Roskin et al. (2011b) indicates that at least another ∼2 m of aeolian sand are present. At a depth of ∼9.25 m, Roskin et al. (2011b) report an OSL age of 14.3 ± 0.8 ka. The basal ∼2.5 m in the exposed portion contain relatively high-angle (25–28°) dips to the north–northeast that we interpret to be foreset beds. The apparent dips to the north–northeast imply paleowinds from the south–southwest, similar to the present. Horizontal beds overlie the crossbeds and massive sand overlies the horizontal beds. The massive sand contains both land snail fragments and carbonate nodules. The carbonate nodules increase in abundance in the meter above the massive sand, where there is a zone again characterized by horizontal beds. Massive sand caps the section in the uppermost meter and is overlain by Byzantine artifacts (∼1.7–1.4 ka).

The Mitvakh section illustrates the importance of OSL geochronology and archeology in understanding dune history in this region. The OSL age of ∼14 ka at a depth of ∼9 m indicates that aeolian sand accretion was in progress during the latter part of the Last Glacial period. The presence of Byzantine (∼1.7–1.4 ka) artifacts at the top of the section permits the possibility of late Holocene activity possibly related to human impact. Nevertheless, no well-developed paleosols, indicating periods of stability within the section, were observed. The only possible evidence of a period of stability is in the form of the carbonate nodules in the upper part of the section, which may be the truncated remnants of a calcic horizon in a paleosol that developed after the late Pleistocene

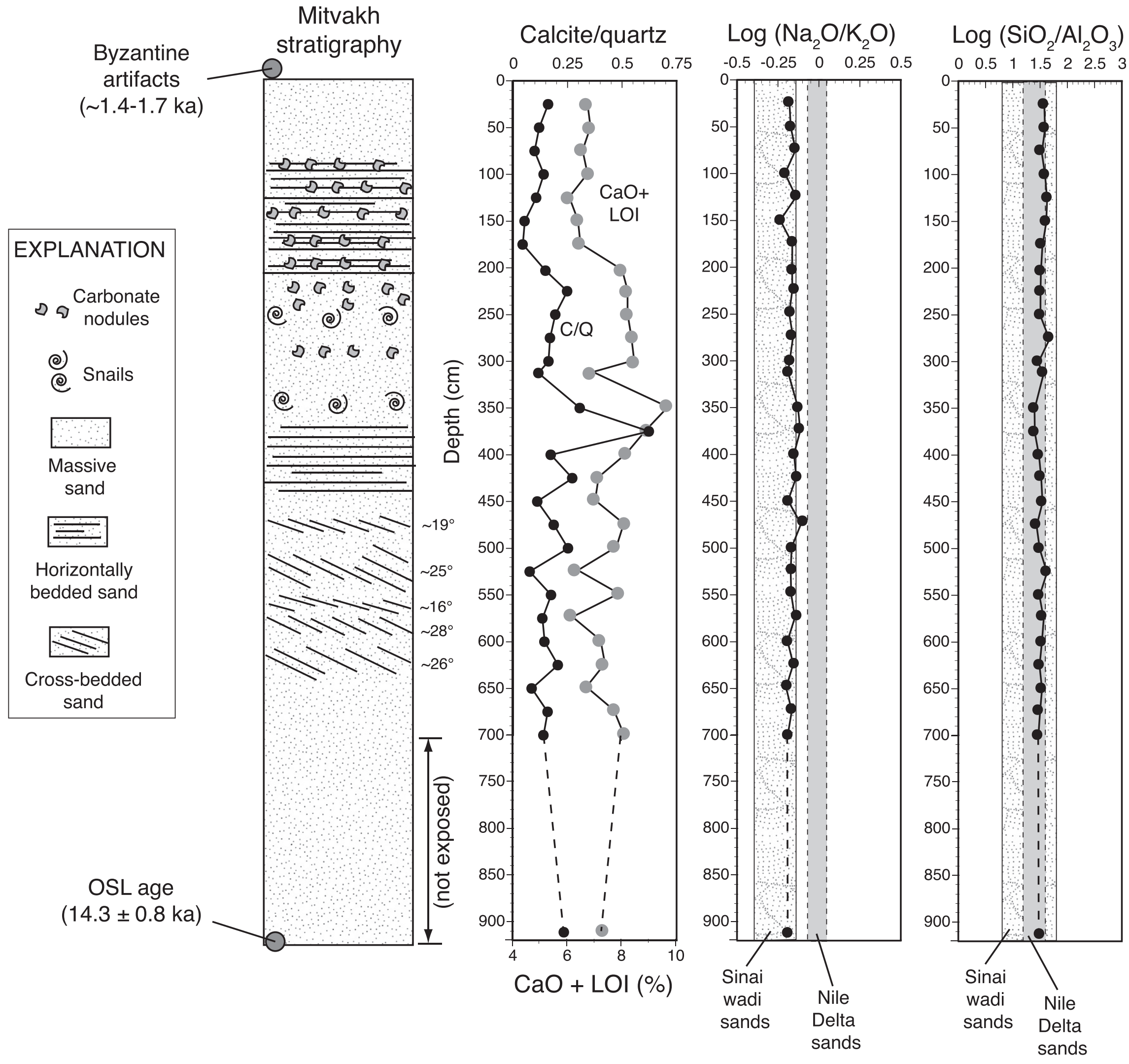


Fig. 6. Stratigraphy, ages and sedimentary structures in aeolian sand at Mitvakh, in the southern corridor of the Negev dunes (see Fig. 3 for location). Also shown are ratios of calcite (29.4°) to quartz (20.8°) XRD peak heights, CaO + LOI, Log [Na_2O/K_2O] values, Log [SiO_2/Al_2O_3] values, and ranges of these values in Sinai wadi sands and Nile Delta sands, shown in Fig. 14.

period of dune formation. If so, then the unbedded sand in the upper meter of the section may have been deposited in the late Holocene, just prior to Byzantine occupation. Many of the sections shown in Fig. 5 illustrate a similar situation, where OSL ages indicate that late Holocene active sand (due to human impact) overlies late Pleistocene sand, but a paleosol representing an early-to mid-Holocene period of stability is not apparent. Such paleosols, if present at one time, apparently were eroded during the late Holocene periods of dune activity.

3. Sampling and mineralogical and geochemical methods

Samples from the Negev portion of the dunefield (Figs. 2 and 3) consist of aeolian sands of both Holocene and Pleistocene ages, as outlined in Roskin et al. (2011a). Sands were also collected in more detail from the Mitvakh section in the southern Negev (N30°53′57.2″; E34°27′36.5″). Altogether, 138 samples from the Negev were analyzed for mineralogy and of these, 99 were analyzed for major element chemistry (29 from Mitvakh and 70 from elsewhere). Aeolian sands (20 samples) from the Sinai portion of the erg (Fig. 2), collected in the 1970's, were all analyzed for both mineralogy and major element chemistry. In addition, we analyzed 13 samples of fluvial sediments (wadi sands) from Sinai (also collected in the 1970's) for both mineralogy and major element chemistry. We limited our analyses of fluvial sediments in Sinai to those samples that are upstream and upwind of the Sinai–Negev erg, in the Wadi El Arish drainage system (Fig. 2). In this fashion, we avoid the problem of sediment recycling (from dunes into wadi channels). For the Nile Delta, we used Holocene and Pleistocene sediments from 8 cores (Fig. 7) collected by Stanley et al. (1996) and archived in the Smithsonian Institution, Washington, D.C. This collection consists of ~90 individual samples, mostly of Last Glacial age (Fig. 7), all of which were analyzed for mineralogy and 28 of which were analyzed for major element chemistry. For comparison with the Sinai–Negev erg sands, we also collected 12 samples of late Pleistocene aeolianite, or "kurkar" (Ramat Gan and Dor units) from a cliff section exposed on the Israeli Mediterranean coast at Gaash (Fig. 8), ~14 km north of Tel Aviv, studied by Porat et al. (2004). In order to make comparisons with what has been called the "Nubian Sandstone", we collected Lower Cretaceous-age sandstones of the Kurnub Group, probably correlative to the Nubian Sandstone (Sneh et al., 1998), from exposures in Makhtesh Ramon (or crater; also referred to locally as an erosional cirque) in southern Israel (N30°37′18.93″; E34°49′03.04″). Correlation of the rocks we collected in Makhtesh Ramon with "Nubian"-type sandstones found in northern Sinai is based on mapping of both as the Kurnub Group (Bartov, 1990), location of both on the same tectonic block, and similar thicknesses and mineralogy (Bartov et al., 1980; Weissbrod et al., 1994; Kolodner et al., 2009).

All aeolian sands and bedrock samples in this study were analyzed as bulk powders, with pulverization to a uniform particle size being the only pretreatment. Sinai wadi sands and Nile Delta sands were pretreated by removal of organic matter with H_2O_2 and dispersion of clays using Na-pyrophosphate. After pretreatments, silts and clays (<53 μm) and coarse sands (>500 μm) were removed by wet sieving in order to produce a particle size distribution similar to that found in aeolian sands; these separates were then pulverized to powders for both mineralogical and chemical analyses. Mineralogy was determined semiquantitatively by X-ray diffractometry. Relative abundances of quartz (20.8° 2θ), K-feldspar (27.4° 2θ), plagioclase (27.8° 2θ) and calcite (29.4° 2θ) were determined by measuring X-ray diffractogram peak heights on bulk

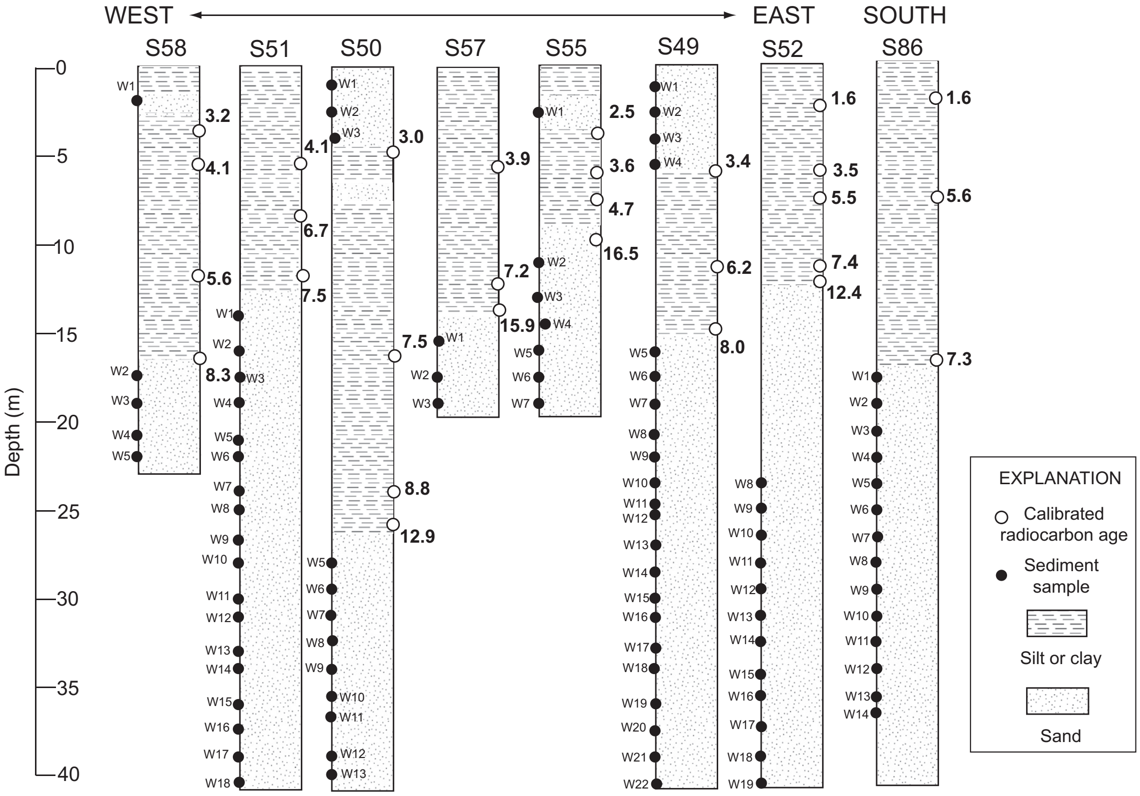


Fig. 7. Stratigraphy of Nile Delta cores (see Fig. 2 for locations), from Stanley et al. (1996). Open circles are calibrated radiocarbon ages in thousands of years, or ka (data from Stanley et al., 1996). Calibration of radiocarbon ages was done by the authors using the program in Fairbanks et al. (2005). Also shown (filled circles) are samples analyzed for mineralogy and geochemistry in the present study.

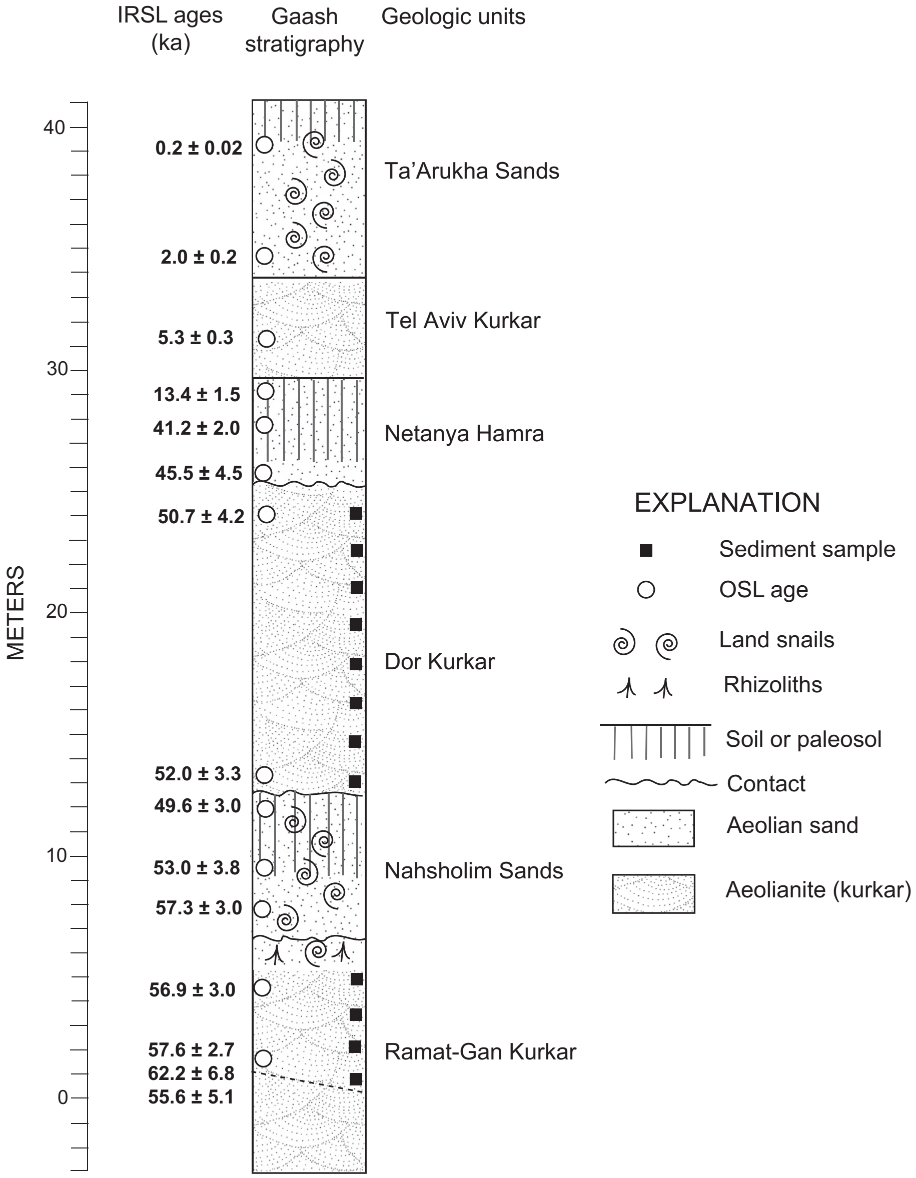


Fig. 8. Stratigraphy of the cliff section with aeolianite units and paleosols at Gaash, Israel, OSL ages (open circles), and sediment samples (filled squares). Stratigraphy and IRSL ages are from Porat et al. (2004).

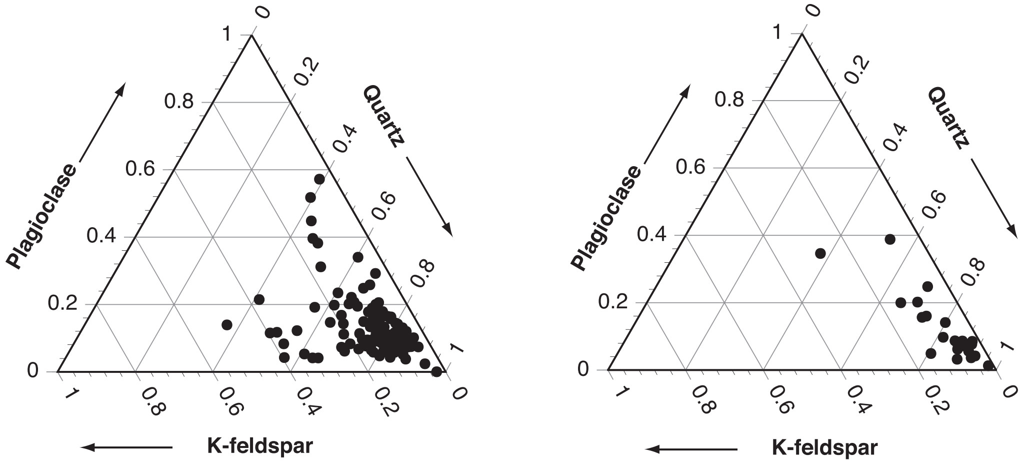
aeolian sands or fluvial sands. We note that these data give *relative* abundances of the major minerals, as given on ternary diagrams, but are not weight-percentages. Major element concentrations were determined by wavelength-dispersive X-ray fluorescence and values given are weight-percentages.

4. Results

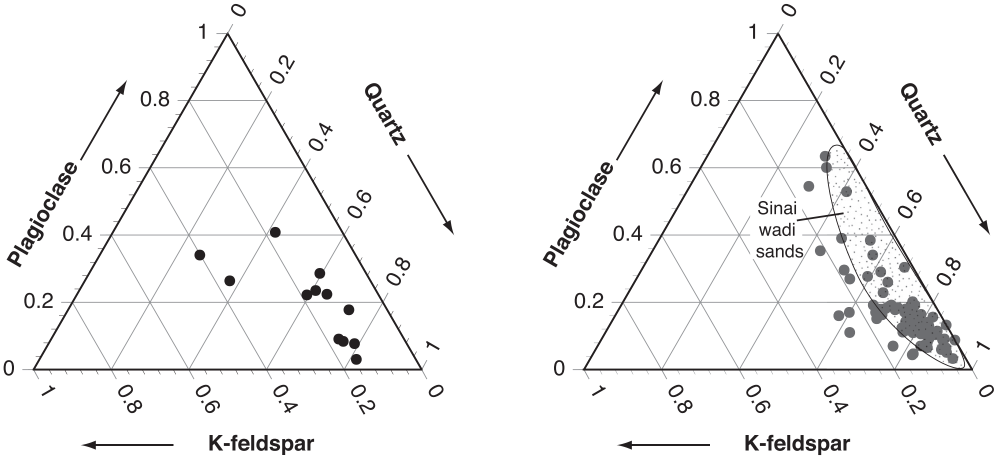
4.1. Mineralogy and geochemistry of sands in the Sinai–Negev erg

Consistent with previous studies (Sneh and Weissbrod, 1983; Roskin et al., 2011b), our analyses indicate that dunes of the Sinai–Negev erg are characterized by a relatively simple mineralogy. The main minerals found in all dunes are, in decreasing order of abundance, quartz, plagioclase and K-feldspar. Ternary diagrams based on relative abundances as measured by XRD peak heights display the quartz dominance in both the Negev and Sinai dunes (Fig. 9). Major element geochemistry supports these interpretations. Negev dunes have SiO_2 contents ranging from ~80 to 95%, whereas Na_2O (reflecting plagioclase) contents range from 0.24 to 0.83% and K_2O contents (reflecting K-feldspar) range from 0.50 to 0.93%. Sinai dunes show a similar composition, with SiO_2 contents ranging from ~76 to 98%, Na_2O contents ranging from 0.09 to 0.79% and K_2O contents ranging from 0.14 to 0.91%. Collectively, the XRD and geochemical data indicate that Negev and Sinai dunes sands do not differ significantly in composition.

Quartz-rich (compared to feldspar) sand dunes are not expected to have significant amounts of calcite, because calcite is usually abraded to finer grain sizes at least as rapidly as feldspar (Kuenen, 1960). Thus, we were surprised to find measurable amounts of calcite in both the Negev and Sinai dunes. Not all dunes contain calcite, and the abundances of this mineral vary considerably, when compared to quartz and total feldspar (K-feldspar + plagioclase) on ternary diagrams (Fig. 10). Major element compositions, plotted as $SiO_2/10–Al_2O_3 + Na_2O + K_2O–CaO$ to mimic the quartz–feldspar–calcite XRD diagrams, support this interpretation (Fig. 11). At least


(a) Negev Desert dunes

(b) Sinai Desert dunes


(c) Aeolianite, Gaash, Israel

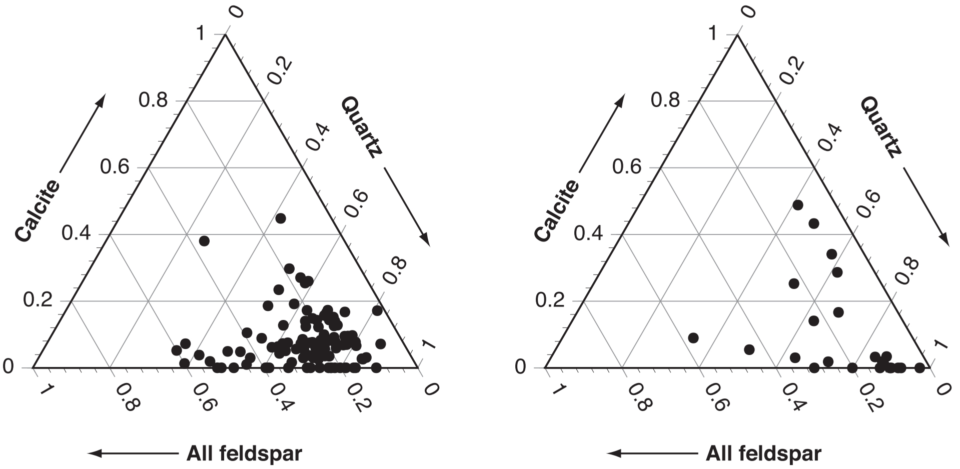
(d) Nile Delta sands (dots) and Sinai wadi sands (stipple)

Fig. 9. Ternary diagrams showing relative abundance of quartz, K-feldspar, and plagioclase, based on XRD peak heights (20.8° for quartz; 27.4° for K-feldspar, and 27.8° for plagioclase) for (a) Negev dunes, (b) Sinai dunes, (c) aeolianite at Gaash, and (d) Sinai wadi sands and Nile Delta sands.

some of the variability in calcite content appears to be related to age and geography. Stratigraphic relations and the OSL geochronology of Roskin et al. (2011b) allow a comparison of the compositions of late Pleistocene and late Holocene dunes, at least in the Negev portion of the erg. On quartz–K-feldspar–plagioclase ternary diagrams, there is no significant difference between the two age groups of aeolian sands (Fig. 12). On quartz–feldspar–calcite diagrams, however, there are several late Pleistocene sand samples that have significantly higher amounts of calcite than the late Holocene sands. As mentioned earlier, Roskin et al. (2011b) identified three east–west trending dune-incursion corridors in the Negev portion of the dunefield (Fig. 3). All of the higher calcite Pleistocene sands from the Negev are from either the southern incursion corridor, or the southern portion of the central incursion corridor. Deposition of relatively carbonate-rich aeolian sand appears to have occurred fairly consistently in the late Quaternary in the southern corridor of the Negev dunes. At the Mitvakh locality, situated in the southern corridor, calcite is detectable in the entire section (Fig. 6). Using CaO + LOI as a proxy for total carbonate content, calcite abundances range from 6 to 10% throughout the section at Mitvakh, from the late Pleistocene (marked by an OSL age of ~14 ka at a depth of ~9 m) up to the late Holocene (marked by Byzantine artifacts 1.7–1.4 ka, at the top of the section).

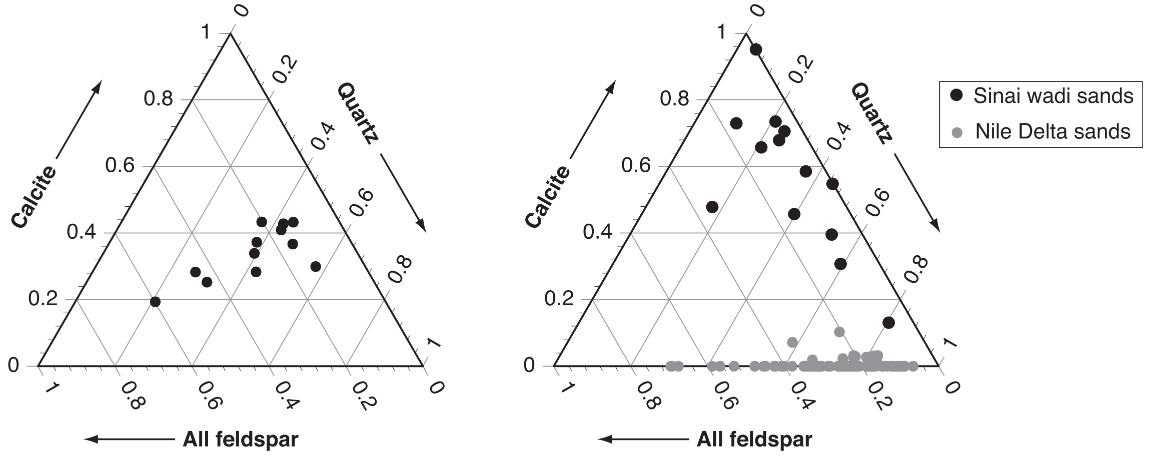
The mineralogy of potential source sediments, sands of the Nile Delta and sands of the Wadi El Arish drainage system of Sinai, are distinct from one another. Nile Delta sands consist mostly of quartz, followed by plagioclase and K-feldspar (Fig. 9). Calcite is present in only a few Nile samples and in very small amounts (Fig. 10). Major element geochemistry is consistent with this mineralogy (Fig. 11), with Nile Delta sands showing SiO_2 contents of 85–95%, Na_2O contents of 0.45–1.2%, and K_2O contents of 0.42–1.1%. In contrast, almost all Sinai wadi sands have calcite (Fig. 10). Based on CaO + LOI as an estimate of mineral abundance, carbonate contents vary widely, however, from ~14 to ~91%. In Sinai wadi sands, SiO_2 contents are inversely related to carbonate content and vary from ~6 to ~82%, with Na_2O ranging from 0.05 to 0.35%, and K_2O ranging from 0.11 to 0.58%. Thus, although the Wadi El Arish drainage system is certainly dominated by carbonate rocks (Sneh, 1982; Bartov, 1990), silicate minerals are also present within the alluvium derived from these rocks, sometimes in substantial amounts.

Nile Delta sands and Sinai wadi sands can also be distinguished from one another by the use of geochemical indicators of heavy mineral assemblages. There is a long tradition of using heavy mineral suites to determine sediment origins. Some of these minerals are resistant to mechanical breakdown and can be distinctive for different source rocks (Blatt et al., 1972; Pettijohn et al., 1972). An alternative approach is possible based on studies that have shown that, in the absence of clay minerals or intergranular cement, heavy mineral assemblages are proxied by geochemical indicators, specifically Fe_2O_3, MgO and TiO_2 contents (e.g., Nesbitt



(a) Negev Desert dunes

(b) Sinai Desert dunes



(c) Aeolianite, Gaash, Israel

(d) Nile Delta sands and Sinai wadi sands (500-53 μm):

Fig. 10. Ternary diagrams showing relative abundance of quartz, all feldspar (K-feldspar + plagioclase) and calcite, based on XRD peak heights (20.8° for quartz; 27.4° for K-feldspar, 27.8° for plagioclase, and 29.4° for calcite) for (a) Negev dunes, (b) Sinai dunes, (c) aeolianite at Gaash, and (d) Sinai wadi sands and Nile Delta sands.

and Young, 1996; Kasper-Zubillaga et al., 1999). As discussed above, our XRD analyses and major element geochemistry indicate that the dominant constituents are all light minerals (quartz, K-feldspar, plagioclase, and calcite), none of which contain significant amounts of Fe_2O_3, MgO, or TiO_2. A very small amount of the total Fe may be present as Fe-oxide coatings on quartz and feldspar grains (Roskin et al., 2012), but this does not explain the bulk of the Fe content. Thus, Fe_2O_3, MgO, and TiO_2 contents most likely reflect the suite of heavy minerals present as accessory constituents in these dunes. We can compare the relative abundance of Fe_2O_3, MgO, and TiO_2 in dunes and potential source sediments as a proxy for heavy mineral assemblages. Ternary diagrams of Fe_2O_3–MgO–TiO_2 show that Nile Delta sands and Sinai wadi sands have distinctive compositions, with no overlap (Fig. 13). Negev dunes fall mostly within or close to the field defined by Nile Delta sands. Sinai dunes also fall mostly within or somewhat above the field for Nile Delta sands, although three samples fall within the range of Sinai wadi sands.

4.2. *Mineralogical maturity in dunes of the Sinai–Negev erg*

The relative abundance of quartz, K-feldspar, and plagioclase in Negev dunes, when compared to other dunefields, shows that the Negev sands are relatively mature mineralogically. Mineralogical maturity, as the term is used here, is defined as a compositional state of a clastic sedimentary body wherein there is a dominance of quartz and an absence or minority of less-resistant minerals such as feldspars, carbonates, gypsum, or lithic fragments. Sandstones that meet this definition are classified as quartz arenites (formerly called orthoquartzites), if they are at least 95% quartz (Pettijohn et al., 1972). Thus, aeolian sediments in many of the world's great sand seas may be properly classified as quartz arenites, a state of maturity that Pettijohn et al. (1972, p. 216) describe as "…the most texturally and compositionally mature of all sands. Some approach the theoretical end point in sand evolution." Dott (2003) elegantly described quartz arenites as "…nature's finest distillate – almost as remarkable as a pure single malt Scotch whiskey."

Mineralogical maturity, whether expressed mineralogically or geochemically, can be a powerful tool in ascertaining sediment sources. A sediment body cannot be less mineralogically mature than its source sediments. If a dunefield has more weatherable minerals (feldspars, calcite, dolomite, gypsum) than its inferred source, then it must have a second source that is supplying these constituents. Examination of quartz–K-feldspar–plagioclase ternary diagrams of Negev and Sinai dunes shows close similarity to the composition of both Nile Delta sands and Sinai wadi sands (Fig. 9). Thus, with regard to these three minerals, dunes of the Sinai–Negev erg could be interpreted to have been derived from either of these sediment sources or some combination of them. Nevertheless, comparison of

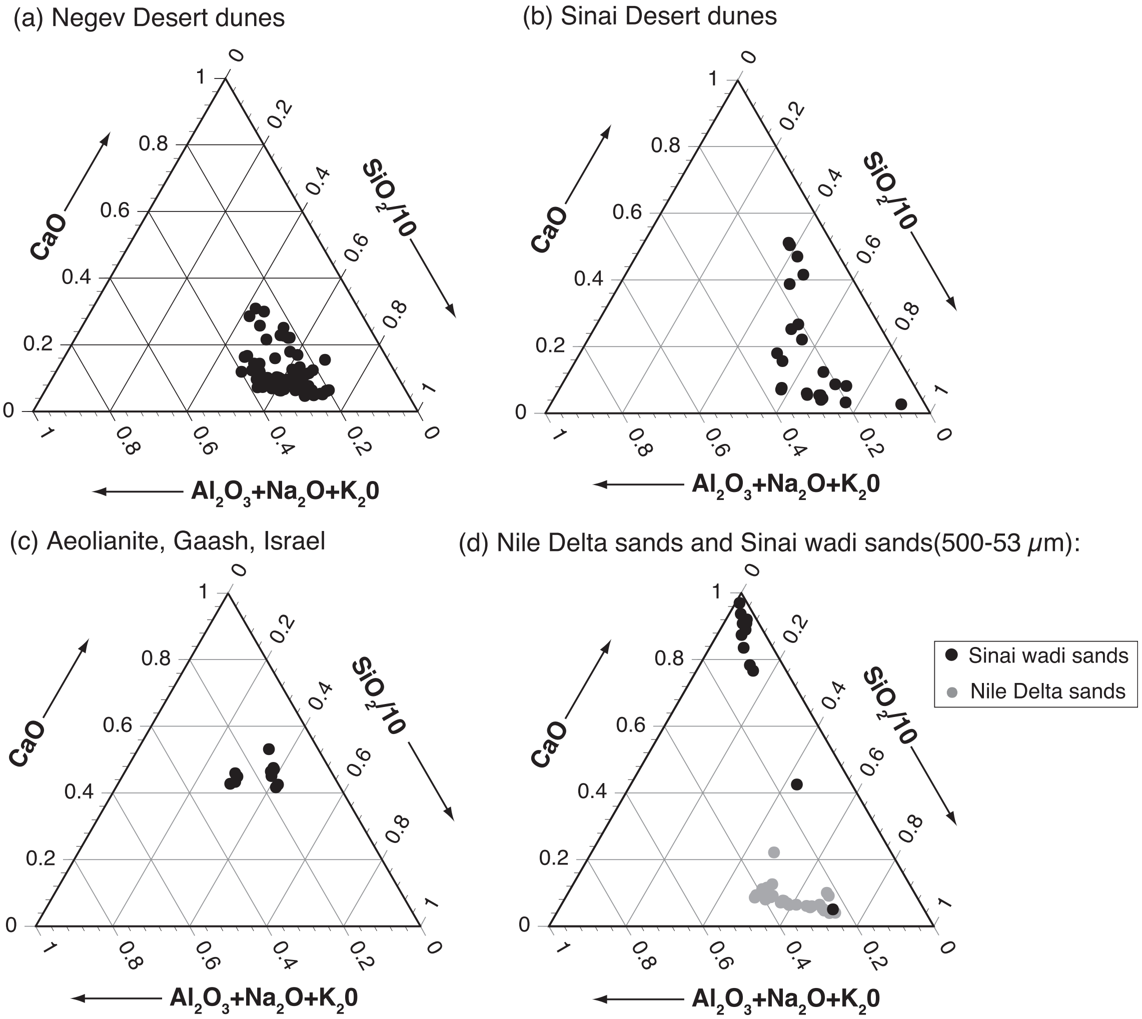


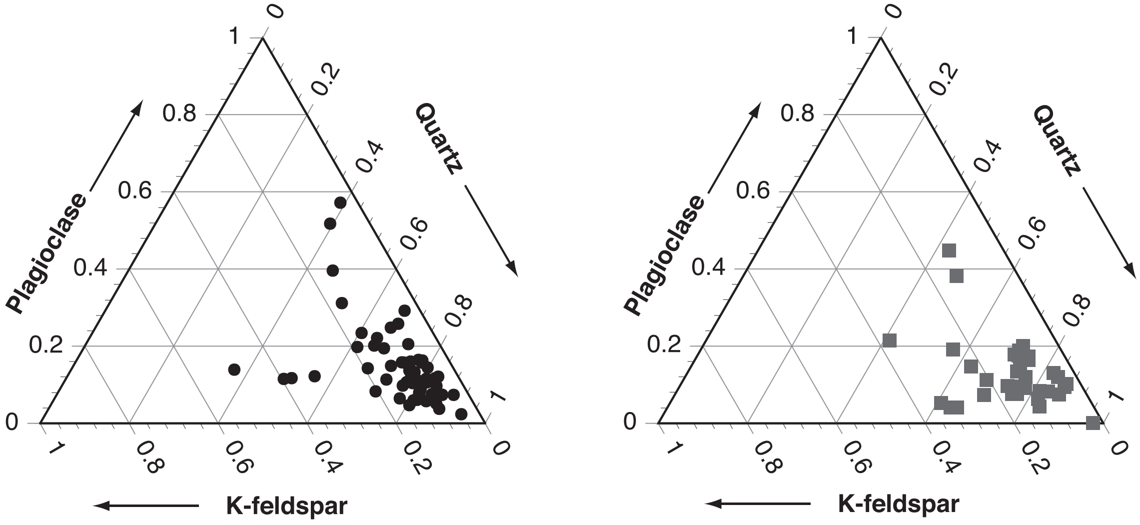
Fig. 11. Ternary diagrams showing relative amounts of $SiO_2/10$ (representing quartz), $Al_2O_3 + Na_2O + K_2O$ (representing all feldspar), and CaO (representing calcite) for (a) Negev dunes, (b) Sinai dunes, (c) aeolianite at Gaash, and (d) Sinai wadi sands and Nile Delta sands. Compare to Fig. 10.

Negev and Sinai sands with these sources on quartz–total feldspar–calcite diagrams (and their geochemical proxies) shows that the presence of calcite in the dunes cannot be explained solely by derivation from a Nile Delta source (Figs. 10 and 11). Few of the Nile Delta sands we studied contain calcite and those that do contain it have very low abundances, as reflected in low CaO content and LOI. Thus, calcite in dunes of the Sinai–Negev erg is likely derived from Sinai and Negev wadi sands.

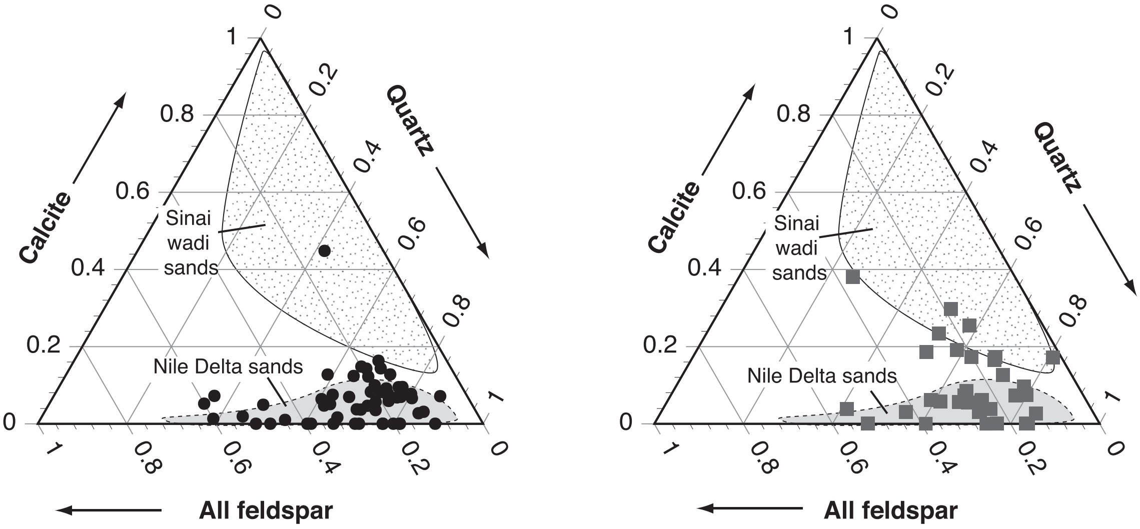
In addition to simple ternary diagrams of quartz, feldspar and calcite abundance, mineralogical maturity can be portrayed geochemically. One approach is to plot total SiO_2 content (as a proxy for quartz) against total $Al_2O_3 + K_2O + Na_2O$ content (as a proxy for total feldspar). Suttner and Dutta (1986) used this approach in paleoclimatic interpretations of ancient sandstones and Muhs (2004) used it in assessing long-term degree of activity of Quaternary dune sands. Another approach, presented by Pettijohn et al. (1972), is to plot the logarithm of Na_2O/K_2O (a measure of plagioclase to K-feldspar) against the logarithm of SiO_2/Al_2O_3 (a measure of quartz to total feldspar). In this method, sandstones that are more mature have lower Log [Na_2O/K_2O] due to plagioclase depletion and higher Log [SiO_2/Al_2O_3] due to overall feldspar depletion. An advantage of the Pettijohn method is that it provides dimensionless comparisons of feldspar versus quartz content, regardless of carbonate content.

On a Pettijohn geochemical maturity diagram, the hypothesized source sediments for the Sinai–Negev erg span the range of values for subarkoses and sublithic arenites (Fig. 14). Nile Delta sands and Sinai wadi sands show about the same ranges for Log [SiO_2/Al_2O_3], but Sinai wadi sands show a greater depletion of plagioclase relative to K-feldspar, based on lower Log [Na_2O/K_2O] values. Negev dune sands fall mostly between these two sediment groups, but Sinai dune sands show less depletion of plagioclase and about half fall within the range of Nile Delta sands. Thus, the Pettijohn diagrams permit an interpretation of Sinai dunes being derived from the Nile Delta, because the dune sands show about the same degree of maturity as the delta sands, or slightly more maturity in the case of a few samples. However, local Sinai wadi sands are eliminated as a likely source for at least the silicate fraction of Sinai dune sands, because the dunes have more plagioclase relative to K-feldspar (i.e., higher Log [Na_2O/K_2O] values) than do the wadi sands. On the other hand, two interpretations are possible with the Negev dunes. Because the Negev dunes display a range of values that is mostly between the two possible source sediments, this can mean either derivation from both sources *or* a solely Nile Delta source followed by depletion of plagioclase from abrasion during transport.

The hypothesis of abrasion during transport for the Negev dunes can be explored by comparison with another aeolian sediment body that is also postulated to have a Nile Delta source, the coastal


(a) Negev Desert, Holocene dunes

(b) Negev Desert, Pleistocene dunes


(c) Negev Desert, Holocene dunes

(d) Negev Desert, Pleistocene dunes

Fig. 12. Comparison of quartz–K-feldspar–plagioclase and quartz–all feldspar–calcite compositions for Holocene [(a) and (c)] and Pleistocene [(b) and (d)] aeolian sands in the Negev Desert. Shown for comparison are the ranges of these minerals for Sinai wadi sands and Nile Delta sands.

aeolianites or kurkar deposits of the Israeli coastal plain. Emery and Neev (1960) and Stanley (1989) report heavy mineral assemblages that point to a Nile source of sand for Israeli beaches. These observations are consistent with models of sediment transport northward by longshore currents from Sinai to the northern coast of Israel, as outlined by Goldsmith and Golik (1980) and Zviely et al. (2007). Although the carbonate fraction of Israeli aeolianites is believed to be derived from local bioclastic sources, longshore transport of Nile Delta sand eastward along the Mediterranean has long been used to explain the origin of the non-carbonate fraction of aeolianite dune sands (Emery and Neev, 1960; Yaalon, 1967; Horowitz, 1979; Frechen et al., 2001). We note, however, that a few of the aeolianite samples may have some influence from Sinai wadi sands, based on heavy mineral assemblages, proxied by Fe_2O_3–MgO–TiO_2 (see Fig. 13(c)). In any case, unlike sands of the Sinai–Negev erg, the aeolianite/kurkar sands of the Israeli coastal plain probably underwent only short distances of aeolian transport from the coast before they were cemented into rock (cf. Tsoar, 2000). IRSL ages presented by Porat et al. (2004) show that aeolianite cementation can take place very rapidly in Israel. Thus, we infer that if Nile-Delta-derived quartz and feldspars in Israeli aeolianites underwent only short distances of aeolian travel before cementation, they should have experienced little depletion of feldspar by abrasion during transport. This hypothesis can be tested by examination of a Pettijohn plot for the aeolianites we collected at Gaash, Israel (Fig. 8). Results indicate that the Gaash aeolianite compositions fall squarely within the range for Nile Delta sands, thus suggesting little or no abrasional loss of feldspar by long-distance aeolian transport (Fig. 15).

5. Discussion

5.1. Origin of sand in the Sinai–Negev erg

Collectively, the mineralogical and geochemical data presented here support the long-assumed hypothesis that sands of the Nile Delta are the primary source of sediments in the Sinai–Negev erg. Nile Delta sands are rich in quartz, with small amounts of K-

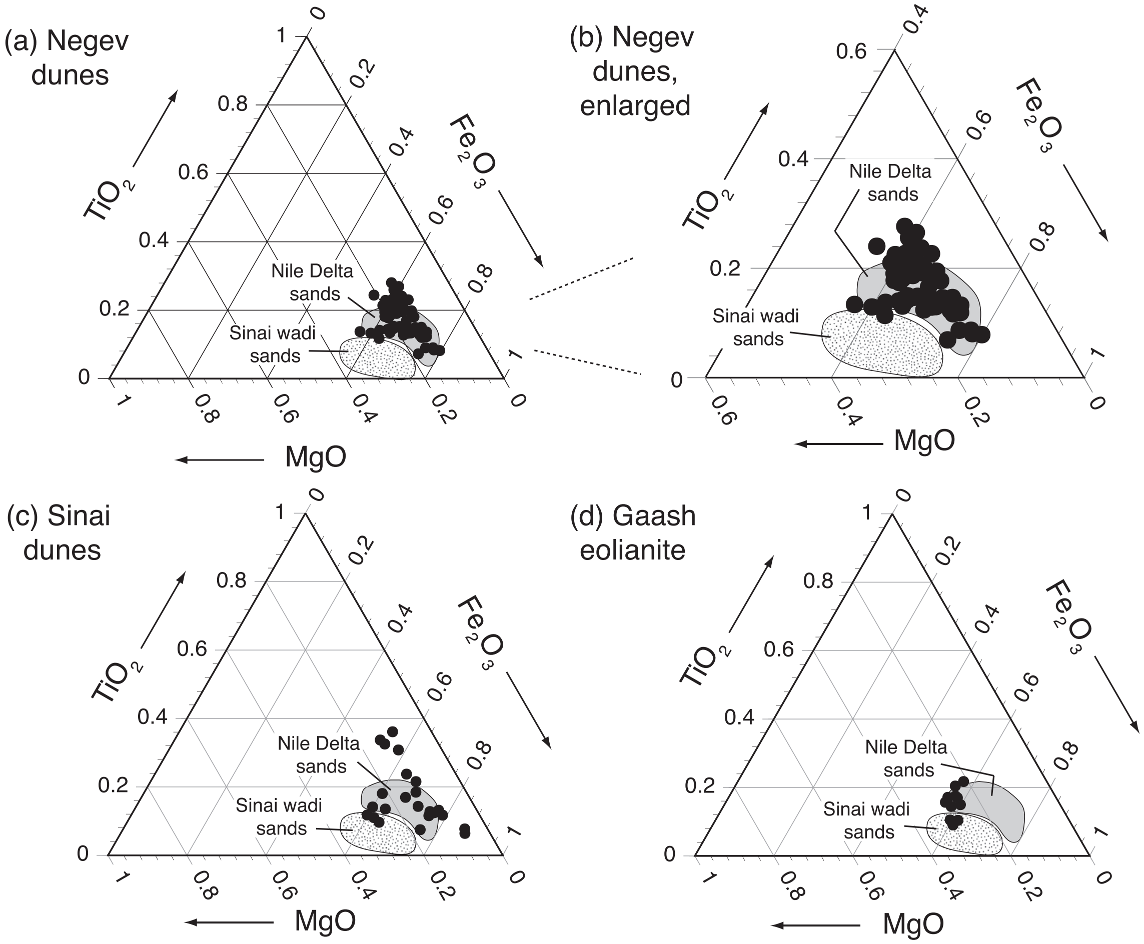


Fig. 13. Ternary diagrams showing relative amounts of Fe_2O_3, MgO, and TiO_2, representing heavy minerals for (a) Negev dunes; (b) Negev dunes, showing an enlarged portion of (a); (c) Sinai dunes; and (d) aeolianite at Gaash. Shown for comparison are ranges of these values in Sinai wadi sands (stipple pattern) and Nile Delta sands (gray shading).

feldspar and plagioclase, in proportions similar to what is found in sands of the Sinai–Negev erg. Pettijohn-style geochemical plots of mineralogical maturity that measure feldspar depletion relative to quartz show that Sinai dune sands have compositions (with respect to quartz and feldspars) very similar to Nile Delta sands. A number of samples of Negev dune sands and a few Sinai dune sands show somewhat greater mineralogical maturity than Nile Delta sands. This does not rule out a Nile Delta source, however, as some feldspar loss is expected during aeolian sand transport. Importantly, neither Sinai nor Negev dune sands show a *lower* degree of mineralogical maturity than Nile Delta sands. If this were the case, then a more feldspar-rich source would have to be invoked at least as a partial source.

Geochemical indicators that proxy for heavy minerals also support a Nile Delta source for the Sinai–Negev erg. Mineralogical compositions, as determined by XRD, show that Fe_2O_3, MgO and TiO_2 likely reside in the trace quantities of heavy minerals in both Nile Delta and Sinai wadi sands, the two candidate source sediments. Thus, Fe_2O_3–MgO–TiO_2 ternary plots provide a means of assessing the heavy mineral composition of the source sediments. Fields defined by the composition of Nile Delta and Sinai wadi sands on these plots do not overlap. Both Sinai and Negev dune sands fall mainly within the field defined by Nile Delta sands, consistent with the mineralogical and geochemical data for the light mineral fraction.

Although the bulk of mineralogical and geochemical data support a Nile Delta source for the Sinai–Negev erg, other mineralogical data show that a second source is required. Most Sinai dunes and many Negev dunes (dominantly in the southern dune incursion corridor) contain measurable amounts of calcite. Based on CaO contents and LOI, the amount of calcite in Sinai dunes ranges from 1 to 19%, with Negev dunes having calcite contents of 1–11%. Calcite is present in small amounts in only a few Nile Delta sands we examined; most delta samples contain no measurable calcite at all. In contrast, fluvial sands from the upper part of the Wadi El Arish drainage basin of Sinai have abundant calcite. This calcite is likely derived from Jurassic, Cretaceous, and Eocene carbonate rocks that constitute the dominant bedrock in central and northern Sinai (Bartov, 1990). Based on both XRD and geochemistry, carbonate contents of these Sinai wadi sands range from 14 to 90% and average ~64%. Thus, a smaller but significant amount of sediment in the Sinai–Negev erg is not derived from the Nile Delta, but from wadi sands of Sinai. Analyses of samples in a thick aeolian sand section at Mitvakh, in the southern dune incursion corridor of the Negev Desert, show that inputs of calcite from Sinai or Negev wadis have been important through the whole period of sedimentation recorded at this locality, which dates from the late Pleistocene to the late Holocene. Furthermore, other localities in the Negev dunes that show significant amounts of calcite are, like the Mitvakh section, all located within the southern dune-incursion corridor. Thus, aeolian inputs of calcite from calcareous Sinai wadi sands appear to be directed mainly toward the southern part of the Negev dunes in Israel. Another possibility is that Nahal Nizzana, a local source for dunes of the southern incursion corridor, provided sediment inputs, as sands in this drainage are carbonate-rich.

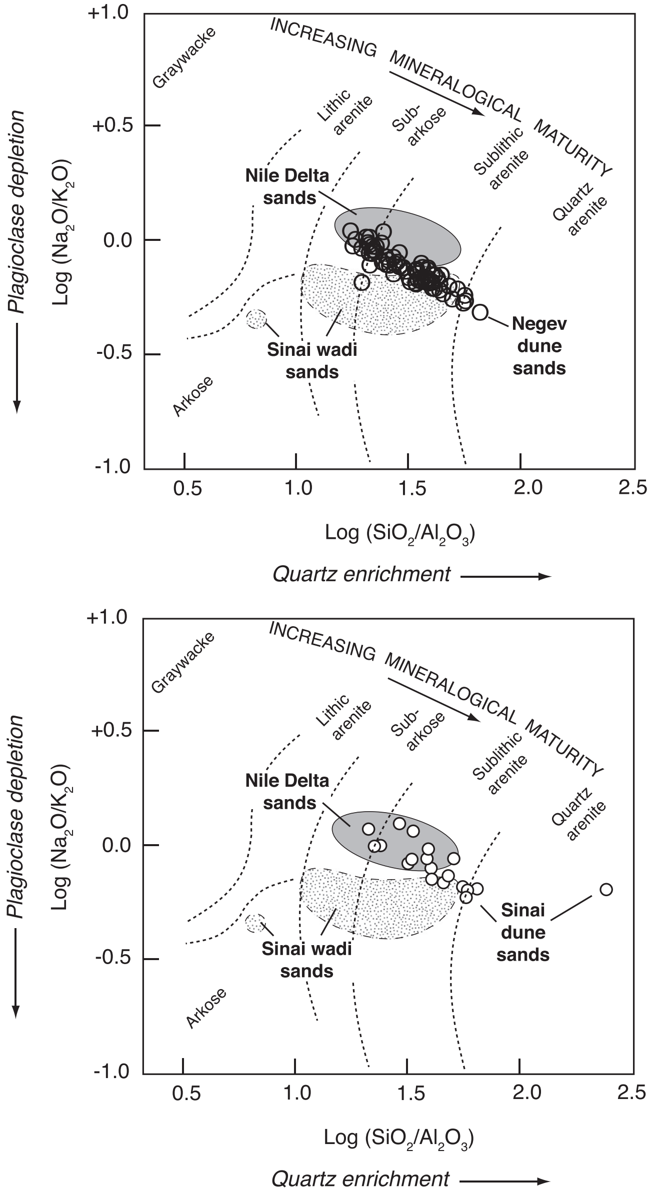


Fig. 14. Geochemical plots of mineralogical maturity using method of Pettijohn et al. (1972) for the Negev dunes (upper) and Sinai dunes (lower) compared to Nile Delta sands and Sinai wadi sands. All data from this study.

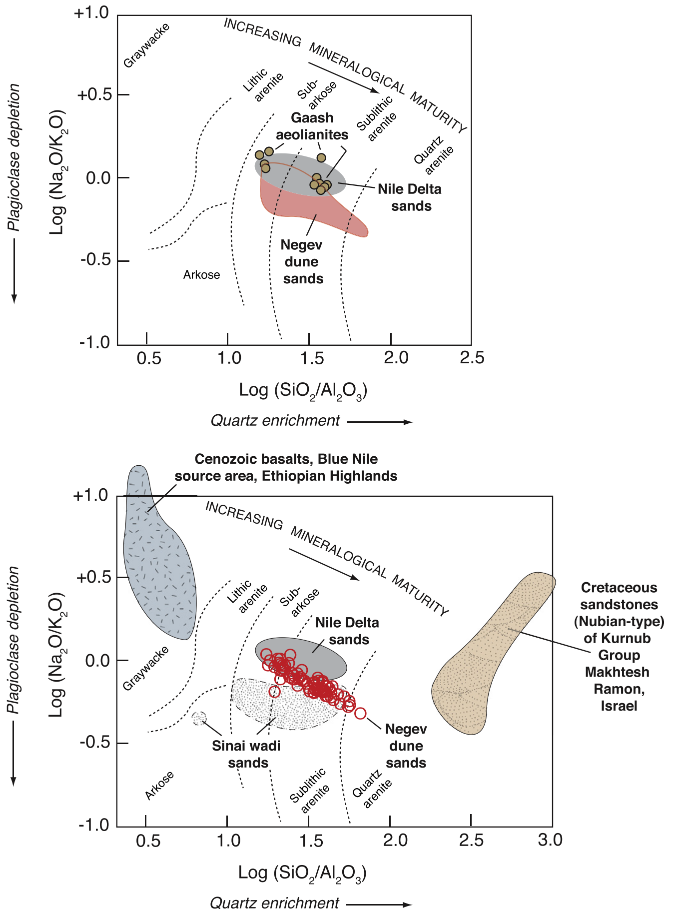


Fig. 15. Upper: Geochemical plots of mineralogical maturity using method of Pettijohn et al. (1972) for the Gaash aeolianites of Israel (this study) and Negev dunes compared to Nile Delta sands. Lower: Geochemical plots of mineralogical maturity using method of Pettijohn et al. (1972) for the Negev dunes (upper) and compared to Nile Delta sands and Sinai wadi sands. Shown for comparison are compositions for Nubian-type sandstones, collected in Makhtesh Ramon, Israel and Cenozoic basalts from the Ethiopian Highlands. All data from this study except basalt data, which are from Pik et al. (1998).

5.2. *Paleoenvironmental conditions favorable to the formation of the Sinai–Negev erg*

The Nile Delta is currently cultivated and has been utilized for this purpose for millennia. Part of the reason that agriculture is possible on the delta is that it hosts fine-grained soils that are productive if there is sufficient moisture. A question that follows from this is how Nile Delta sands could be entrained to form dunes when the present sediment cover is so fine grained. We infer that the answer lies in the changing conditions of the Nile Delta over the Last Glacial period and into the Holocene. Stratigraphic studies by Stanley et al. (1996; see also Fig. 7 herein) and reconstruction of the late Pleistocene-to-historic-period paleogeography of the region by Stanley and Warne (1993) show that during the Last Glacial period, ~35 ka to ~13 ka (in calibrated radiocarbon years), the Nile Delta was characterized by a series of broad, braided or anastomosing channels that were seasonally dry. The dominant sediments in the delta at this time were quartz-rich sands, as shown by the stratigraphy in Stanley et al. (1996) and Fig. 7. Sea level was as much as ~130 m below present, and the shoreline lay farther north (Fig. 1), based on the Barbados sea-level record (Peltier and Fairbanks, 2006). Fine-grained floodplain sediments likely were found only near what is now the shoreline, in limited areas compared to the present size of the delta (Fig. 16). Seasonally dry, braided or anastomosing channels were separated by dry, sandy plains over most of what is now the main part of the Nile Delta. We suggest that this broad, dry, sandy plain, which would have been extensive, set the stage for the growth of the Sinai–Negev erg.

Concurrent with a readily available source of sand, there was probably an increase in the frequency of high-velocity winds during the Last Glacial period. Wind strength is one of the major controls on dune activity (Tsoar, 2005). Under reasoned scenarios of Last Glacial synoptic climatology, it is likely that there were higher velocity, and more frequent, west-to-east winds over the area now occupied by the Sinai–Negev erg, due to more frequent eastern Mediterranean cyclonic systems (see discussion in Enzel et al., 2008). With an abundant sand supply from the Nile Delta, high-velocity winds would have brought about optimal conditions for initiation and growth of the Sinai–Negev erg during the Last Glacial period, a favorable combination of conditions also outlined by Roskin et al. (2012).

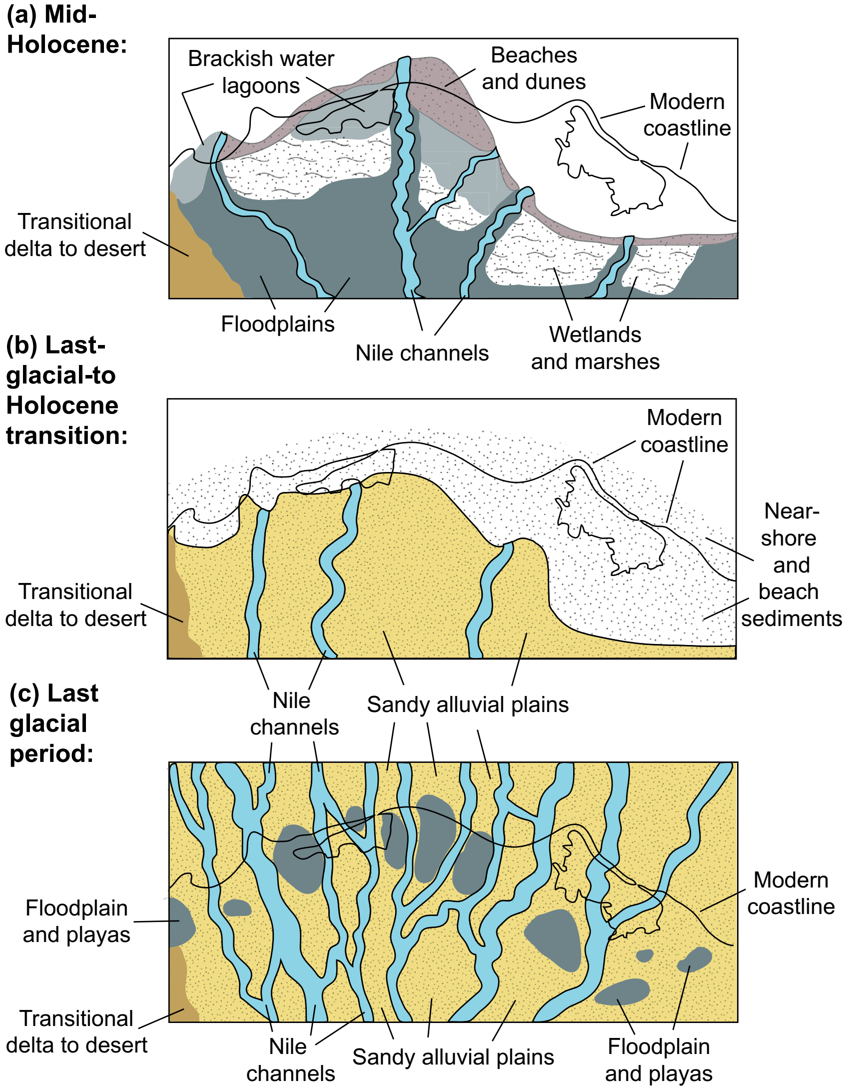


Fig. 16. Paleogeography of the Nile Delta region at the mid-Holocene (a), Last Glacial-to-Holocene transition (b), and Last Glacial period (c). Redrawn in simplified form from Stanley and Warne (1993).

With the insolation-forced transition to the Lateglacial period and early Holocene, global ice volume decreased, sea level rose (Fig. 17), and base level for the Nile rose, followed by a decrease in stream power. Sea-level rise initiated Nile aggradation and a shift to a dominantly suspended, fine-grained load. Furthermore, higher insolation in the Northern Hemisphere at this time is thought to have brought about a northward migration of the ITCZ, a period from ~15 ka to ~5 ka (cal yr BP) that has been referred to as the African Humid Period (DeMenocal et al., 2000; Bernhardt et al., 2012; Williams, 2012). A shift to a major period of aggradation with rising sea level, coupled with increased moisture during the African Humid Period, brought about a drastic change in the morphology and dominant sediments on the Nile Delta (Figs. 16 and 17). By the Last Glacial-to-Holocene transition, the overall size of the sandy plains would have diminished and fewer anastomosing channels would have existed. By the mid-Holocene, the dry, sandy plains between the former anastomosing channels were covered with floodplains, wetlands and marshes, and brackish-water lagoons were present on the outer part of the delta (Stanley and Warne, 1993).

The increase of fine-grained particles as the dominant sediment carried by the Nile during the African Humid Period is recorded in sediments of the eastern Mediterranean, off the coast of Israel, studied by Hamann et al. (2008, 2009). During the Last Glacial period, the main fine-grained sediment input to the eastern Mediterranean Sea was dust from the Sahara, based on both particle size and clay mineralogical data. Saharan dust that reaches the eastern Mediterranean Sea is rich in illite and contains much less smectite, a trend that has been observed for glacial periods over much of the Quaternary (Zhao et al., 2012). A core (SL 112) off Israel studied by Hamann et al. (2008, 2009) shows abundant illite during the LGM and particle size modes of ~40 μm, interpreted to be dominantly aeolian. With the advent of the African Humid Period at ~15 ka, the most important sediment input to the eastern Mediterranean Sea became the Nile, with greatly reduced aeolian inputs. This is reflected in the finer grain size (interpreted to be fluvial) and abundance of smectite, which is found in the Nile drainage basin (Fig. 17). The scenario is consistent with the evidence for the shift to fine-grained (silts and clays) sedimentation on the Nile Delta, seen in the core stratigraphy of Stanley et al. (1996) and shown in Fig. 7.

The significance of the sequence of events outlined above for the Sinai–Negev erg is that changes in the fluvial regime of the Nile, controlled both by sea level and climate, dictated when sand supplies would have been available from the delta for building dunes.

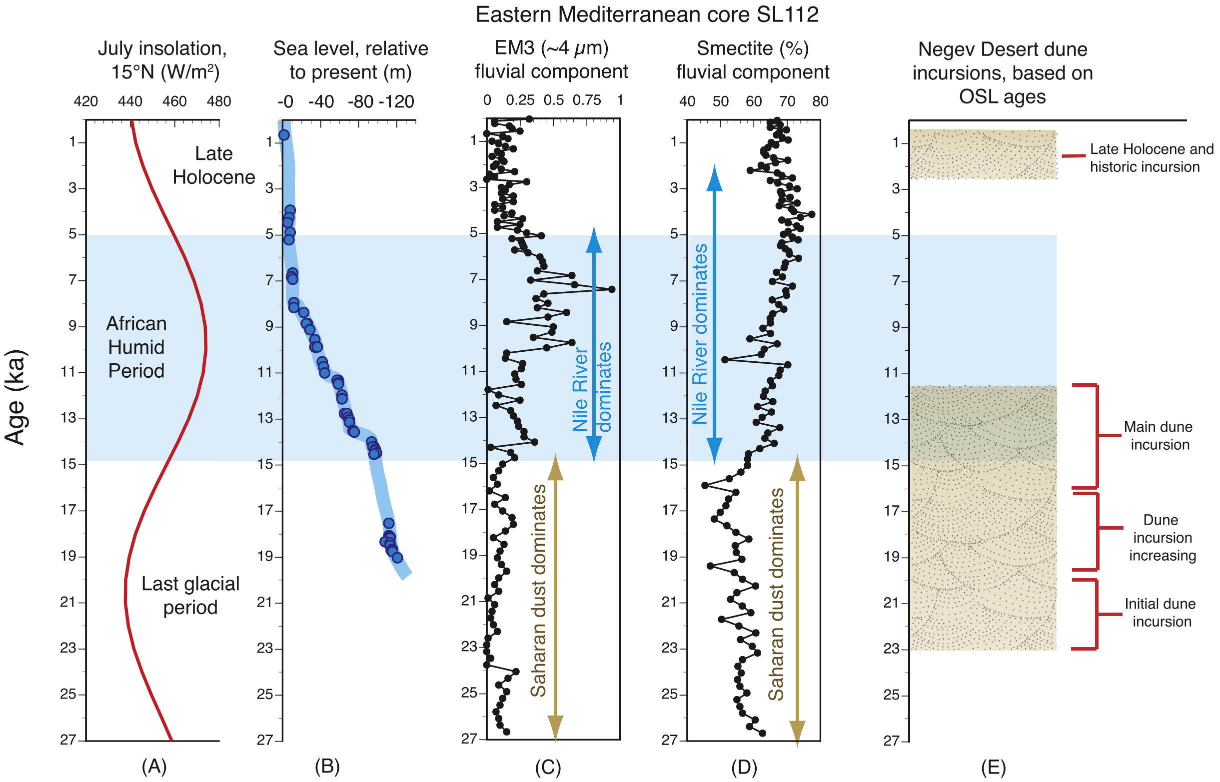


Fig. 17. (A) July insolation at the top of the atmosphere at 15°N (data from Berger and Loutre, 1991); (B) sea level history from the Last Glacial period to present, based on data from Barbados, the Florida Keys and the Bahamas (compiled by the authors from Bard et al., 1990; Toscano and Lundberg, 1998; Toscano and Macintyre, 2003; Peltier and Fairbanks, 2006); (C) particle size data, expressed as fractions of 1 for fluvial (EM3) sediment and (D) clay mineralogy in eastern Mediterranean Sea core SL 112 and inferred dominant sediment sources (data from Hamann et al. (2008, 2009)); and (E) periods of dune activity in the Negev Desert of Israel, based on OSL ages (Roskin et al., 2011b).

During the Last Glacial period, when broad, dry, sandy plains with seasonally dry channels typified what is now the Nile Delta region (Fig. 16c), sand supplies were abundant and initial dune incursions to the Sinai–Negev erg began (Fig. 17). Dune building continued into the Lateglacial, but diminished sometime after sea level began to rise in the Holocene and the African Humid Period began. A decrease in dune building activity in the Sinai–Negev erg at this time is consistent with a diminution in sand supplies, caused by aggradation of the Nile and a shift to finer grained sedimentation on what is now the Nile Delta. Williams (2012) points out that finer grained sedimentation (as opposed to sand and gravel deposition) also occurred in the upper reaches of the Nile at this time. Little or no dune building occurred during the early-to-mid-Holocene because of a lack of sand supply, but dune building began again in the late Holocene, after the African Humid Period had ended (Fig. 17). Similar compositions of Holocene and Pleistocene dunes, except for calcite (Fig. 12), permit the possibility that some of the Holocene aeolian sand could have been reworked from Pleistocene dunes. A recent study shows that much or all of this late Holocene dune activity is due to anthropogenic causes, namely destruction of biological soil crusts (from grazing) or removal of vascular vegetation (from grazing or fuel collection) as well as possible brief periods of increased wind strength (Roskin et al., in press).

5.3. *Origin of quartz in the Nile Delta*

Earlier, we pointed out that recently computed sediment budgets, based on both petrography and isotopic compositions, indicate that the largest contributors to the Nile are tributaries, such as the Blue Nile and Wadi Atbara, that drain the Ethiopian Highlands. The Ethiopian Highlands are dominated by basalts of Cenozoic age, rocks that lack quartz. Nevertheless, our studies show that Nile Delta sands, at least those of Late-Last-Glacial age (Fig. 7) are very rich in quartz and in fact qualify as subarkoses or sublithic arenites (Fig. 14). This leads to the question of what the source of quartz was for the Nile Delta during the Last Glacial period. One possibility that must be considered is simple aeolian transport of sand from the Western Desert of Egypt (Fig. 1), where the Great Sand Sea, a large dunefield, is situated (Fig. 18). El-Baz et al. (1979) analyzed a limited number of samples from this sand sea, but their data indicate that the dunes are indeed quartz-rich (>90%). Bubenzer et al. (2007) show that dunes in this sand sea were active during the Last Glacial period and, at least in the northern part of region, paleowinds could have been from the west. Nevertheless, the extent of this sand sea does not reach the Nile drainage basin (Fig. 18). Although it is possible that small amounts of quartz sand could have reached the Nile from this source, it is unlikely that such tiny additions can explain the dominance of quartz in Nile Delta sediments that date to the Last Glacial period.

Farther south in the Sudan, however, there is abundant aeolian sand that could have been delivered by wind transport to the Nile drainage basin. We note that much of this aeolian sand overlies what has been mapped as Cretaceous “Nubian Sandstone,” a quartz arenite. Given the similar spatial distribution of both aeolian sand and Nubian Sandstone in northern Sudan (Fig. 18), we suspect that this Cretaceous bedrock is the likely source of the dunes and sand sheets in this region. This hypothesis requires testing, but it leads to the possibility that quartz in the Nile system, whether delivered by fluvial or aeolian processes, ultimately could be derived from the Nubian Sandstone. Indeed, Williams (2012) notes that during the Pleistocene, dunes migrated across a dry White Nile river bed. Butzer and Gladfelter (1968) studied Pleistocene fluvial sediments

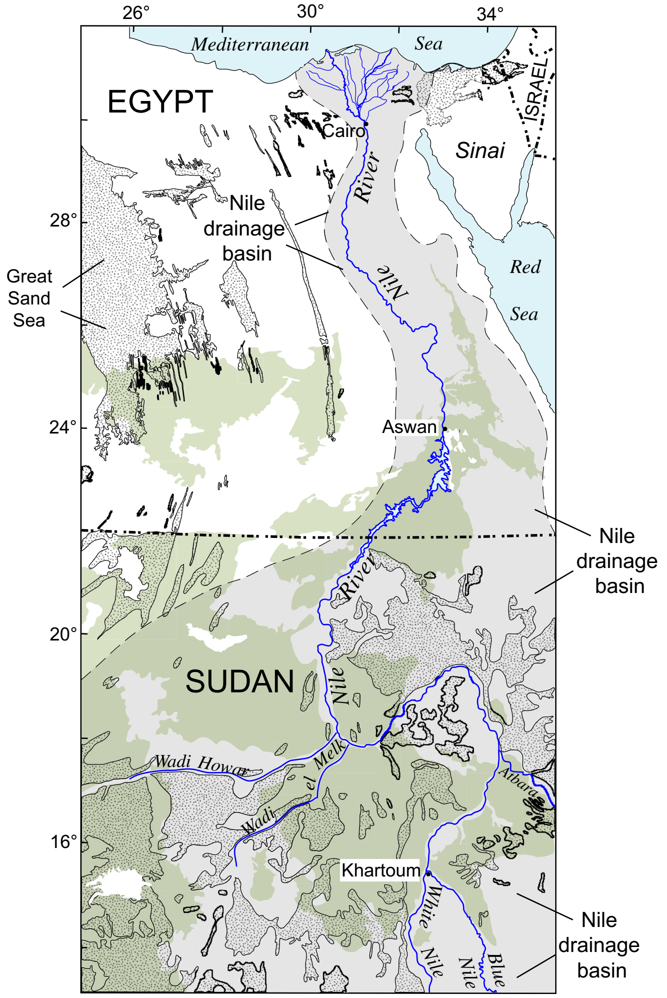


Fig. 18. Map of portions of Egypt and Sudan, showing parts of the Nile drainage basin (gray shade) and areas of occurrence of aeolian sand (stipple pattern) and Cretaceous Nubian Sandstone (green). Nile drainage basin from Woodward et al. (2007) and Williams (2012); aeolian sand and Nubian Sandstone geology from Egyptian Geological Survey and Mining Authority (1981) for Egypt and Geological and Mineral Resources Department (1981) for the Sudan. (For interpretation of the references to colour color in this figure legend, the reader is referred to the web version of this article.)

of the Nile along numerous reaches in the Sahara, including segments that are now flooded because of the construction of the Aswan High Dam. They document very high quartz contents in Nile sands and infer that Nubian Sandstone is the source of this mineral. Although the present sediment budget of the Nile seems to be dominated by basalt-derived inputs from the Ethiopian Highlands (Padoan et al., 2011; Williams, 2012), Garzanti et al. (2006) point out that this is partly a function of high sediment yields from anthropogenic erosion due to deforestation and land use in the upper part of the drainage basin. Indeed, Garzanti et al. (2006) caution that their sediment budget probably cannot be extrapolated very far into the past. Furthermore, it is clear from detailed geomorphic and stratigraphic studies by Butzer and Hansen (1968) that Nubian Sandstone was an important contributor to fluvial sands in downstream reaches of the Nile during Pleistocene time. We did not have access to samples of the Nubian Sandstone in Egypt, but the correlative rocks of the Kurnub Group (Cretaceous) we collected from Makhtesh Ramon confirm that they are very mature mineralogically, consistent with studies done on the Nubian Sandstone itself in Egypt (El-Hinnawi et al., 1973). Examination of a Pettijohn geochemical plot of mineralogical maturity shows that the composition of Pleistocene Nile Delta sands can be explained by a mix of feldspar-rich basalts from the Ethiopian Highlands and quartz-rich sources derived from the Nubian Sandstone (Fig. 15).

5.4. Implications for the origin of loess from aeolian sand in the Sinai–Negev erg

As alluded to earlier, a number of recent studies (Crouvi et al., 2008, 2010, 2012; Enzel et al., 2008, 2010; Amit et al., 2011) have concluded that dunefields, and the Sinai–Negev erg in particular, are important generators of silt-sized quartz that constitute a major part of "desert" (i.e., non-glaciogenic) loess. The main mechanism envisioned in this process is reduction of sand-sized quartz to silt-sized quartz by abrasion during aeolian transport. The mechanism has intuitive appeal, based on the geography of the Sinai–Negev erg located upwind of the main loess body in Israel (Fig. 1). In addition, experimental work by Kuenen (1960), Dutta et al. (1993), Wright et al. (1998) and Wright (2001a, 2001b) have shown that both aeolian abrasion and ballistic impacts are surprisingly effective processes for reduction of sand-sized quartz, feldspars, and calcite to smaller sizes, including particle sizes that fall within the range of loess sediments.

Nevertheless, a geographic association of a dunefield and a loess body need not be due to a genetic relationship. In China, for example, the Loess Plateau is downwind of several desert basins with dunefields, but Sun (2002) concludes that the silt is produced by glacial and periglacial processes in the mountains surrounding the basins and that the dunefields occupying the desert basins are temporary storage areas for silt-sized sediment, not the location of silt particle genesis. In the Great Plains region of North America, loess in Nebraska is immediately downwind of the Nebraska Sand Hills, the largest dunefield on the continent. Mineralogic, geochemical, and isotopic studies by Aleinikoff et al. (2008) and Muhs et al. (2008) show, however, that while an active Nebraska Sand Hills dunefield probably played an important role in *transporting* silt to the loess bodies downwind, sand-sized particles in the dunefield itself apparently did not *generate* a significant amount of loess by abrasion of dune sand.

The data we present here can be used to provide a partial test of the importance of the Sinai–Negev erg to the origin of loess in Israel. The classical aeolian experimental studies conducted by Kuenen (1960) documented aeolian abrasional loss, using various particle sizes, surfaces of transport, wind velocities, and mineral species. Under similar conditions (particle size, transport surfaces, wind velocity), the greatest amount of mass loss per unit of transport distance was from calcite and feldspar, not quartz. Although it is important to keep in mind that experimental results such as these may not always be applicable to field settings, Kuenen's (1960) results are consistent with the greater hardness of quartz (7) compared to feldspar (6) or calcite (3). Thus, if the Sinai–Negev erg is contributing coarse-silt-sized quartz particles to the loess of Israel, the erg should also be generating a *relatively* greater amount of silt-sized calcite and feldspar. This hypothesis requires, therefore, that calcite and feldspars should be enriched in loess (relative to quartz) when compared to sands in the Sinai–Negev erg. Crouvi et al. (2009) and Enzel et al. (2010) reported percentages of quartz, K-feldspar, plagioclase, and calcite in loess downwind of the Sinai–Negev erg. They calculated percentages of these mineral species using a method by Dr. Amir Sandler of the Geological Survey of Israel (written communication, 9 August 2012), wherein the following factors are applied to XRD peak heights at two-theta, summed, and calculated as percentages: quartz, 26.6°, ×1.0; K-feldspar, 27.4°, ×3.0; plagioclase, 27.8°, ×3.5; and calcite, 29.4°, ×1.1. We followed this protocol with our XRD

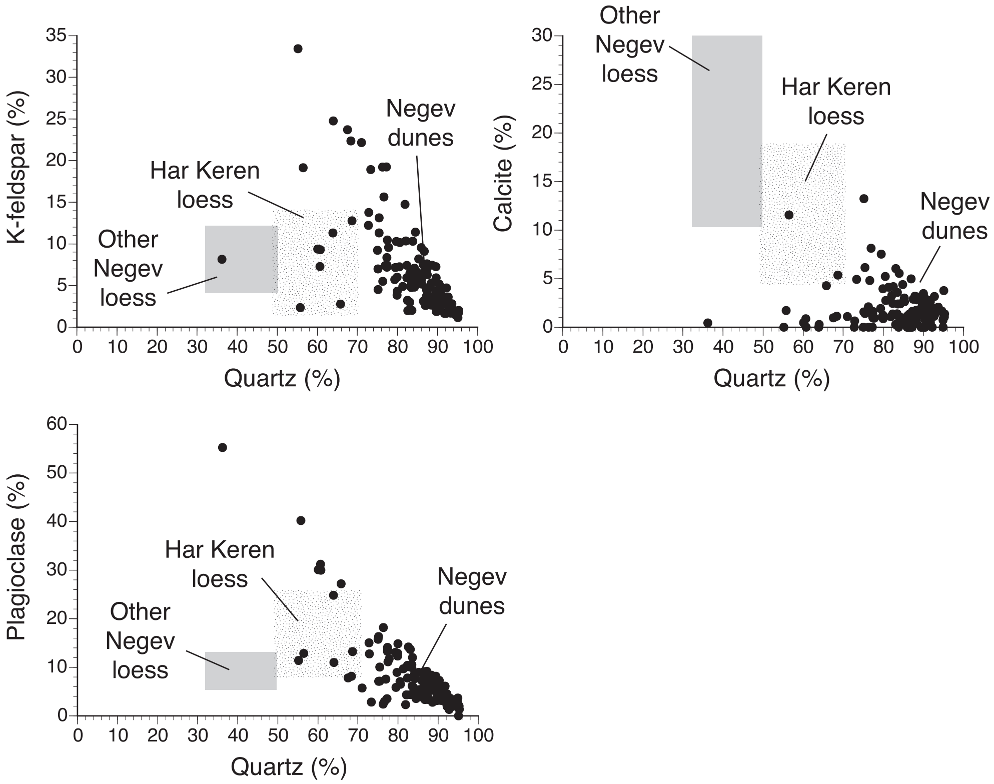


Fig. 19. Plots showing abundance of quartz versus K-feldspar, plagioclase, and calcite in the Negev dunes (this study) compared to loess at Har Keren (data from Enzel et al., 2010) and elsewhere in the Negev Desert of Israel (data from Crouvi et al., 2009).

data in order to make direct comparisons with the loess mineralogical compositions reported by Crouvi et al. (2009) and Enzel et al. (2010). Mineral percentages calculated in this manner are consistent with major element chemistry. Comparison with the Israeli loess mineralogy indicates that, for the most part, loess at Har Keren (Enzel et al., 2010) and elsewhere in Israel (Crouvi et al., 2009) is enriched in K-feldspar, plagioclase, and calcite, relative to quartz, when compared to these minerals in the Negev dunes (Fig. 19). Thus, our feldspar and calcite results support the hypothesis of Crouvi et al. (2008, 2010, 2012), Enzel et al. (2008, 2010), and Amit et al. (2011) that the Sinai–Negev erg could be at least a partial source for loess in Israel. It is important to point out, however, that loess in Israel, at least in places, contains significant amounts of very fine-grained particles that are unlikely to be produced by abrasion in the Sinai–Negev erg. For example, in the Ruhama badlands area, in the northern part of the loess area shown in Fig. 1, Wieder et al. (2008) studied a 15-m-thick sequence of loess and loess-derived paleosols. Clay (<2 μm) contents in the loess and/or the loess-derived buried soils range from ~25% to ~55%, which are significant amounts of the loess particle-size population. It is likely that these fine-grained particles owe their origins to long-range-transported dust from Sinai or the Sahara (Dan and Yaalon, 1971), rather than genesis by abrasion of sand-sized particles in the Sinai–Negev erg.

6. Conclusions

Based on our studies of the Sinai–Negev erg sands and potential source sediments, we reach the following conclusions:

(1) Mineralogical and geochemical data indicate that the primary source of sand in the Sinai–Negev erg is the Nile Delta. Aeolian sand of the Sinai–Negev erg has long been inferred to be derived from this source, but previous studies have been largely hypothetical. Our examination of dated cores from the delta shows that there are thick deposits of well-sorted sand, dating to the Last Glacial period, that are quartz rich, as are the dunes in the Sinai–Negev erg. A minor source is sand from the large Wadi El Arish drainage system in central and northern Sinai. This drainage basin is situated in carbonate-rock terrain and likely contributes calcite particles that are found in some Sinai dunes and dunes in the southern incursion corridor of the Negev.

(2) Sea level exerts a major influence on dune supplies in the Sinai–Negev erg through its role as a control on base level for the Nile. Stratigraphic studies show that during the Last Glacial period, when dune incursions in the Sinai–Negev erg began, what is now the Nile Delta area was characterized by a broad, sandy, minimally vegetated plain with seasonally dry, braided or anastomosing channels. Such conditions were ideal for providing a ready source of sand for aeolian transport under what were probably much stronger glacial-age winds. With the post-glacial rise in sea level, the Nile began to aggrade and sedimentation was dominated by fine-grained silts and clays, as documented in the stratigraphic record of the delta and in Mediterranean cores. Thus, sea level emerges as a major influence on the timing of dune activity in the Sinai–Negev erg, through its control on the supply of sand from the Nile Delta.

(3) Recent studies proposing that the Sinai–Negev erg is a partial source of loess in Israel are supported by our studies. The proposed mechanism is abrasional reduction of aeolian sand, primarily quartz, to silt sizes, with transport downwind from the Sinai–Negev erg. Under this scenario, minerals less resistant to abrasion, feldspars and calcite, should be relatively enriched in the downwind loess compared to the upwind dunefield. Our mineralogical data for the Sinai–Negev erg,

when compared to Israeli loess, support this mechanism, although clays in Israeli loess are likely derived from distant sources by long-range transport.

Acknowledgments

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