Late Quaternary weathering, erosion, and deposition in Nahal Yael, Israel: An "impact of climatic change on an arid watershed"[1]?

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ABSTRACT

In their seminal paper in 1979, Bull and Schick proposed a conceptual model for the geomorphic response to Pleistocene to Holocene climate change, based on the hyperarid Nahal Yael watershed in the southern Negev Desert. In this model, the change from semiarid late Pleistocene to hyperarid early Holocene climates reduced vegetation cover, increased the yield of sediment from slopes, and accelerated aggradation of terraces and alluvial fans. The model is now over 30 yr old, and during this time, chronologic, paleoenvironmental, and hydrogeomorphic research has advanced. Here, we reevaluate the model using data acquired in Nahal Yael over the 30 yr since the original model was proposed. Recent studies indicate that the late Pleistocene climate was hyperarid, and a transition from semiarid to hyperarid climates did not occur. The revised chronology reveals a major 35–20 ka episode of accelerated late Pleistocene sediment production on slopes (with lower rates probably already at ca. 50 ka) due to increased frequency of wetting-drying cycles caused by frequent extreme storms and floods between 35 and 27 ka. Without lag time, these sediments were transported and aggraded in depositional landscape components (fluvial terraces and alluvial fans). This intensified sediment production and delivery phase is unrelated to the Pleistocene-Holocene transition. The depositional landforms were rapidly incised between 20 and 18 ka. Since and/or soon after this Last Glacial Maximum (LGM) incision, most material leaving the basin originated from sediments stored in depositional landforms and was not produced from bedrock.

Using these new data, we propose a revision to the Bull and Schick model in this hyperarid environment. Our revision suggests that the model should include the frequent storms and floods responsible for a late Pleistocene pulse of intense weathering due to numerous cycles of wetting and drying on slopes and coeval sediment transport to fluvial terraces and alluvial fans. We also discuss the common use and pitfalls of using the Bull and Schick conceptual model to explain observations in diverse arid environments, usually without sufficient data on basin-specific stratigraphic, chronologic, paleoenvironmental, and paleoclimatic information.

INTRODUCTION

Bull and Schick (1979) and later Bull (1991) presented a conceptual model of dryland geomorphic dynamics, sediment production, and sediment delivery from talus slopes to aggrading terraces and alluvial fans. This model was driven by what they thought to be a pronounced change in climate across the Pleistocene to Holocene transition, based on contemporaneous understanding. Their model was probably originally based on observations made by Bull in drainage basins in the arid southwestern United States. There, an increased sediment flux was related to a documented climate change across the Pleistocene to Holocene transition (e.g., Bull, 1991). The first journal publication on the subject (Bull and Schick, 1979) focused on Nahal Yael, a small, well-documented catchment in southern Negev, Israel, that is currently hyperarid (Fig. 1). Their proposed geomorphic response model (Fig. 2, modified after Bull, 1991) shows a chain of processes (rainfall, infiltration, deposition, degradation, and aggradation) triggered by an assumed Pleistocene-Holocene climate change. These changes and the resultant processes/responses were presumed to affect diverse parts of the landscape (hillslopes, talus-colluvium, vegetation, terraces, and alluvial fans) in different ways.

Bull and Schick's conceptual model has been influential. It has fueled discussions on climate change and its geomorphic effects during the late Quaternary. For example, the conceptual model has been widely applied to interpret the climatic impact on alluvial-fan deposition in a wide range of drainage basins in the arid and semiarid (50–250 mm yr^{-1}) southwestern United States. Some published research (Wells et al., 1987; Smith, 1994; Reheis et al., 1996; Harvey et al., 1999; Pederson et al., 2000; Ritter et al., 2000; Harvey, 2002; McDonald et al., 2003; Pazzaglia, 2004; Etheredge et al., 2004; Anders et al., 2005; Nichols et al., 2005; DeLong et al., 2008; Spelz et al., 2008; Miller et al., 2010) supports the proposed model with some modifications or simply applies it in order to extend a spatially limited alluvial-fan chronology to the entire drainage basin. Other research points to regional, in-phase (e.g., McDonald et al., 2003) alluvial-fan aggradation in different parts of southwestern North America. Nevertheless, in some areas in the western United States, fan aggradation is out of phase (e.g., DeLong et al., 2008). Only a few of these studies (e.g., Anders et al., 2005) have reported sufficiently detailed stratigraphy and enough ages of depositional landforms, beyond the alluvial-fan environment,

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[1]The title of the seminal paper by Bull and Schick (1979), whose steps we followed to Nahal Yael.

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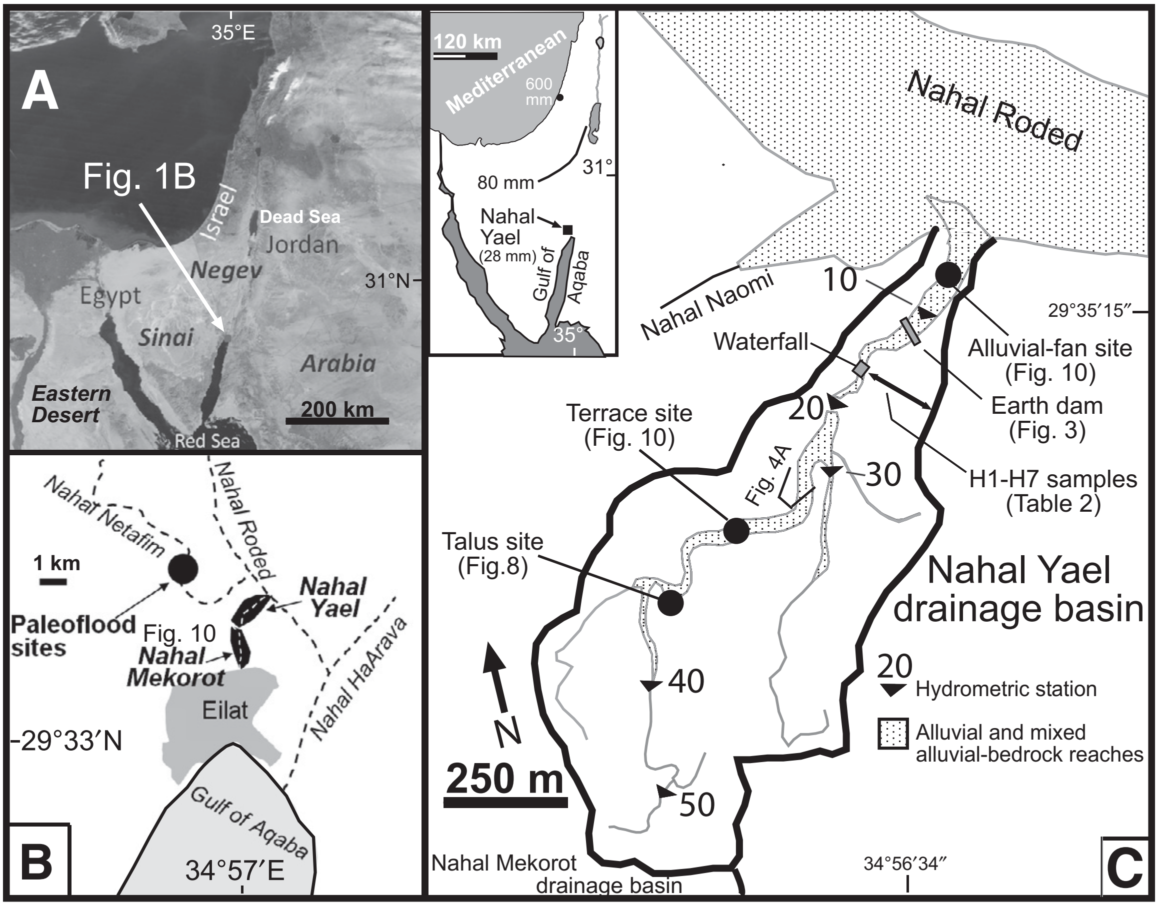

Figure 1. Location of the Nahal Yael drainage basin in the hyperarid southern Negev Desert near the tip of the Gulf of Aqaba and the Red Sea. Specific field sites in Nahal Yael, Nahal Mekorot, and Nahal Netafim are shown in Figures 1B and 1C. Note the gradient in rainfall from central Israel to Nahal Yael with the estimated location of the 80 mm yr^{-1} isohyet.

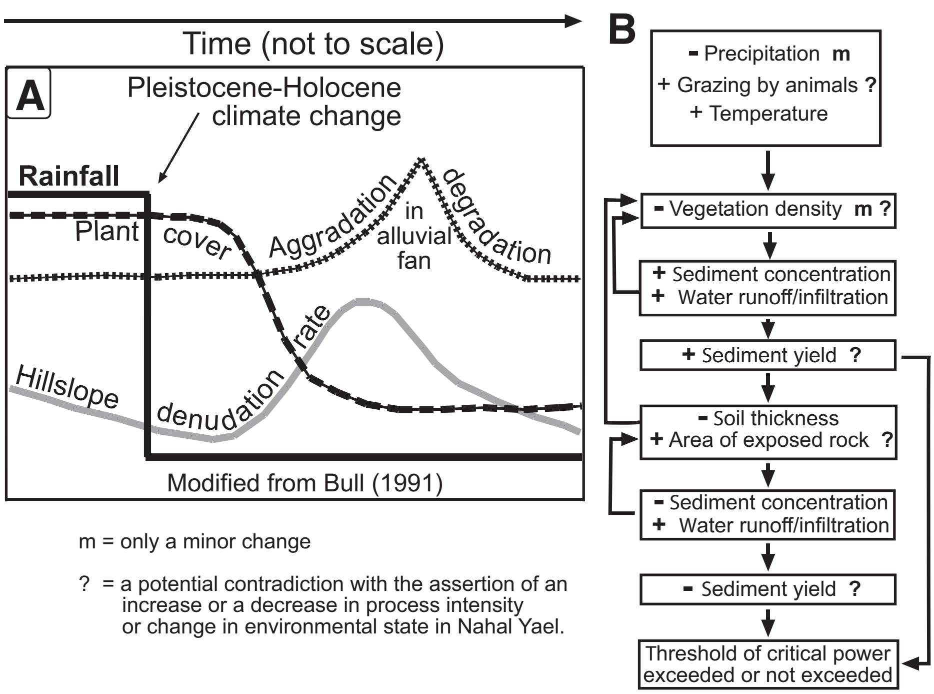

Figure 2. The conceptual models of drainage basin response to wetter to drier climate change as proposed by Bull and Schick (1979) for the late Pleistocene to early Holocene transition. Both figures are modified from Bull (1991). The following are additions based on current knowledge from and understanding of Nahal Yael discussed in this study: m = only a minor change was detected, if at all; ? = existing evidence does not support an increase or a decrease in the process intensity or the environmental state.

to support or challenge the proposed geomorphic-response model.

More than three decades after it was first published, the conceptual model, basically unchanged, is still widely used. Occasionally, however, studies in arid lands have questioned the causes, specific climatic conditions, lag times, synchroneity, rates, and spatial scales of responses of landscape components to climatic perturbation (e.g., Ritter et al., 2000; Etheredge et al., 2004; Miller et al., 2010; DeLong et al., 2008). In the past decade, other studies have explicitly discussed the controls on geomorphic responses and alluvial-fan deposition in arid regions exerted by vegetation (e.g., Ritter et al., 2000), lithology (Etheredge et al., 2004), storm type and/or seasonality (e.g., Etheredge et al., 2004; Miller et al., 2010), and regional climate (DeLong et al., 2008). Here, we emphasize the long-term effects of episodic sediment production and sediment storage on arid drainage basin evolution and consider the Bull and Schick model in the context of a basin-scale sediment budget.

At the core of the proposed conceptual model, as applied to Nahal Yael, there are inferences about: (1) lithologic control on sediment production and sediment delivery from hillslopes (see also Bull, 1991, chapter 3; Clapp et al., 2000), (2) pedogenic characteristics of soils developed on taluses, terraces, and alluvial-fan surfaces, (3) animal trails as indicators of increased past grazing, and increased vegetation cover for feeding the grazers, and (4) past climate changes in the deserts of the Near East. The model relies on a delicate interplay between the timing and effects of climate change. However, little or no independent chronological control was available to Bull and Schick (1979) when they conducted their work in the mid-1970s and even a decade later (Bull, 1991, chapter 3). Therefore, the chronology underlying the Bull and Schick model is based only on relative ages of alluvial-fan surfaces and the degree of soil development; there were few reliable, independent ages available for desert landforms and sediment in the 1970s. Recent research, numerical chronologies developed in the southern Negev in general, and in the Nahal Yael watershed in particular, and a better understanding of paleoclimate allow us to test and refine the conceptual model of Bull and Schick.

Here, we critically evaluate observations made by Bull and Schick (1979) in Nahal Yael by using results of research conducted in that drainage basin and its vicinity since 1979. Then, we (1) evaluate the conceptual model as it was applied in Nahal Yael in the framework of these data, (2) point to major disagreements between the model and new observations, and (3) discuss the general use of the conceptual model in lieu of collecting systematic data, particularly chronologic data, at a time when such methods have become widely available. We support the principles proposed by Bull and Schick (1979), but we object to the ways in which these principles are applied elsewhere without considering site-specific differences in climate history and hydrogeomorphic responses reflected in depositional landforms.

The geomorphic and chronologic details now available for Nahal Yael are available for few if any other arid drainage basins. Specifically, recent studies of soils and sediment in the southern Negev Desert and chronologies of alluvial surfaces (e.g., Amit et al., 1993, 2006, 2007, 2011; Porat et al., 1996, 1997, 2009, 2010; Matmon et al., 2009) support prevailing hyperarid conditions for most of the Quaternary, at least since the middle Pleistocene. If the southern Negev has remained hyperarid during the late Pleistocene, then what force is changing the geomorphic response of Nahal Yael? What drove the changes that motivated the Bull and Schick model?

In this study, we use stratigraphy, pedogenic development, oxygen and carbon isotopic composition of pedogenic carbonates, and chronological, weathering and erosion, and paleoclimatological data that have been gathered for Nahal Yael, and we integrate them with data from the surrounding region. Such an update has implications for not only the late Quaternary depositional history of Nahal Yael, but also the use of the Bull and Schick model elsewhere in hyperarid and arid regions. We view this research as a contribution to the ongoing discussions on geomorphic responses to climatic impacts through the production, storage, and delivery of sediment, and alluvial-fan formation everywhere (e.g., Wells et al., 1987; Harvey et al., 1999; Harvey, 2002; Anders et al., 2005; Eppes and McFadden, 2008; Miller et al., 2010).

LOCATION, FIELD SETTINGS, AND CURRENT HYDROCLIMATOLOGY

Nahal Yael is a small (~0.5 km^2), hyperarid (~28 mm yr^{-1}), hyperthermic (mean annual temperature ~25 °C) instrumented watershed located in the southern Negev Desert (Fig. 1), where temperatures are recorded as high as 50 °C in summer and as low as 5 °C in winter. The potential evaporation measured at Nahal Yael is ~2800 mm yr^{-1} (Bar-Lavee, 1976). This instrumented watershed was established in 1965 as a pioneering, long-term, basin-scale research site for field measurement of geomorphic processes to better understand the climatology, hydrology, geomorphology, and ecohydrology of hyperarid environments (Schick, 2000). Instrumentation, field campaigns, and other studies have monitored some Nahal Yael hydrogeomorphic processes continuously (e.g., rainfall, runoff, and sediments), and other processes episodically. These efforts include measurements of rainfall and runoff (e.g., Fig. 1C; Schick, 1968, 1970; Sharon, 1970; Yair and Klein, 1973; Greenbaum, 1986), flood generation (e.g., Bahat et al., 2009), transmission losses (Schwartz, 1986), short- and long-term sediment transport and delivery (e.g., Schick, 1977; Lekach and Schick, 1982, 1983, 1995; Schick et al., 1987; Lekach et al., 1992; Clapp et al., 2000), soil formation (Amit et al., 1993, 2006), and activity of the channel bed (Lekach et al., 1998; Amit et al., 2007). BenDavid-Novak and Schick (1997) also studied the response of the sparse Acacia trees to the diminished flows in the channels of the alluvial fan induced by the construction in 1977 of an earthen dam and a reservoir (Fig. 3), which were constructed to store and measure all sediment yield from the basin (Schick and Lekach, 1993). A few of the hydrometric stations in the basin are marked on Figure 1.

The catchment is situated in the Eilat Massif of the Arabian Shield, and it consists of exposed Precambrian rocks (pelitic schists, amphibolites, and the coarse-grained, jointed, and sheared Eilat Granite; Shimron, 1974). Abundant dike swarms are exposed in the basin (Fig. 3). The rocky catchment of Nahal Yael has 160 m of relief; when compared with other arid watersheds, it is a small headwater tributary basin in terms of Anders et al. (2005). The slopes are rugged and steep, often >25°, devoid of vegetation, and in places thinly covered by colluvium (Fig. 4). Field-based drainage density is relatively high, with ~100 first-order channels combining into the fourth-order main channel flanked discontinuously by depositional and strath terraces. Originally, the straths were thought to be of Holocene age (Bull and Schick, 1979).

Channel width is ~3 m downstream of hydrometric station 04 (Fig. 1B), widening downstream, and then narrowing again in the reach between hydrometric station 02 to the waterfall as it cuts through and exposes relatively unweathered Eilat Granite (Fig. 1B; see GSA Data Repository[2]). The channel is relatively steep, with gradients of 2%–5% (1.15°–3°), with mixed braided alluvial and bedrock reaches

[2]GSA Data Repository item 2012070, Earlier published luminescence ages, photograph of sampling sites near the waterfall related to weathering indices (Table 2 in text) and cosmogenic radionuclide results from these sites, is available at http://www.geosociety.org/pubs/ft2012.htm or by request to editing@geosociety.org.

Figure 3. The earth dam and reservoir constructed in 1977 to accumulate all suspended and bed-load sediments before storm flows exited the basin. All the earth material is from downstream of dam (i.e., without digging in the reservoir area). For scale: the gauge station (circled in black) is ~3.5 m tall. The apex of the late Pleistocene alluvial fan of Nahal Yael is seen with desert pavement surface just ~100 m downstream of the reservoir before the confluence with Nahal Roded (Fig. 1C)

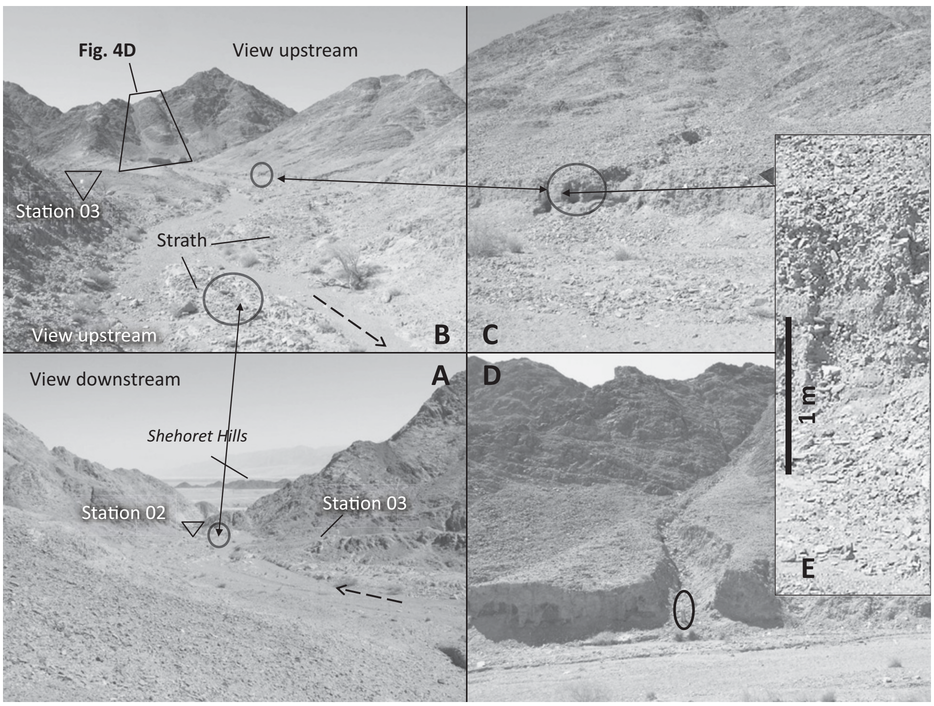

Figure 4. View downstream (A) and upstream (B) of Nahal Yael channel and slopes. Note the gullies incising colluvium and high-gradient debris fans and their interaction with and sediment supply to the main channel (4C and 4E). Location of Figure 4A is marked in Fig. 1C. Note the location of hydrometric stations 2 and 3 and the person for scale in 4D.

(Fig. 4) and many remnants of ~2-m-high fluvial terraces. Nahal Yael ends in an active alluvial-fan upstream of its confluence with Nahal Roded (Figs. 1, 3, and 5).

Present-Day Rainstorms in the Southern Negev

In arid drainage basins, underlying questions include the following. How do rainstorms and synoptic-scale climatology affect sediment transport? What weather and climate states are responsible for the formation of the depositional landforms? Currently, three synoptic-scale climatic systems may influence sediment transport in the Nahal Yael area. These climatic systems set the high temporal and spatial variability of rainfall distribution and intensities in the Eilat area and in the southern Negev in general: (1) the Active Red Sea Trough, (2) Mediterranean frontal cyclones, and (3) tropical plumes from the Intertropical Convergence Zone (ITCZ) across northeast Africa (e.g., Schick, 1988; Greenbaum et al., 1998; Dayan et al., 2001; Kahana et al., 2002; Rubin et al., 2007).

Although there is pronounced spatial rainfall variability during storms that is caused by the size of convective cells (typically ~5 km in diameter; Sharon, 1972), the mean annual precipitation is regionally similar. These convective rain cells typically occur for a few individual days between October and May (e.g., Barzilay et al., 1999), and the mean annual precipitation in the region is 25–31 mm (e.g., Sharon, 1970; Schick and Lekach, 1993; Amit et al., 2010), with a recent series of years almost without rainfall. For example, Nahal Yael has experienced annual rainfall totals as low as <1 mm and an individual, 1- to 2-day-long storm with >60 mm in February 1975. This storm produced the entire 1975 annual rainfall in a single event; the frequency of such high daily rainfall amounts is relatively low (estimated annual probability is between 1% and 2%), but the associated hourly intensities of that rare storm are not as high as the storm duration is relatively long (12–36 h). The recorded intensities in the region, for intervals of minutes, are relatively high, with 25% of the rain falling with intensity >60 mm h^{-1} (Barzilay et al., 1999) and ~50% at intensities >14 mm h^{-1} (Greenbaum, 1986; Schick, 1988).

Relatively large amounts of storm rainfall are associated with rare winter tropical moisture plumes from the ITCZ across North Africa (Dayan and Abramski, 1983; Zangvil and Isakson, 1995; Ziv, 2001; Rubin et al., 2007). For example, the February 1975 and the January 2010 storms resulted from such tropical plumes (Dayan and Abramski, 1983; U. Dayan, 2010,

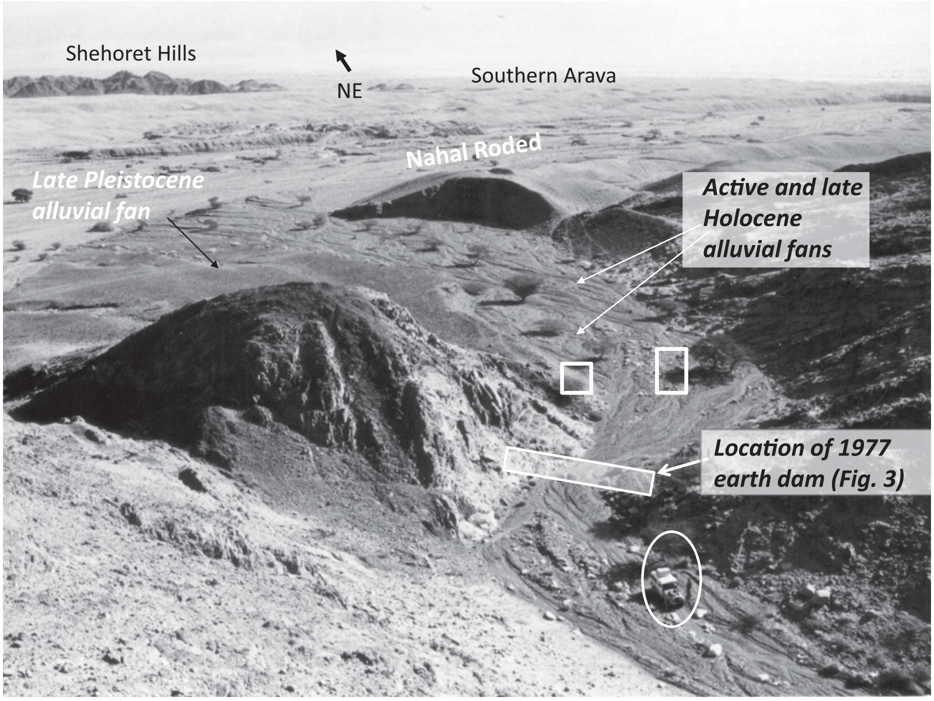

Figure 5. Lower reaches of Nahal Yael, its alluvial fan, and confluence with Nahal Roded in 1975 (pre–dam construction). View is to the NE. Marked are locations of (1) the 1977 earth dam and (2) the sites of trenches (squares), which are the basis for Figure 10. Note a vehicle and a person next to it for scale (white oval). Photograph by Ran Gerson.

oral and written commun.). In contrast with the localized intense, short-duration (up to a few hours, but usually much shorter) convective storms associated with the active Red Sea Trough, the rainfall associated with tropical plumes and Eastern Mediterranean low pressure systems can last 12–24 h. Rainstorms associated with tropical plumes are assisted by an intense southwesterly subtropical jet (e.g., Kahana et al., 2002; Rubin et al., 2007).

In Nahal Yael, the hydrological response to these rainstorms results in half of the natural flows becoming discontinuous downstream and terminating within the drainage basin, following high transmission losses along the alluvial reaches (Schwartz, 1986). Obviously, such floods do not export sediment from the basin. Flow passes hydrometric station 02 (Fig. 1) and reaches the waterfall a few meters downstream on average once every 2.5 yr (Schick, 1988). Recently, this average has dropped to only once every 3–5 yr, with a general reduction in mean number of flow events in Nahal Yael due to a general reduction of rainstorms in the southern Negev since 1999 (Shlomi and Ginat, 2009). The 1997 flood was the largest in the 50-yr-long flood record; this flow is the only one that filled the reservoir and overflowed its spillway (Fig. 3). A decade (1999–2009) of no flow ended on 18 January 2010 with a moderate-flow event past station 02, reaching the reservoir, following a tropical plume system.

PALEOCLIMATE OF THE SOUTHERN NEGEV

In building their conceptual model, Bull and Schick (1979) followed the then-contemporary interpretation (e.g., Neev and Emery, 1967; Begin et al., 1974; Horowitz, 1979) of wetter than present-day late Pleistocene climates in northern and central Israel, based on the high water levels in the Dead Sea Basin (Fig. 1). Horowitz (e.g., 1979) argued that a Mediterranean maquis ecosystem covered the entire Negev at that time. This ecosystem is usually composed of densely packed bushes, shrubs, and evergreen trees, with limited vegetative activity restricted to the winter moist season. Following this assertion, Bull and Schick (1979) advocated wetter or even much wetter late Pleistocene climates in the currently barren southern Negev. Wetter late Pleistocene conditions in the more northern areas in Israel were then deduced from shorelines (e.g., Bowman, 1971) and deposits associated with the late Pleistocene Lake Lisan (e.g., Neev and Emery, 1967; Kaufman, 1971; Begin et al., 1974). It was then a common practice to extrapolate this observation to areas farther south and deeper into the deserts of the southern Negev, Sinai, and Arabia (see Horowitz, 1979, 1992).

Bull and Schick (1979) were the first to caution against the simplistic extrapolation to the south of these wetter climatic conditions inferred in northern Israel. They added that, "An intriguing question is what were the magnitudes of the concurrent climate changes in [northern Israel and in] southern Israel and in Sinai" (Bull and Schick, 1979, p. 154). However, this is still the starting point of their conceptual model, as they needed an accepted scenario of climate change in the area that was independent of their geomorphic observations and interpretations. Therefore, they followed others and assumed that the Pleistocene-Holocene transition in the Eilat area was, respectively, a change from a wetter to a drier (and/or warmer) climate (Bull and Schick, 1979, p. 154). This assumption was also the basis of other studies, such as those by Gerson (1982) and Grossman and Gerson (1987), who analyzed hyperarid Negev Desert landforms. Bull and Schick (1979) emphasized that the time, type, or magnitude of this climate change could not be easily quantified.

The extrapolation to the south of the late Pleistocene wetter mean climate is likely not valid, especially in the scale of the proposed climate change. This extrapolation to the south was recently questioned (Amit et al., 2006; Enzel et al., 2008). Enzel et al. (2008) emphasized that maintaining the modern north-south steep precipitation gradient, with a contemporaneously wetter north but still hyperarid south, is likely a valid scenario for the late Pleistocene, considering the main drivers of regional rainfall in the southeastern Mediterranean and its neighboring deserts. The north could have been much wetter (i.e., double modern mean annual rainfall) and therefore was capable of generating large inflows to raise and then maintain the level of the late Pleistocene Lake Lisan by >200 m (e.g., Bartov et al., 2002, 2003; Bookman et al., 2006). In contrast, the southern Negev remained arid, and the Eilat area probably was hyperarid (Amit et al., 2006). It should be noted that if late Pleistocene annual rainfall amounts in the Eilat area were also doubled, as in northern Israel, the Eilat area would still have remained hyperarid (see fig. 5 *in* Enzel et al., 2008). Therefore, the evidence and inferences used by Bull and Schick (1979) to constrain the climate history of Nahal Yael require revision due to these new insights. In other words, what is the magnitude of change in climate? What aspect of the minimal (if at all) climate could have affected the geomorphology of Nahal Yael? When did it occur?

SOIL HORIZONS AND PAST VEGETATION COVER

Calcic versus Gypsic-Salic Soil Horizons in Stable Alluvial Surfaces

Facing the lack of any independent local indicator of past climates, Bull and Schick (1979) characterized the paleopedology of soils developed in Pleistocene alluvial terraces in the Dead Sea, Arava, Eilat, and coastal western Sinai areas. The main features they presented (e.g., in their table 1 and fig. 10), as indicators of environmental changes, are the calcic soil horizons (denoted by them as Bca, Cca, or here as Bk; table 1.1 of Birkeland, 1999). The importance of the presence of such Bk horizons on the relatively flat, abandoned alluvial fans and fluvial terraces of the southern Arava lies in the vegetation cover necessary to produce the pedogenic calcic soil horizons on these currently barren alluvial surfaces (e.g., Amit et al., 2006, 2010).

Such calcic soil horizons form primarily by the reprecipitation of carbonates dissolved in the upper soil horizons; their existence mandates downward leaching and a specific range of soil hydrological balance (e.g., McFadden and Tinsley, 1985; Mayer et al., 1988; Bull, 1991; Amundson, 2004). The dissolution of the carbonates is possible due to increasing soil pCO_2 respiration at the root zone in the near-surface environment. This increase in soil pCO_2 is essential for dissolving and subsequently depositing the calcic horizons farther down profile. Since Holocene alluvial surfaces in the area are devoid of any vegetation, the presence of calcic soil horizons in late Pleistocene alluvial deposits could indicate a dramatic change in past soil moisture conditions and the existence of an active root-zone environment on these surfaces for relatively long duration. That is, the calcic soil horizons indicate an environment capable of supporting vegetation-covered alluvial surfaces, even if such vegetation was sparse. Therefore, Bull and Schick (1979) inferred climatic conditions much wetter than the present.

In contrast to the assumptions of Bull and Schick in the 1970s, extensive research in the past 30 yr concerning the Aridisols of the Negev (Gerson et al., 1985; Amit and Gerson, 1986; Gerson and Amit, 1987; Amit and Yaalon, 1996; Amit et al., 1993, 1995, 1996, 2006, 2011) indicates that no Bk-soil horizons were formed in flat alluvial surfaces of this region since at least the middle Pleistocene (Amit et al., 2006) or even since the earliest Pleistocene (Amit et al., 2011). The Cca/Bca/Bk horizons reported earlier from stable alluvial surfaces are actually (1) By/Bmy soil horizons, i.e., gypsic-B horizons rather than calcic horizons (Fig. 6;

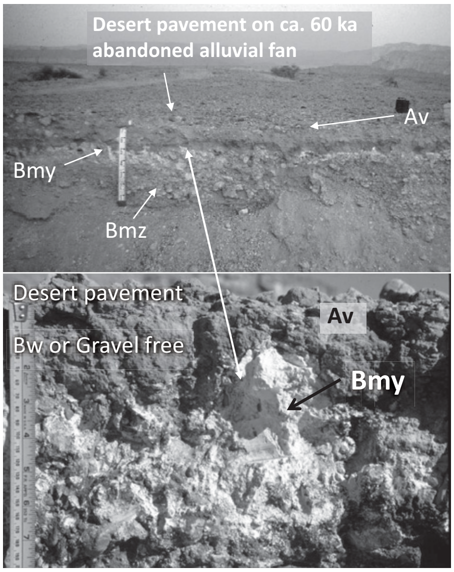

Figure 6. The gypsic (Bmy) and salic (Bmz) soil horizons developed in an abandoned ca. 60 ka Nahal Shehoret alluvial-fan surface with a well-developed desert pavement (details, location, and ages are in Amit et al., 1993; Porat et al., 1996; its location is just east of the Shehoret Hills in Fig. 5). No calcic horizons were developed in this hyperarid environment (see text).

e.g., Amit and Yaalon, 1996; Amit et al., 1993, 1995, 1996, 2006), and/or (2) fluvio-pedogenic units (discussed later herein). In the southern Negev alluvial surfaces, gypsic-soil horizons are always associated with deeper salic soil horizons (Bz or Cz horizon), which can further develop into a petrosalic (Bmz) horizon on late Pleistocene (ca. 60 ka) or older alluvial surfaces (Fig. 6; Amit et al., 1993, 2011; Amit and Yaalon, 1996). These horizons continue to accumulate salts under modern climatic conditions and on abandoned alluvial surfaces of all ages (Amit et al., 2006). Therefore, they potentially indicate only insignificant increases in annual rainfall during various episodes since the early Pleistocene (Amit et al., 2011). Our field observations indicate that the soil developed in the late Pleistocene alluvial fan of Nahal Yael presents only weakly developed gypsic and salic soil horizons; there is no carbonate accumulation, removing Bull and Schick's apparent need for vegetated surfaces (and thus a moister climate) during the later Pleistocene.

The spatial distribution of soil characteristics from the hyperarid southern Negev to the semiarid northern Negev presents a clear climatic-geographic threshold boundary: salic-gypsic soils in the southern and eastern Negev and calcic soils in the northern Negev (e.g., Amit et al., 2006, 2011). This boundary follows and is subparallel to the 80 mm isohyet (Fig. 1; Amit et al., 2006; and fig. 4 *in* Enzel et al., 2008). This isohyet is 2.5–3 times the modern mean annual rainfall in the Nahal Yael–Eilat area (25–30 mm yr^{-1}). Therefore, to shift the abandoned flat alluvial surfaces of the southern Negev into a calcic soil–forming phase, under current rainfall regime, episodes would need to be characterized by a mean annual rainfall approximately three times the modern mean. This probably has not occurred since at least the early Pleistocene, because progressively developed salic-gypsic soils characterize middle and late Pleistocene alluvial surfaces (Amit et al., 2006, 2011).

SECONDARY $CaCO_3$ ACCUMULATIONS IN NAHAL YAEL

Although no calcic soil horizons were identified in soils developed on middle to late Pleistocene stable alluvial surfaces of the southern Arava, we observed two types of surficial secondary carbonates in Nahal Yael and the region that warrant discussion in the framework of potential paleoenvironmental changes. The source of these carbonates in Nahal Yael drainage is most likely in eolian dust; the rocks exposed in the basin are magmatic and metamorphic, containing no calcite. These secondary carbonates were identified only in specific environments where additional local runoff contribution is possible. Therefore, they represent the hydrologically wettest niches in this generally hyperarid landscape. The first niche underlies the active channel, and it is termed the fluvio-pedogenic unit (Lekach et al., 1998; Amit et al., 2007). The second niche is located on talus slopes where water running off bare bedrock upslope is concentrated.

Fluvio-Pedogenic Units

Fluvio-pedogenic units were recognized first under active channel bed deposits, termed the fluvial-active unit layer, along the trunk stream of Nahal Yael (Fig. 7A; Lekach et al., 1998; Amit et al., 2007). They are located beneath the maximum depth to which modern and past floods scour (the active layer) and fill the alluvial bed, and they have pedo-features similar to those of desert soil (Amit et al., 2007; Lekach et al., 2008). Fluvio-pedogenic units are continuous, compact, and reddened, with an average depth of 50 cm for their upper contact and surficial gray, noncohesive active alluvium (Fig. 7A). Fluvio-pedogenic unit clay content is ~5%, which is more than twice that in the fluvial-active layer. These fluvio-pedogenic units are slightly cemented by $CaCO_3$, which has morphology typical of soil carbonate nodules and gravel coatings. Reddening is due to iron-oxide coatings formed in the vadose zone of a channel. The upper contact of the fluvio-pedogenic unit is abrupt (i.e., transition between fluvio-pedogenic unit and overlying fluvially active unit is up to 1 cm thick) and contains silts that form a thin, upper horizon; the reddish color diminishes gradually downward, forming a diffuse lower boundary.

The formation of these in-channel units is tied to the cumulative influence of persistent differences in water availability to various parts of the channel before, during, and after flood events (Lekach et al., 1998, 2008). The water left in the vadose zone of the channel bed after floods is estimated to be equivalent to an annual rainfall of ~300 mm (Amit et al., 2007). Ultimately, fluvio-pedogenic units are interpreted as a pseudosoil forming at the lower limit of the contemporary scour-and-fill processes, and its depth reflects the bed stirring capability of contemporary flows in the ephemeral channel (Lekach et al., 2008). Formation of these units requires relative stability of the channel bed elevation within a reach.

The secondary carbonate nodules deposited in the fluvio-pedogenic unit result from the long intervals between floods, limited sediment moisture content, and little to no involvement of soil pCO_2 respiration by vegetation (see details later herein). The isotopic analyses of secondary calcic crusts from the currently active channel fluvio-pedogenic unit and from the late Pleistocene paleo–fluvio-pedogenic unit in terraces indicate that extreme arid climatic conditions, very similar to today's conditions, prevailed during their formation. When paleo–fluvio-pedogenic units (Amit et al., 2007) are exposed in fluvial terraces, they can be easily mistaken for calcic, reddish buried soils.

Diffusive Calcic Nodules on Slopes

Sparse, weakly developed, diffuse calcic nodules are also recognized in the upper parts of the talus slopes (Figs. 8A and 8E). Unlike in wetter (100–300 mm yr^{-1}) environments in the northern Negev, where such nodules in talus are very common (e.g., Wieder et al., 1985; Kadmon et al., 1989), they are rare in the talus of Nahal Yael. When compared with the central and northern Negev, these diffuse, weakly developed nodules of the hyperarid southern Negev slopes probably indicate limited contributions of surface water running off of bedrock exposed above the top of talus (e.g., Yair and Lavee, 1985), along with very sparse vegetation cover (Fig. 8). Similar to the channel bed, these talus deposits represent a specific environmental niche where runoff from rainstorms occasionally allows surface water to concentrate and thus to increase soil moisture. The much lower frequency of secondary carbonate nodules in the Nahal Yael talus slopes than in the central and northern Negev slopes may indicate fewer runoff-contributing events (e.g., Yair et al., 1980; Yair and Lavee, 1985). This may be caused by the smaller number of rainstorms in Nahal Yael since the late Pleistocene incision into, and abandonment of, the surfaces of talus slopes.

Isotopic Composition of the Secondary Carbonates

The isotopic composition of the incipient secondary carbonates developed in the fluvio-pedogenic units of active channels and terraces and on the talus slopes can assist in (1) determining the validity of paleoenvironments of Nahal Yael assumed by the model of Bull and Schick (1979) and (2) in understanding of climate change in the region. The $\delta^{13}C$ compositions of the carbonate nodules from the talus slopes and channel indicate formation under very arid conditions.

Stable isotopic compositions ($\delta^{18}O$ and $\delta^{13}C$) were measured for 99 pedogenic carbonate nodules collected from active channels (fluvio-pedogenic units), terraces (fossil fluvio-pedogenic units), and talus slopes in Nahal Yael (Fig. 9). The $\delta^{13}C$ values of all these carbonate nodules range from 4.3‰ to –1.3‰. The $\delta^{18}O$ values of the same nodules have a much larger range, varying between 8.1‰ and –3.3‰. Carbonate nodules from the active channels (n = 59) are characterized by the lowest $\delta^{18}O$ and $\delta^{13}C$ values. Their $\delta^{18}O$ values vary between 2.3‰ and –3.3‰ (average –0.6‰), and $\delta^{13}C$ values range from 4.3‰ to –1.3‰ (average 1.1‰). Carbonate nodules from terrace fluvio-pedogenic units (n = 30) are characterized by higher $\delta^{18}O$ and $\delta^{13}C$ values. Their $\delta^{18}O$ values vary between 6.2‰ and 0.4‰ (average 2.0‰), and $\delta^{13}C$ values range from 3.3‰ to 1.6‰ (average 2.4‰). Carbonate nodules from the slopes (n = 10) are characterized by the highest $\delta^{18}O$ values, ranging between 8.1‰ and 4.1‰ (average 5.9‰), with slightly lower $\delta^{13}C$ values than those of the terraces, in a narrow range between 2.1‰ and 1.1‰ (average 1.6‰).

The $\delta^{18}O$ and $\delta^{13}C$ values measured on secondary carbonates from paleo–fluvio-pedogenic units in the terraces of Nahal Yael (average +2.4‰) are very similar to those measured for the soil carbonate samples from the hyperarid Namib Desert (average +2.8‰; Amit et al., 2010) (Fig. 9). Slightly lower $\delta^{13}C$ values (+1.6‰) coupled with very high $\delta^{18}O$ values (4.1‰–8.1‰; average 5.9‰) characterize the secondary carbonates from the slopes of Nahal Yael, which have very sparse vegetation cover. These high values are indicative of hyperarid conditions, signifying relatively low biologic activity and low respiration rates (e.g., Quade et al., 1989). For comparison, these $\delta^{18}O$ and $\delta^{13}C$ values are significantly higher than those measured on pedogenic carbonates from the northern Negev Desert, where calcic soils are common, and where $\delta^{13}C$ ranges between ~–11‰ and 0‰ (Magaritz and Heller, 1980; Magaritz et al., 1981). The $\delta^{13}C$ values of secondary carbonates from the terrace fluvio-pedogenic units and slopes of Nahal Yael are also similar to those obtained for the arid eastern Mojave Desert, Nevada, reaching +4‰ (Amundson et al., 1988; Quade et al., 1989), the earliest Pleistocene Paran plains (hyperarid southwestern Negev) (–0.4‰ to +2.5‰; Amit et al., 2007, 2011), and the hyperarid Atacama Desert in northern Chile (Quade et al., 2007). Indeed extreme $\delta^{13}C$ values from the Atacama Desert are up to +7.9‰; however, most are similar to values measured in samples from Nahal Yael (table 3 of Quade et al., 2007).

The high $\delta^{13}C$ values of Nahal Yael carbonates probably indicate significant contribution of atmospheric CO_2 during their formation and insignificant impact of vegetation. Rapid loss of CO_2 through advection of soil air is the most plausible explanation for the elevated $\delta^{13}C$ values (e.g., Quade et al., 2007) in extreme dry areas. Quade et al. (2007) suggested that respiration rates are the main predictor of the $\delta^{13}C$ value of soil carbonate in the Atacama Desert, whereas the fraction of C3-type to C4-type vegetation biomass at individual sites has a subordinate influence. They claimed that the high average $\delta^{13}C$ value (+4.1‰) of carbonate from the driest study sites indicates that it may have formed abiotically, in the presence of just atmospheric CO_2. We suggest that the $\delta^{13}C$ values obtained for the secondary carbonates from the slopes of Nahal Yael support minimal biotic involvement in their formation, with only a minor contribution from sparse annual plants that may sprout after rare rainstorms.

Despite frequent visits to Nahal Yael in the past 45 yr, with specific emphases on poststorm field campaigns, the only reported sprouting of annuals in this basin followed the heaviest storm on record on 20 February 1975 (65 mm in 12 h, over twice the mean annual rainfall). However, even following that storm, only north-facing slopes showed minimal to sparse sprouting (Bull and Schick, 1979, p. 168). The scarce calcic nodules and their isotopic composition are consistent with a low frequency of such storms during both the last glacial and current interglacial.

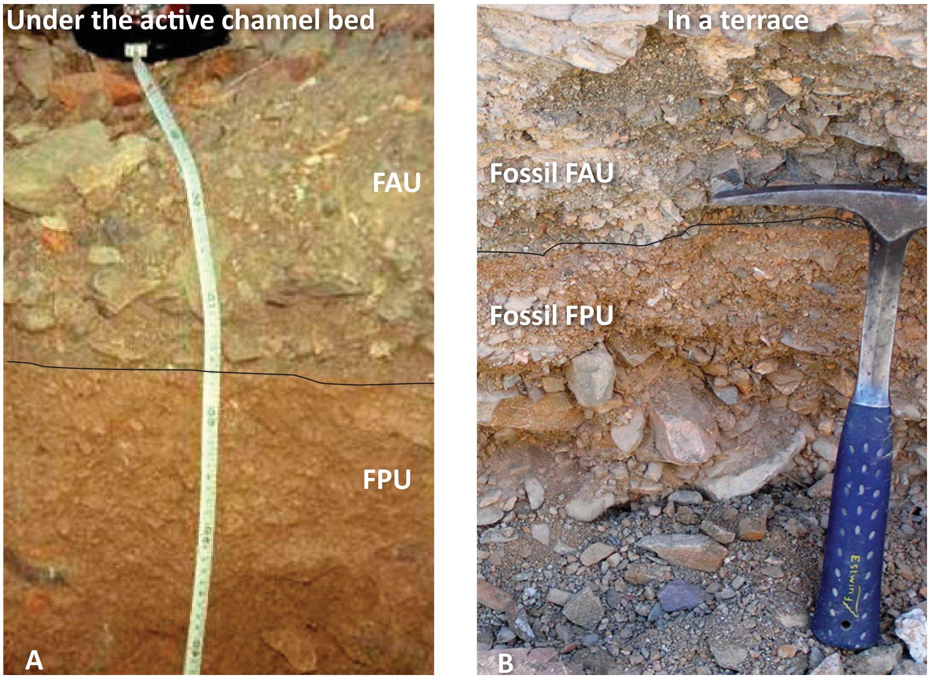

Figure 7. Examples of fluvio-pedogenic units (FPUs) that are marked by a reddish unit overlain by a grayish fluvial-active unit (FAU; Lekach et al., 1998, 2008; Amit et al., 2007): (A) under the currently active channel bed, and (B) a fossil fluvio-pedogenic unit–fluvial-active unit exposed in a Nahal Yael terrace.

The pedogenic carbonates from the active channels of Nahal Yael are characterized by the lowest δ^{13}C values and the lowest δ^{18}O values (Fig. 9). These values indicate that higher amounts of water are episodically present in the fluvio-pedogenic unit, leading to carbonate deposition in isotopic equilibrium with floodwater.

The δ^{18}O values are higher for secondary carbonate samples from Nahal Yael slopes than values obtained for active channels and the terraces, showing the effects of significant evaporation of soil water on slopes prior to carbonate formation. Our observations are in accord with other studies (e.g., Quade et al., 1989; Liu et al., 1996) in showing that evaporation, in addition to temperature and the δ^{18}O value of rainfall, likely influences the δ^{18}O value of soil carbonates in deserts. This pattern indicates that soils undergo significant dewatering by evaporation prior to soil-carbonate formation, as suggested by Quade et al. (2007) for the Atacama Desert. This pattern must be the result of extreme evaporation due to the hyperaridity of the Nahal Yael (current potential evaporation >2600 mm yr^{-1}), similar to conditions prevailing in the Namib Desert (Amit et al., 2010). These observations indicate that when these secondary carbonates formed, the southern Negev climatic conditions were far drier than the climate in the northern Negev and farther north.

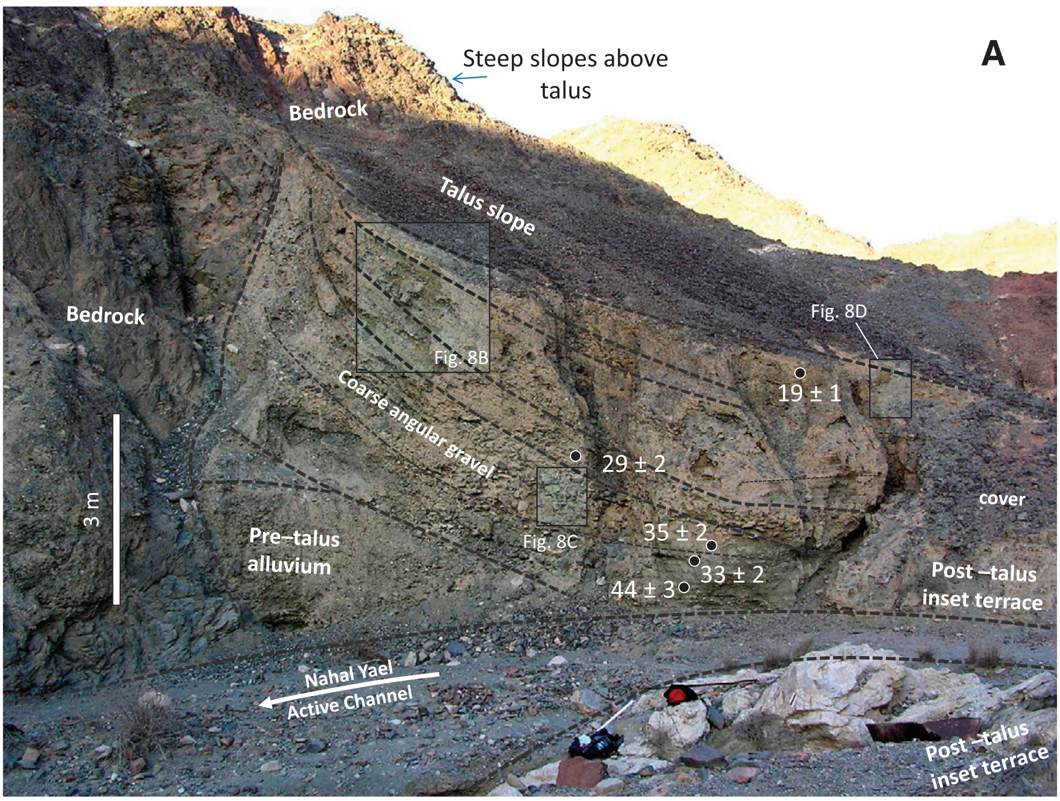

Figure 8 (*on this and following page*). (A) Stratigraphy and optically stimulated luminescence (OSL) ages in ka (see Table 1) of a talus in Nahal Yael. This talus is the same one that appears in figure 9 of Bull and Schick (1979).

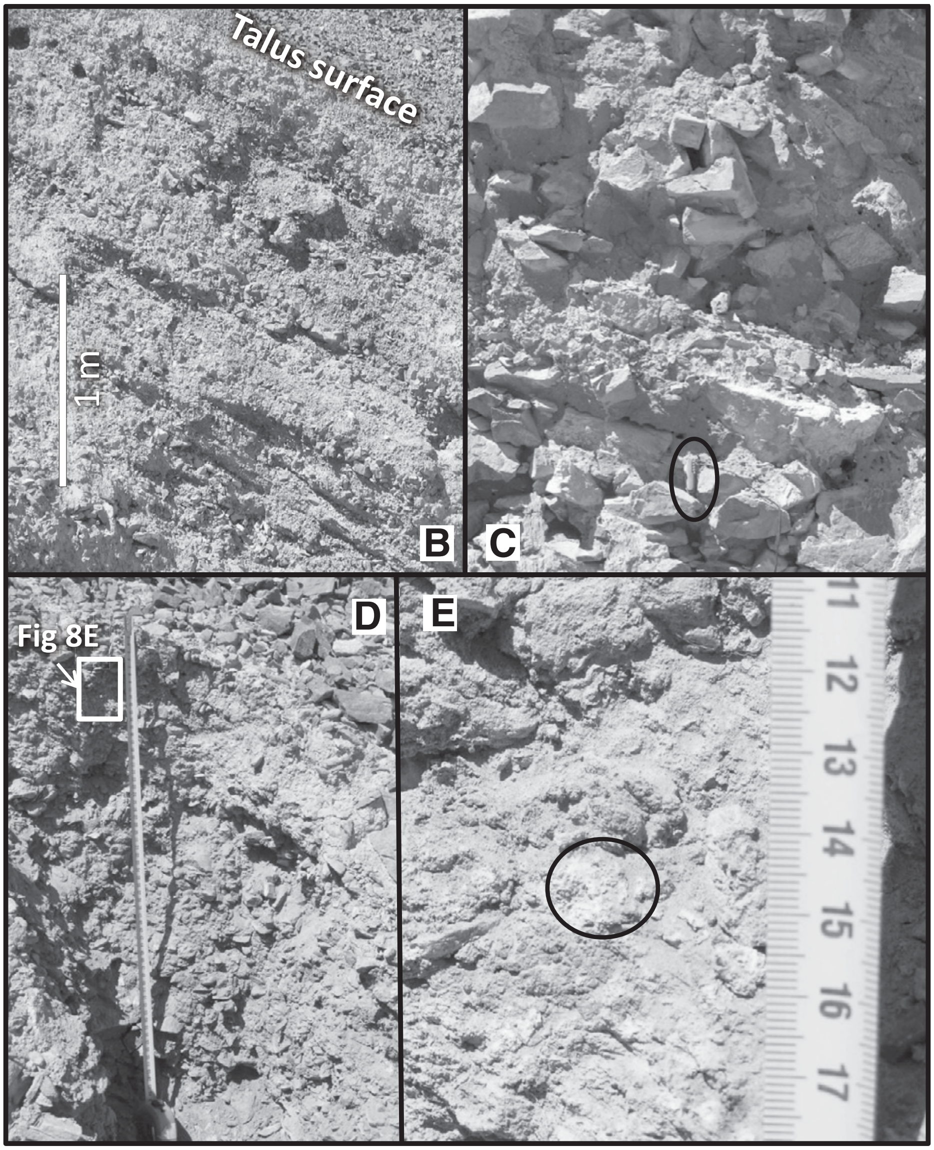

Figure 8 (*continued*). (B) Close-up photograph of the talus sediments composed of coarse, poorly sorted angular clasts with occasional mud-supported clasts alternating with better-bedded, poorly sorted clasts; both probably indicate debris-flow deposition. (C) The top part of the talus with relatively well-stratified talus deposits; sediments are usually finer than the rest of the talus. Note the pavement on talus surface. (D) As in B, but a close-up of the topmost deposits that show incorporation of later eolian dust into the talus surface; again, note the pavement surface. (E) Diffuse calcic nodule developed in the top of the talus sediments (location is marked in D). All specific locations are marked in A.

CHRONOLOGY OF TALUS, TERRACE, AND ALLUVIAL-FAN DEPOSITS

Ages for the depositional landforms of Nahal Yael were not available to Bull and Schick (1979). Such ages are still rare for terraces and taluses in arid drainage basins of the world. However, there is a large increase in chronologies of alluvial fans. New chronologic and stratigraphic data from Nahal Yael are now available and indicate that the depositional landforms mostly predate the Last Glacial Maximum.

An important observation in Nahal Yael is that soils that formed in the surfaces of the alluvial fan, terraces, and talus slopes of Nahal Yael since their abandonment are relatively well developed. Therefore, these surfaces were abandoned long ago. The characteristics of these soils and their degree of development are most similar to Aridisols developed in abandoned surfaces of alluvial fans and terraces in the southern Arava, which have independent ages >13,000 yr old (Amit et al., 1993, 1995, 1996, 2007). This soil-stratigraphy and short-distance correlation indicate that most of the Nahal Yael late Pleistocene surfaces were abandoned and at least partially incised already before 13 ka; i.e., the channel incised the Nahal Yael alluvial fan and its terrace earlier than 13 ka. Therefore, we suggest that the incision probably occurred immediately following the final depositional age of the terraces and alluvial fan ca. 20–18 ka. The causes for this incision are unknown, and therefore we can only suggest that they include reduction in sediment production and or supply; this reduction could have been associated with extreme floods. Base-level change is a less favored explanation here, as the alluvial fan and upstream terraces are separated by an ~10 m waterfall (location in Fig. 1; the oversteepened reach [Haviv et al., 2006] immediately above the waterfall lip is shown in GSA Data Repository [see footnote 2]).

Talus Deposits and Ages

Remnants of extensive talus deposits exist along Nahal Yael (e.g., Yair and Klein, 1973; Bull and Schick, 1979; Clapp et al., 2000). Characteristic of such landforms, the talus deposits thicken downslope; at their lower ends, they interfinger with fluvial deposits. Upslope, they thin, and bedrock is either fully exposed or covered by a thin, usually single-clast-thick layer. The talus is primarily characterized by coarse angular gravel, which moved downslope partially as dry material or at least without evidence of flows. However, other parts of talus are composed of poorly sorted, fine-grained, matrix-supported, coarse angular gravel (e.g., Fig. 8B) delivered by debris flows during the period of talus accumulation. Fine clasts characterize the upper parts of the talus deposits (Fig. 8C). The talus geometry and its contact with bedrock (Fig. 8A) indicate that the valley slopes were characterized by a higher percentage of exposed bedrock as well as a small terrace at the channel edge (Fig. 8A). The sedimentology and geometry of the talus deposits indicate a transition at the lower part of slopes from a weathering-limited to a transport-limited catchment. We suspect that the rate at which colluvium formed and moved downslope increased after 45 ka, allowing the talus to prograde into the channel of Nahal Yael (Fig. 8A).

We obtained five optically stimulated luminescence (OSL) ages (Table 1) from the thicker, lower parts of the talus deposits photographed by Bull and Schick (1979, p. 161). The chronology indicates that talus deposition began ca. 45 ka and that most of its thickness accreted

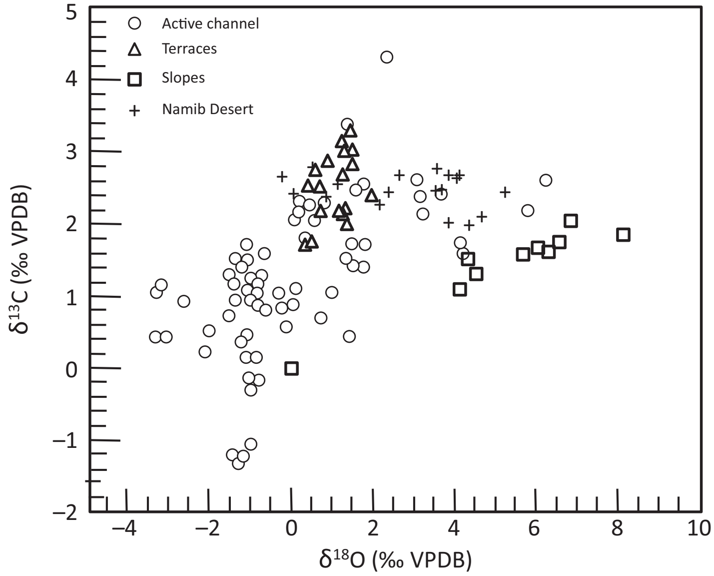

Figure 9. Isotopic composition of calcic nodules from Nahal Yael compared with calcic soil nodules in the hyperarid (10–20 mm yr^{-1}) Namib Desert. VPDB—Vienna Peedee belemnite.

between 35 and 20 ka (Fig. 8A). The OSL analyses are based on the very fine sand fraction (88–125 µm, mode ~100 µm) to avoid incorporating primary and/or secondary (i.e., redeposition of desert dust settling on slopes) eolian silt. For the youngest OSL age from the talus, ca. 19 ka (Table 1), this threshold in grain size was particularly important, because silty dust could have accumulated in the talus since the cessation of slope activity (Fig. 8D). On the basis of one OSL age (Fig. 8A; Table 1), the accretion of talus deposits probably began sometime during early marine isotope stage (MIS) 3 (ca. 44 ka). The two main debris-flow deposits observed within the talus are dated to 35 ± 2 ka and 29 ± 2 ka (Fig. 8A; Table 1). As these and other remnants of debris flows in the talus present erosional contacts (i.e., crosscutting relationships), the talus may have once contained more and/or thicker debris-flow deposits than those preserved now.

These talus deposits are indicative of frequent, high-intensity rainstorms of sufficient duration to deliver sediment downslope, a rare condition capable of generating debris flows on hyperarid slopes (e.g., Yair and Klein, 1973; BenDavid-Novak et al., 2004). These talus deposits are therefore indicative of increased storminess (in contrast with the potential for dry avalanches). In this regard, Greenbaum et al.'s (2006) documentation of an exceptional MIS 3 episode characterized by frequent, extremely large floods from 35 to 27 ka in the neighboring Nahal Netafim (paleoflood site in Fig. 1B) is probably most crucial for our Nahal Yael interpretation. In the region, large floods are most likely related to rare, extreme rainstorms (e.g., Kahana et al., 2002; Greenbaum et al., 2006). Such rainstorms in adjacent Nahal Netafim probably also flooded Nahal Yael.

Nahal Yael and Nahal Mekorot Terraces

Two terrace sites were dated, one in Nahal Yael and the other in Nahal Mekorot, an unofficial name for the small adjacent drainage basin with which Nahal Yael shares a drainage divide (Figs. 1B, 1C, and 10; GSA Data Repository [see footnote 2]). The ages of these terraces indicate an episode of aggradation at ca. 35–20 ka, involving sediment stripped from slopes in the two drainage basins. This age range overlaps and corresponds well to the main phase of talus aggradation and propagation into the Nahal Yael main channel. Considering the temporal resolution of the terrace and talus ages, we cannot detect a lag time or a delayed response between the deposition of the talus and the terraces.

Nahal Yael Alluvial Fan

The stratigraphy and OSL ages (Fig. 10) of the late Pleistocene and active alluvial fans of Nahal Yael indicate that (1) aggradation of the alluvial fan occurred before 28 ka and ended ca. 20 ka and (2) alluvial-fan abandonment (i.e., channel incision) occurred at or immediately after ca. 20 ka, because the soil developed in this alluvial-fan surface is similar to >13 ka soils in the nearby Nahal Shehoret (Fig. 5; Amit et al., 1993, 1995, 1996). Since then, an active channel bed has delivered sediments down valley. The deposits of the fluvio-pedogenic unit characterize the sediment underlying the channel bed and the apex of the alluvial fan (Fig. 2) and indicate that both aggradation on the alluvial fan and channel transport involved episodes of relatively stable channel levels needed for fluvio-pedogenic unit formation. It should be noted that terrace deposition in the drainage basins of both Nahal Mekorot and Nahal Yael ceased at the same time that alluvial-fan aggradation ceased (probably ca. 20–18 ka).

Sediments of the fluvio-pedogenic unit experienced numerous cycles of entrainment, exposure, and redeposition at the channel surface. Therefore, their ages probably indicate mean timing of fluvio-pedogenic unit activity and may support the previously assigned age of incision (20–18 ka). However, a few of the fluvio-pedogenic unit sediments may be more recently derived from terraces. From stratigraphy and

TABLE 1. OPTICALLY STIMULATED LUMINESCENCE (OSL) AGES FROM THE NAHAL YAEL TALUS DEPOSITS (SEE FIG. 8)

Lab no.	Depth (m)	K (%)	U (ppm)	Th (ppm)	Ext. α (µGy/yr)	Ext. β (µGy/yr)	Ext. γ (µGy/yr)	Cosmic (µGy/yr)	Total dose (µGy/yr)	Aliquots used	De (Gy)	Age (ka)
NYT-100	2.8	1.58	1.4	4.4	7	1392	1180		2580 ± 121	13/14	113 ± 5	44 ± 3
NYT-101	3.4	1.58	1.5	3.9	7	1393	1128		2528 ± 116	15/25	84 ± 2	33 ± 2
NYT-102	3.6	1.49	2.3	6.2	11	1491	1302		2804 ± 132	14/24	98 ± 5	35 ± 2
NYT-103	4.2	1.58	2.1	5.2	10	1503	1189		2702 ± 121	19/25	79 ± 2	29 ± 2
NYT-104	0.5	1.66	2.0	5.1	9	1543	862	210	2625 ± 120	16/25	49 ± 3	19 ± 1

Note: Gamma + cosmic dose rates were measured in the field using a portable gamma spectrometer, except for sample NYT-104, for which gamma dosing was calculated from the radioelements and the cosmic dose was estimated from burial depth. Grain size for all samples was 88–125 µm. Water contents are estimated at 1% ± 0.5%. Quartz was etched by concentrated HF for 40 min. De was obtained using the single aliquot regeneration (SAR) protocol, using preheats of 10 s at 220–260 °C. Aliquots used—the number of aliquots used for the average De out of the aliquots measured.

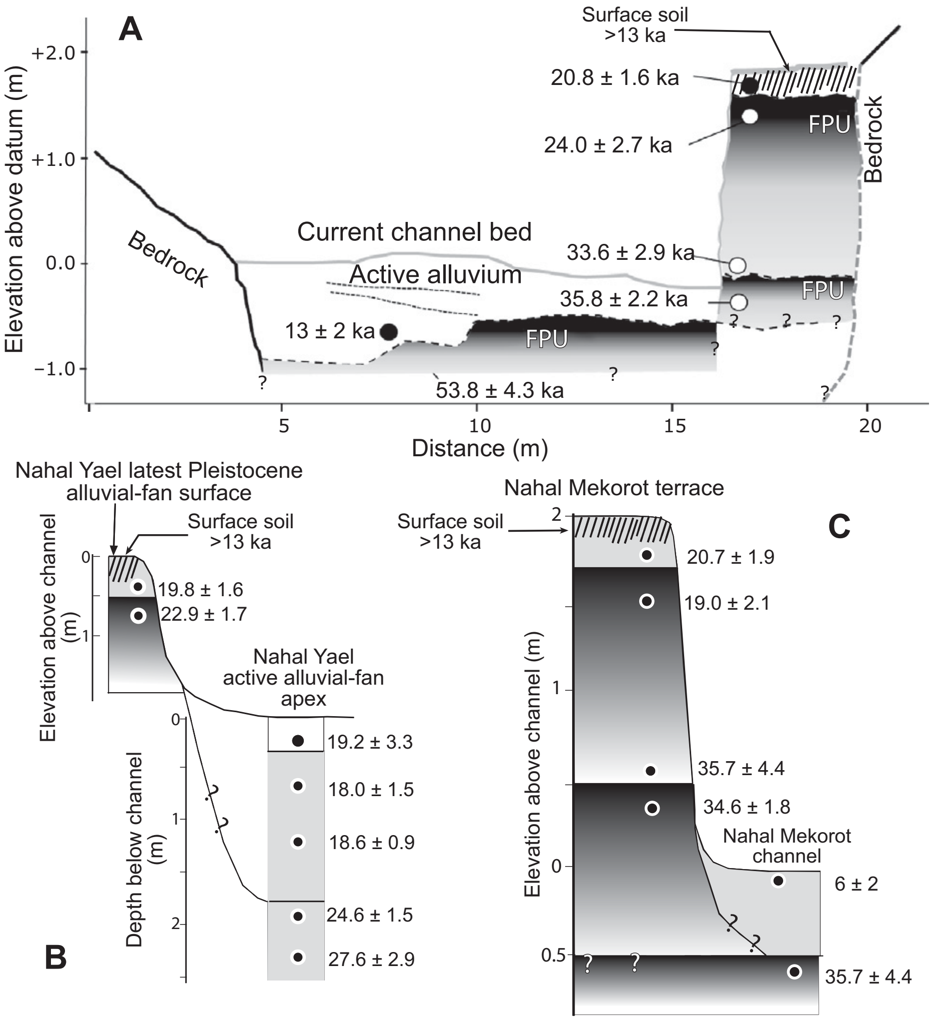

Figure 10. General stratigraphy and optically stimulated luminescence (OSL) ages in ka (GSA Data Repository [see footnote 2]; Amit et al., 2007) of terraces of Nahal Yael and Nahal Mekorot (A and B), indicating a major terrace accretion ca. 35–20 ka. Nahal Mekorot shares a water divide with Nahal Yael (Fig. 1). FPU—fluvio-pedogenic unit. (C) Stratigraphy at the apex of the alluvial fan of Nahal Yael, indicating alluvial-fan accretion >28 ka to ca. 19 ka, after which the alluvial fan incised. Please note the surface soils developed in the abandoned alluvial-fan and terrace surfaces; according to the southern Arava soil stratigraphy (i.e., mainly in Nahal Shehoret dated soils; see Fig. 5 for location of Shehoret Hills; e.g., Amit et al., 1993, 1996), such a degree of development requires >13,000 yrs.

ages (Fig. 10), we propose that the episode of incision was relatively short, at least when compared with the duration of aggradation.

Animal Trails

The relative abundance of animal trails on the slopes of Nahal Yael led Bull and Schick (1979, p. 167) to propose increased grazing by animals in the late Pleistocene but little grazing since then. They argued that this provided evidence of increased vegetation cover during the late Pleistocene; i.e., there was enough vegetation to support animals grazing on the slopes. This argument assumes that the surfaces of the slopes are fossilized as formed, and that there has been no downslope movement of sediments since the formation of trails.

Similar densities of animal trails are also distinct on the developed desert pavement of the Nahal Yael alluvial fan. It is estimated that in this part of the world, it takes more than 10–15 thousand years (e.g., Amit et al., 1995) to reach the observed degree of development of the desert pavement in the Nahal Yael alluvial fan. As the alluvial fan surface was abandoned at ca. 20–18 ka, this animal trails–desert pavement relationship probably indicates trail formation and maintenance also during the Holocene.

On slopes, without reactivations of the trails, downward movement of sediments would have erased or largely smoothed the trail morphology. We cannot estimate how active these trails are. However, their sometimes-fresh appearance may suggest occasional reactivation. Based on the soil and isotopic data, we propose that the region was hyperarid during pre–Last Glacial Maximum times, and the trails are much younger than the talus they cross.

Today, grazing animals are common only where they are protected on the nearby flat basin floor of the southern Arava; they are only rarely observed in the bordering watersheds (Parks and Reserves Authority, 2010, written commun.). In prehistoric times, following rare storms, grazers may have migrated occasionally to bordering drainage basins such as Nahal Yael. Hence, the trails may not represent a mean climate much different from the current climate, and they may be reactivated rarely.

SOURCES OF SEDIMENT TO NAHAL YAEL CHANNEL

Sediment production, source, and availability are central to the conceptual model of Bull and Schick (1979), and they are central to discussions of alluvial-fan deposition that rely on this model (e.g., Wells et al., 1987; Harvey et al., 1999; McDonald et al., 2003). In Nahal Yael, analyses of cosmogenic radionuclide activities (Clapp et al., 2000) and modern sediment yield measurements (e.g., Schick and Lekach, 1993) assist in estimating rates of erosion and sediment delivery at various time scales. These studies indicate that (1) current sediment yield exceeds sediment production, and (2) yield from Nahal Yael today is derived from sediment stored in the basin and not from current bedrock weathering (Clapp et al., 2000).

In agreement with the general views presented in Bull and Schick (1979) and Bull (1991), Clapp et al. (2000) suggested that sediment flushed from Nahal Yael is probably mined from colluvial and talus deposits. Gullies incised into colluvial deposits, and eroded toes of talus deposits are the main sources of sediment today (Clapp et al., 2000). Alluvial terraces serve only as secondary sources of sediment to the present-day channel (Clapp et al., 2000). This relative importance among sediment sources is supported by the large areal extents of remnants of colluvial deposits in contrast to linear, and usually narrower and thinner terraces. Furthermore, field observations indicate that toes of numerous colluvial deposits are eroded by and occasionally directly collapse into the active channel, and that large and small gullies heading at runoff-producing bedrock exposures incise slopes (e.g., Yair and Lavee, 1985). More importantly, Clapp et al. (2000) interpreted cosmogenic nuclide concentrations as showing that colluvium deposits mined today were probably produced during the late Pleistocene and possibly prior to the Last Glacial Maximum. The OSL ages obtained indicate that talus was deposited during the interval 45–19 ka, with the main episode of talus buildup at 35–19 ka (Fig. 8). These ages better constrain the timing of sediment generation on hillslopes above the talus, buildup of talus in the basin, and perhaps a time of enhanced bedrock weathering.

The question remains: Was a layer of clasts, thicker than the current single-clast layer, ever stored on the slopes? The high gradients (frequently >35°) of bedrock upslope of the talus deposits indicate that these steep slopes are unlikely to have stored very much sediment, as they are closer to transport rather than depositional slope angles in arid lands (e.g., Schumm and Chorley, 1966; Carson and Kirby, 1972). Therefore, we consider that production of slope sediment was/is likely continuous. When the talus was deposited, the adjacent steep slopes probably were not sediment-covered but were rather sediment producers.

Stratigraphic relationships between slopes and terraces along Nahal Yael indicate that sediment production on hillslopes during the late Pleistocene was so intense that talus deposits propagated into the narrow channels (Fig. 8) and directly interacted with aggrading terraces. These relationships indicate that hillslopes were active and delivered more sediment than the channels could transport. Thus, the channels were transformed from sediment-limited to transport-limited regimes during the period 35 to 19 ka. Even with the increased frequency of extreme flows inferred from the paleohydrologic studies of Greenbaum et al. (2006) in the nearby Nahal Netafim (Fig. 1), channels were still unable to transport all the supplied sediment out of the basin and aggraded relatively thick (2–3 m) terraces.

The lack of buried soils indicates that talus and terrace accumulations were not associated with pronounced depositional hiatuses. However, sedimentologic changes within individual talus and fluvio-pedogenic units within terrace stratigraphy (Lekach et al., 1998; Amit et al., 2007) indicate that sediment accumulation was not continuous. The presence of 2–3 fossil fluvio-pedogenic units in a terrace (e.g., Fig. 10C) suggests alternating modes of net aggradation and net transport at temporal scales of at least a few thousands of years based on the available chronologies (Lekach et al., 1998). In summary, terrace aggradation was episodic, and probably occurred as pulses of sediment moved down the main channel, perhaps in response to major but rare floods and storms.

Intensified Weathering in Nahal Yael

The rapid accretion of talus demands a large amount of sediment production and immediate or subsequent release from slopes in a relatively short time. This, in turn, requires increased rates of physical weathering to produce large amounts of coarse sediment quickly. In this section, we use available, partly unpublished information to gain insights on weathering and erosion in Nahal Yael and on the potential processes involved.

Chemical analyses suggest the rocks in the watershed (specifically, the more extensively studied Eilat Granite exposed in the lower one third of the watershed; Shimron, 1974) have experienced only slight chemical weathering (Table 2); this is consistent with the hyperarid environment in the region today and in the late Pleistocene. For example, the variation in several weathering indices between the freshest sample in the watershed, exposed at the waterfall, and the most weathered samples is less than 10% (indices are listed in Table 2; see also Price and Velbel, 2003).

Several studies published in the past few years proposed that Pb (and Sr) isotopes could be sensitive indicators for the degree of chemical weathering of granitoids (Erel et al., 1994, 2004; Harlavan et al., 1998, 2009; Harlavan and Erel, 2002). Those studies suggest that the age and the ratios of radioactive parent to daughter elements such as U/Pb and Th/Pb in minerals determine their $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{206}Pb/^{207}Pb$, and $^{208}Pb/^{204}Pb$ values. Therefore, the isotopic composition of Pb in the weathering products can be used to characterize the minerals that are weathering. For example, elevated $^{206}Pb/^{204}Pb$, $^{206}Pb/^{207}Pb$, and $^{207}Pb/^{204}Pb$ values in solution suggest that urogenic (U-enriched) minerals such as apatite are preferentially being weathered, and elevated $^{208}Pb/^{204}Pb$ values suggest that thorogenic minerals such as monazite weather preferentially. Because different minerals weather at different rates, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values in weathered granitoids and in the overlying soils change systematically with the degree of weathering.

In the Nahal Yael hyperarid environment, we measured Pb isotopic composition in samples having varying concentrations of in situ–produced ^{10}Be. The samples were collected in an upslope transect beginning at the main channel near the waterfall (see supplement data for exact sampling sites and measured ^{10}Be [see footnote 1]). The ^{10}Be concentrations serve as indicators of the duration of the sample residence near the surface; i.e., the higher the ^{10}Be concentration, the lower is the erosion rate and the longer the sample resided near the surface. Despite the low degree of chemical weathering of the major minerals (Table 2), $^{206}Pb/^{207}Pb$ values change systematically with ^{10}Be concentration, except for the freshest sample collected at the top of bedrock waterfall (Fig. 11; see Fig. 1C for sample locations), which is a fast-incising point along a bedrock knickpoint (Haviv et al., 2006). Moreover, the $^{206}Pb/^{207}Pb$ ratio becomes more radiogenic with exposure time (i.e., slower erosion rates), indicating that the weathering products, more prone to dissolution

TABLE 2. WEATHERING INDICES (SEE TEXT) OF EILAT GRANITE ROCKS EXPOSED IN NAHAL YAEL

Weathering indices	WIP*	V†	CIA§	CIW#	PIA**
Fresh rock (average)	86	1.6	48	56	47
H1 (average)	85	1.7	50	58	50
Average H1 (%)	99	106	104	104	106
H2 (average)	81	1.7	50	59	50
Average H2 (%)	94	108	104	104	105
H3 (average)	74	1.7	50	58	50
Average H3 (%)	86	106	105	103	107
H5 (average)	81	1.7	49	58	49
Average H5 (%)	95	106	102	103	104
H6 (average)	83	1.7	51	59	51
Average H6 (%)	97	108	106	105	108
H7 (average)	85	1.7	50	58	50
Average H7 (%)	98	107	104	104	106
Difference from fresh rock (minimum – maximum, %) ($N = 38$)	1–14	6–8	2–6	3–5	4–8

Note: Fresh rock—rock exposed at the Nahal Yael waterfall, estimated to be the freshest rock in the watershed. Sampling locations of H1–H7 are marked in Fig. 1. Average rock difference from fresh rock = 5.7%, σ = 3.7; H1–H7—Eilat Granite samples collected up the southern slope at the site of the waterfall. When compared with the fresh rock, the indices are presented in percent of fresh rock.

*WIP = $100 \times (2 \times Na_2O/0.35 + MgO/0.9 + 2 \times K_2O/0.25 + CaO/0.7)$ (fresh rock value >100; decreases with weathering).

†V = $(Al_2O_3 + K_2O)/(MgO + CaO + Na_2O)$ (fresh rock value <1; increases with weathering).

§CIA = $100 \times [Al_2O_3/(Al_2O_3 + K_2O + CaO + Na_2O)]$ (fresh rock value ≤50; increases with weathering).

#CIW = $100 \times [Al_2O_3/(Al_2O_3 + CaO + Na_2O)]$ (fresh rock value ≤50; increases with weathering).

**PIA = $100 \times (Al_2O_3 – K_2O)/(Al_2O_3 + CaO + Na_2O – K_2O)$ (fresh rock value ≤50; increases with weathering).

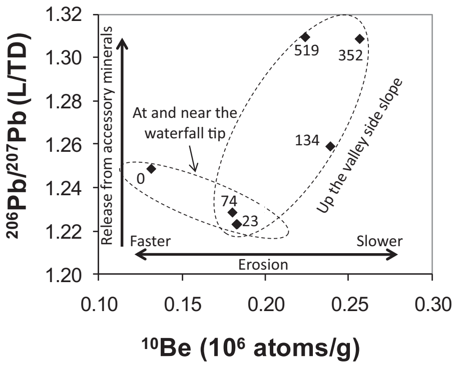

Figure 11. $^{206}Pb/^{207}Pb$ ratio of the 0.5 *M* HNO_3 leached samples (L) divided by the same ratio in the total digested residue of the leached samples (TD) plotted against in situ ^{10}Be concentrations, which represent here a proxy for near-surface residence time (erosion rate). Numbers next to markers are elevation (in cm) above the tip of the waterfall on the valley side slope. Note that the flows in the waterfall probably do not reach the 74 cm sample.

by weak soil acid, remained near the parent mineral. This trend is opposite to trends in temperate-climate soil chronosequences (Erel et al., 1994, 2004; Harlavan et al., 1998; Harlavan and Erel, 2002), where such products are removed quickly by water. The only samples that resemble those in temperate climates (i.e., fresher sample has a more radiogenic $^{206}Pb/^{207}Pb$ ratio in the labile fraction) are the two samples closest to the active bedrock channel (Fig. 11), where mobilization of radiogenic weathering products by intermittent stream flows, or under intermittently saturated in-channel alluvium, is plausible.

A Pulse of Sediment Production and Delivery

The bedrock-talus deposit relationship indicates that sediment once covered the slopes of Nahal Yael, the result of accelerated debris production, and that the talus preserved today accumulated as the result of increased downslope transport. Because the regolith that produced the large thick taluses could not have been stored on the steep slopes of Nahal Yael, we infer an episode of accelerated sediment production and delivery and term it a "sediment pulse." This pulse dramatically influenced Nahal Yael then, and it affects basin sedimentology and geomorphology even today, tens of thousands of years after it occurred.

Fundamental questions remain regarding intense physical weathering, the production of coarse sediment on Nahal Yael slopes, and the buildup of taluses: What are the processes that drive intensive weathering in this hyperarid basin and what were the environmental conditions that accelerated sediment production from bedrock during the late Pleistocene in comparison with the Holocene? So far, the answers to these questions remain elusive. We can only hypothesize on the basis of the available observations from the region and the literature on weathering.

Several environmental changes could increase weathering rates, including (1) lowered temperatures with more CO_2 dissolved in rain and groundwater, (2) increased rainfall, probably manifested as increased frequency/magnitude of rainstorms rather than a large increase in annual totals, and (3) wider cover of the bedrock by weathered clasts, thereby allowing the maintenance of infiltrating moisture for weeks rather than days at the bedrock–soil mantle contact. The third explanation is unlikely on the upper parts of talus slopes, because, as presented already, rates of chemical weathering are relatively low in Nahal Yael.

In our opinion, the main driver in debris production was the frequency of regional storms at 35–27 ka reported by Greenbaum et al. (2006). These storms could have increased the frequency of wetting-drying cycles on slopes in this arid environment. Such wetting-drying cycles together with the presence of salts in the water could have dramatically accelerated physical disintegration of the rocks as shown by experiments on the Eilat Granite (Anselmi et al., 2004).

Changes Needed in the Conceptual Model

The observations and chronologies from Nahal Yael (summarized in Fig. 12) indicate that Bull and Schick's conceptual model for geomorphic response to dryland climate change should be altered. Changes in the model for Nahal Yael include:

(1) Timing: Accelerated sediment production, delivery, and deposition in various landforms occurred within the late Pleistocene rather than following the Pleistocene-Holocene transition.

(2) Climate change: The proposed climate change from mean semiarid to mean arid or hyperarid at the Pleistocene-Holocene transition was probably not the driver of the pronounced geomorphic process change in Nahal Yael as proposed; a different explanation is required, one that maintains hyperaridity as the climate mean across that chronostratigraphic transition.

(3) Synchronous and connected deposition: All major depositional landform components were constructed after ca. 50 ka, with the main phase of deposition at 35–20 ka, in simultaneous well-connected sediment pulses (within chronological resolution). This is possible only through undisturbed connections in sediment delivery along the slopes and channel of Nahal Yael rather than the previously proposed chain of processes delivering sediment from storage in one depositional landform to the other following the Pleistocene-Holocene transition.

(4) Rapid sediment production: The sediment pulse in Nahal Yael was characterized by rapid and widespread production of angular coarse clasts on basin slopes, and sediment delivery quickly downstream triggered aggradation in the basin and simultaneous sediment export to the alluvial fan.

(5) Incision: If the ages of the fluvio-pedogenic units and the process they represent are valid, incision probably affected all the depositional landscape components within a short time interval at 20–18 ka, just after the Last Glacial Maximum. This is supported by soil-stratigraphy that indicates an abandonment of terrace and alluvial-fan surfaces and their incision before 13 ka. Following this incision of alluvial deposits, the channel returned to bedrock incision, a state probably characteristic of the drainage basin before the storm-induced weathering pulse.

(6) Present-day sediment yield: Sediments moving through the watershed are mainly the product of the 50–20 ka weathering pulse, and they are eroded from colluvium, terraces, and alluvial-fan deposits (in that order of importance; Clapp et al., 2000).

Earlier Applications of the Model

Harvey (2005) pointed out that there are very few systematic chronologies along the chain of depositional landscape components typically present in arid watersheds. Initial efforts at defining chronologies were limited by lack of suitable dating methods or materials suitable for existing dating methods. Furthermore, recent dating efforts (e.g., DeLong et al., 2008; Spelz et al., 2008) also have focused on the chronology of alluvial-fan deposition. Alluvial-fan chronologies have been used to infer sediment dynamics in the contributing drainage basins and have adopted climatic explanations based on existing regional knowledge. Here, we suggest a more direct approach to understanding basin behavior by establishing a chronology of the various depositional landforms in arid landscapes (see example by Anders et al., 2005). Better understanding of the timing of sediment production and its dynamics, as well as the timing of landform deposition in diverse regions may lead us to better understanding of geomorphic responses to changing climate.

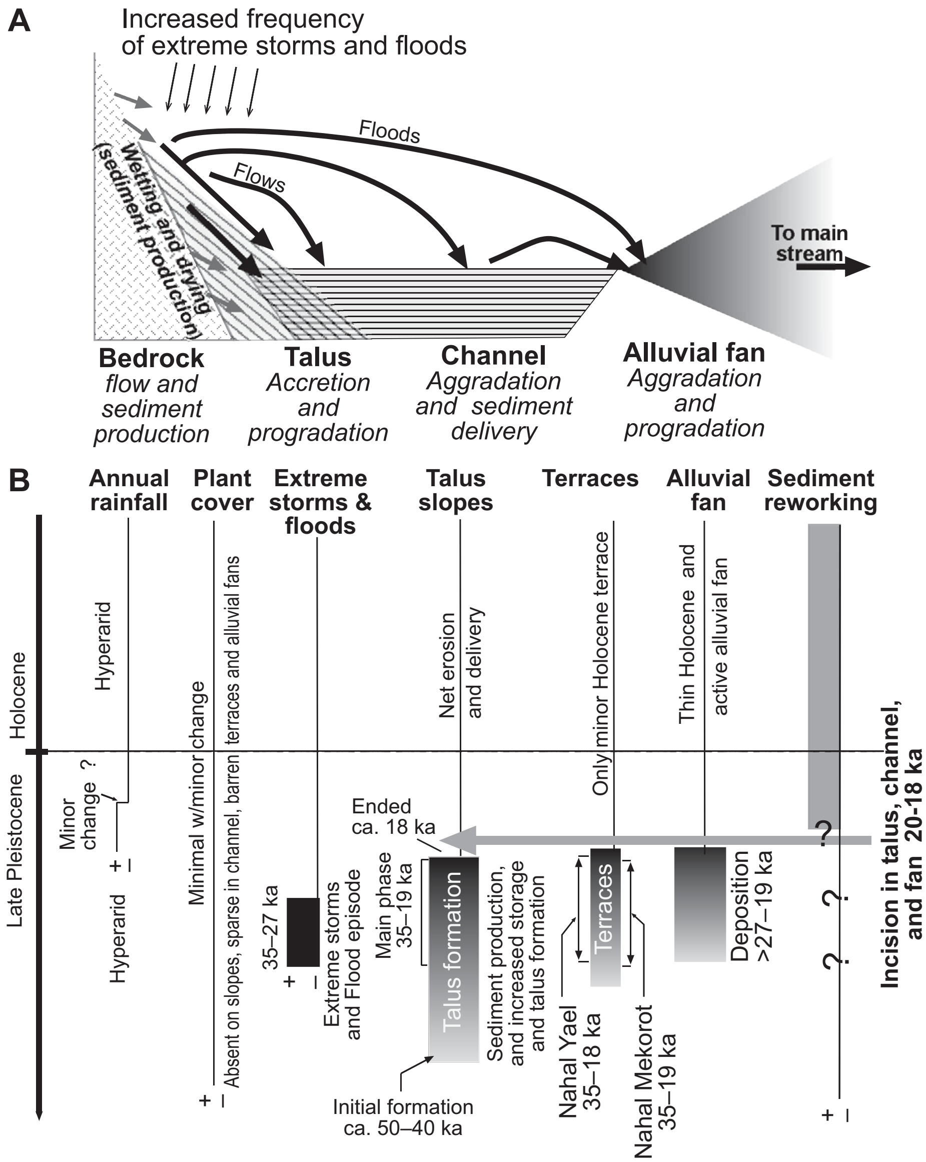

Figure 12. (A) A generic view of the main geomorphic components of an arid headwater drainage basin. (B) A summary of estimated late Pleistocene and Holocene environmental changes in the Nahal Yael watershed and surroundings; all parts are related to Figure 12A. Only minor mean annual rainfall and vegetation changes are estimated since the middle Pleistocene (see text). The episode of frequent large floods (Greenbaum et al., 2006) and the talus, terraces, and alluvial fan accretion are also marked. The relative distances between the pluses and minuses are according to the relative magnitude of change.

So far, little but increasing use has been made of recent developments in luminescence methods that are particularly suitable to various landform components in arid and hyperarid environments (e.g., Singhvi and Porat, 2008; Rittenour, 2008; Porat et al., 2010). An exception is the work of Anders et al. (2005; see also comments by Harvey, 2005). These authors produced a systematic chronology of landscape components of a minor tributary to the Colorado River. As in Nahal Yael, many changes were temporally associated with the MIS 3 to MIS 2 transition and were out of phase with local terraces along the main-stem Colorado River.

It should be stressed that the field area of Anders et al. (2005) is far different from the southern Arava (e.g., mean annual rainfall is >5 times larger than in Nahal Yael and varies across a much larger altitudinal change). However, studies from both the Colorado River tributaries and Nahal Yael indicate that geomorphic chronologies within a region that include small headwater basins where the sediments are produced provide insights into potential controls on geomorphic processes. We suggest that interregional comparison between such small headwater watersheds and larger basins may yield insights on differences or similarities in geomorphic rates and responses. The current practice of using depositional geomorphic sequences preserved at basin mouths or in main-stem, lowland terraces as a tool for interpreting basin-scale geomorphic changes may obscure the actual timing (Anders et al., 2005), and therefore causes, of such changes. Looking only at the distal depositional system cannot reveal the details of geomorphic responses to changing climate.

In Nahal Yael, as well as in the Colorado River tributary, observations indicate a pulse of increased sediment production, mainly through physical weathering. We propose that the main cause for this production of coarse sediment in Nahal Yael was more frequent storms, documented by the well-dated paleoflood record in the nearby Nahal Netafim (Fig. 1; Greenbaum et al., 2006). We note that the Greenbaum et al. (2006) record is of extreme storms and floods (<1% annual probability) unaccounted for in the modern record. Such a record is also consistent with a higher frequency of smaller storms (annual probability of 10%–30%) that can wet the slopes more frequently than today. These occasional storms, though they did not alter the mean state of hyperaridity, may have accelerated weathering and were capable of delivering sediment at the same time. This pulse of sediment production initiated accumulation, delivery, aggradation, and export of sediment downstream without noticeable lags in time. The lack of lag time might be a result of the relatively short length (~1000 m) of Nahal Yael; in larger drainage basins in the hyperarid environments of the world, discontinuities of sediment transport at the scale of 10^4–10^5 yr may result in longer lag times. We propose that episodes of increased storm frequency may be the common climatic parameter that can drive drainage basins into phases of production, delivery, and deposition of sediments in diverse arid environments.

TEMPORAL SCALES AND CAUSES OF PULSED SEDIMENT PRODUCTION

The observations and conclusions presented here raise two questions: (1) Is sediment commonly produced in pulses at time scales of 10^4–10^5 yr? (2) Are these pulses related to changes in climate? Such response is suggested by studies concluding that deposition on arid-region alluvial fans is discontinuous in time (e.g., Wells et al., 1987; McFadden et al., 1989; Bull, 1991; Harvey and Wells, 1994, 2003; Reheis et al., 1996; Ritter et al., 2000; McDonald et al., 2003; Eppes and McFadden, 2008; Bacon et al., 2010). Such conclusions may well be correct; however, data actually connecting these lowland features to sediment production on the watershed slopes are rare. Such temporal connections are usually assumed with a reference to (1) the original conceptual model of Bull and Schick (1979) or other studies, or (2) accepted regional climatic change, but without specifying the basin scale or considering the connectivity of the sediment delivery system.

Our synthesis of results for Nahal Yael indicates that causes for such pulses at the 10^3–10^5 yr time scale can be connected to changes in one of the parameters that comprise the mean state of climate; i.e., frequency and intensity of extreme storms. Elsewhere, these pulses can be related to changes in the mean state of climate, but specifics are lacking, especially in the arid and hyperarid areas worldwide, where sediment connectivity is uncertain. Consideration of pulses of sediment production and storage into landform models is currently uncommon, although they appear to be important in determining the course of landscape change over time. For example, in Nahal Yael, even with its relatively high channel gradient (5% mean slope), such a sediment pulse aggraded fluvial terraces and postponed bedrock channel incision for millennia.

We do not understand the specific climatic conditions that lead to sediment production pulses in arid regions, although such sediment pulses are usually attributed to climate change. Identifying and understanding the drivers of pulses of sediment production require a detailed chronology of sediment production and storage, first on slopes, then in colluvium, and finally in terraces and alluvial fans of arid regions. There is also a need to better determine the specifics of climate. Simplistic terms such as "wetter and colder" may not represent the climate that affects basin geomorphology well enough. For example, our Nahal Yael case study indicates that "wetter" is too vague a term, as the mean annual rainfall cannot explain the geomorphic outcome. Therefore, we must seek more geomorphically meaningful climate descriptions (e.g., Miller et al., 2010). In hyperarid areas, episodes of increased weathering may not result from changes in the mean state of climate but rather from changes in the frequency of wetting and drying cycles that result from changes in storm frequency.

In some areas, an increase in storm frequency is large enough to affect and increase the mean annual precipitation and shift the region into a different climatic regime. In the Nahal Yael, a clear increase of mean annual rainfall is not documented by other paleoenvironmental information. The existing evidence suggests that in this region, the changes in the mean annual rainfall were probably minor; i.e., the area was always hyperarid, although the frequency of storms and floods varied (Amit et al., 2006; Greenbaum et al., 2006). For example, an additional one rare storm per decade may add little to the mean annual rainfall but, at the scale of a millennium, will result in an additional 100 cycles of wetting and drying that may very effectively increase weathering rates.

It is common practice to infer that regionally contemporaneous deposition on alluvial fans is the geomorphic response to a change in regional climate. Such a practice is probably valid; however, it may lead to misinterpretation. For example, both the late Pleistocene and late Holocene alluvial fans of Nahal Yael were formed under relatively hyperarid climates. However, there is a major difference; the Pleistocene fan resulted directly from an increased frequency of rare storms and the 35–20 ka weathering episode. The Holocene alluvial fan, on the other hand, was generated by sediments produced during that same Pleistocene episode and reworked from storage. Thus, both generations of alluvial fans could have resulted from one major perturbation of the basin. This observation suggests that although episodes of alluvial-fan deposition can be well correlated between drainage basins, different generations of alluvial fans can be the result of very different geomorphic responses to a changing climate.

The ideas underlying Bull and Schick's (1979) influential conceptual model originated in the arid southwestern United States before the model was applied to hyperarid Nahal Yael (see Bull, 1991, p. 113–119). Therefore, it may still be valid elsewhere, such as in drainage basins in southwestern North America deserts, at least as a testable hypothesis with which to consider stratigraphic and chronologic results (e.g., Wells et al., 1987; Bull, 1991; Ritter et al., 2000; Pederson et al., 2001; Anders et al., 2005; Eppes and McFadden, 2008).

We stress that any generalized conceptual model should be applied with care. For example, in southwestern North America, the climate is highly diverse; today's climate in that region is characterized by a wide range of mean annual rainfalls (~50–300 mm yr^{-1}), with either summer or winter precipitation regimes, or both, dominated by local to megaconvective, tropical, or frontal storms. Each subregion experiences diverse storm intensities and orographic effects, and within individual basins, there are different soil and vegetation characteristics.

In the past, environmental and climatic parameters were diverse as well, and, therefore, the application of one conceptual model may be unrealistic because basin responses may be controlled by other factors (e.g., Reheis et al., 1996; Ritter et al., 2000; Eppes and McFadden, 2008). For example, doubling of modern annual rainfall in the late Pleistocene in the southwestern United States may bring the lower regions of the Mojave Desert to values of 100–200 mm yr^{-1}. As these precipitation values exist in parts of this and nearby deserts even today, can they serve as analogs to the late Pleistocene lower Mojave Desert? If not, is a controlling climatic parameter missing?

The role of extreme rainfall in stripping semiarid slopes of their debris and catalyzing sediment delivery downstream in semiarid watersheds of southwestern North America has been discussed before (e.g., McDonald et al., 2003; Etheredge et al., 2004), but it has been linked to the sequence of events following climatic changes. Miller et al. (2010) went a step further and hypothesized that in the Mojave Desert, frequent warm season storms caused hillslope erosion and fan aggradation, whereas cold season storms will cause fan incision. However, extreme storms vary in seasonality, duration, frequency, and magnitude within such a large arid region (e.g., Etheredge et al., 2004; Bacon et al., 2010) and are different in other deserts of the world (Amit et al., 2010). Therefore, extreme storms in different seasons may produce contrasting geomorphic effects in basins of different types and sizes. Furthermore, it remains to be shown which of the flood-producing storm types can actually activate sediment transport throughout the entire basin, a crucial question that has not been fully answered since raised by Schick (1974), especially when considered along with the associated question of sediment storage that prolongs geomorphic responses over 10^4–10^5 yr.

FUTURE TESTING OF THE MODEL

Nahal Yael is an extreme hyperarid setting that does not exist in North American deserts, where most of the work underlying and using the Bull and Schick model has been conducted. Nahal Yael provides an end member for assessing geomorphic controls on desert drainage basins. As indicated above, doubling present-day mean annual rainfall in Nahal Yael will bring the southern Negev to mean climatic conditions experienced in the lower parts of Death Valley, among the driest areas in southwestern North America. An important aspect of Nahal Yael that distinguishes it from counterparts in North American deserts is the total absence of vegetation from its slopes and fluvial surfaces probably throughout the latest Quaternary. In the North American deserts, changes in vegetation type and density are considered crucial elements in determining the distribution and intensity of Quaternary geomorphic processes, which can buffer and/or mediate impacts of climate changes (e.g., section 5.2 of Ritter et al., 2000). Under the diverse conditions of southwestern North America, as well as other deserts, the impacts of climate change on sediment delivery and storage in the landscape of arid to semiarid basins are still debated, with only limited detailed efforts made toward resolving these issues (e.g., Anders et al., 2005).

It is important to note that areas in arid southwestern North America and elsewhere include drainage basins experiencing 2–10 times the annual rainfall of Nahal Yael, and some are characterized today by frequent much heavier and longer-duration rainstorms than in Nahal Yael. We propose that analyses of their respective talus slopes, terraces, and alluvial fans (in that order) can be compared to our results, but more importantly, they should be systematically compared with other basins in the larger region of southwestern North America. This will allow insights into long-term, storm- and/or climate-induced geomorphic changes across the hyperarid-arid-semiarid continuum in areas of winter and/or summer rainfall domination. This comparison should be carried out on drainage basins of similar size and gradients, and it should be based on detailed observations and chronology; it should not interpret Quaternary-scale basin history solely based on the limited alluvial-fan history.

CONCLUSIONS

A late Pleistocene episode from 35 to 20 ka of relatively frequent extreme storms under hyperarid climate altered the long-term depositional geomorphology of Nahal Yael. This increased frequency of wetting and drying cycles dramatically increased physical weathering and sediment production, which were assisted by minimal but influential chemical weathering. Surface and channel flows generated by these storms transferred the debris to talus slopes and to depositional terraces along Nahal Yael and then to an alluvial-fan downstream. The synchronous deposition of these landforms contrasts with the model proposed by Bull and Schick (1979), which advocated a chain of processes and a sequence of depositional landforms in response to the Pleistocene-Holocene transition from "wetter" to "drier" mean conditions.

Contrary to the Bull and Schick model, evidence from Nahal Yael suggests that (1) the Pleistocene-Holocene transition was characterized by only a minor change in annual rainfall, (2) the intensified sediment production and delivery phase predated the Last Glacial Maximum and was unrelated to the Pleistocene-Holocene transition, and (2) these sediments were transported and aggraded without lag time. The depositional landforms generated by this pulse of sediment production and delivery were rapidly incised during (20–18 ka) and immediately after the Last Glacial Maximum. Since then, sediment has been eroded from the depositional landforms and not intensively produced from bedrock. Incision of the steep bedrock channels began again after being shut off by channel aggradation for 10–20 thousand years. The impact of the late Pleistocene episode of sediment generation continues in Nahal Yael, with sediments produced then still delivered to the channel and fan today.

We suggest that even if aspects of the original conceptual model of Bull and Schick (1979) are probably correct, it has been applied too frequently and too generally, and for too long in lieu of collecting new data at a basin scale. Observations, usually from the alluvial-fan environment, are too often being fit either to the same or to a modified version of the model, without substantiating the timing and sediment connectivity across the landscape. This practice should change, particularly now that better (1) chronologies can be obtained, (2) erosion rates can be determined, and (3) direct measurements of processes on slopes and in channels can be carried out to improve our understanding of geomorphic responses to climate variations in arid watersheds.

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