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Impact of Climatic Change on an Arid Watershed: Nahal Yael, Southern Israel

WILLIAM B. BULL* AND ASHER P. SCHICK†

*Department of Geosciences, University of Arizona, Tucson, Arizona 85721, and †Department of Geography, Hebrew University, Jerusalem, Israel 91000

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The Nahal Yael basin is underlain chiefly by schist, amphibolite, and granite. Thin (generally <1 m thick), grussy colluvium which covered the lower portions of granitic hillslopes in the late Pleistocene has now been stripped completely, causing marked contrasts in outcrop morphologies, even where there is no contrast of fracture density or petrologic characteristics. Formerly mantled slopes are now smooth and crumbly, and lack desert varnish. Previously unmantled slopes are rough and craggy, and varnished but little weathered. Such stripping suggests a change from a semiarid to a drier and/or warmer climate. Slopes underlain by amphibolite responded similarly to the climatic change, but the amphibolite was more deeply weathered, and the colluvium was only partially stripped. The least stripping of colluvium occurred on schist hillslopes, partly because schist outcrops require more rain to generate runoff, and partly because angular blocks of schist require larger flows for transport, compared to other slope lithologies. The stream subsystem responded to the climatically induced changes in the discharge of water and sediment from the hillslopes. Increase in sediment yield caused valley alluviation in the early Holocene, and a decrease in sediment yield later in the Holocene caused entrenchment of the valley fill. More granite and amphibolite gravel-size particles are transported now than when the hillslopes were extensively mantled. Dense networks of trails are not common on Holocene geomorphic surfaces, but are present on remnants of Pleistocene surfaces.

INTRODUCTION

Little information is available about the dates and magnitudes of climatic change in the core areas of the world's great deserts. Sweeping and often contradictory statements on the subject by some researchers are balanced by more reasonable conclusions reached by others. Some maintain that it may not be necessary to invoke any substantial climatic change in order to explain geomorphic phenomena presently found anywhere in core desert areas. Butzer (1975, p. 403), for example, states that "in hyperarid environments such as Egypt even very modest increases of precipitation have had disproportionately great effects on geomorphologic equilibrium. . . . Yet even here true 'pluvial' conditions were last experienced during the first half or so of the Würm. The later, full glacial was as dry as today in Egypt." Furthermore, during the glaciation of Europe the climate became drier in the tropics, but wetter in the deserts of North Africa. Such climatic changes are most likely the result of different but concurrent changes in airmass circulation. Thus the study of climatic changes in the Middle East is complicated further by the assumption that apparently opposite regional trends in Quaternary climate must have converged somewhere.

The Dead Sea area contains considerable evidence for a wetter past climate in the watersheds that drain to it, such as the subhumid Jordan River basin of northern Israel (Horowitz, 1971). Strandlines are present up to 220 m above present lake level (Neev and Emery, 1967; Bowman, 1974), and the Pleistocene Lisan Formation was deposited during the Pleistocene between about 70,000 to 60,000 yr B.P., and about 18,000 to 15,000 yr B.P. (Neev and Emery, 1967; Kaufman, 1971; Vogel and Waterbolk, 1972). The higher lake levels of the past in-

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dicate wetter and/or cooler climatic conditions in northern and central Israel, and in Transjordan. An intriguing question is what were the magnitudes of the concurrent climatic changes in southern Israel and in the Sinai?

In part of the southern Sinai, Gerson and Yair (1974) have described a sequence of geomorphic processes that suggest a change to drier and/or cooler climate. Weathering that formed abundant gruss was followed by erosion of the slopes to backfill the adjacent valleys with water-laid and debris-flow deposits. On the hillslopes, mechanical weathering became more important relative to chemical weathering, and in the valleys, erosion became the dominant process.

Such a regional Pleistocene–Holocene climatic change probably included the

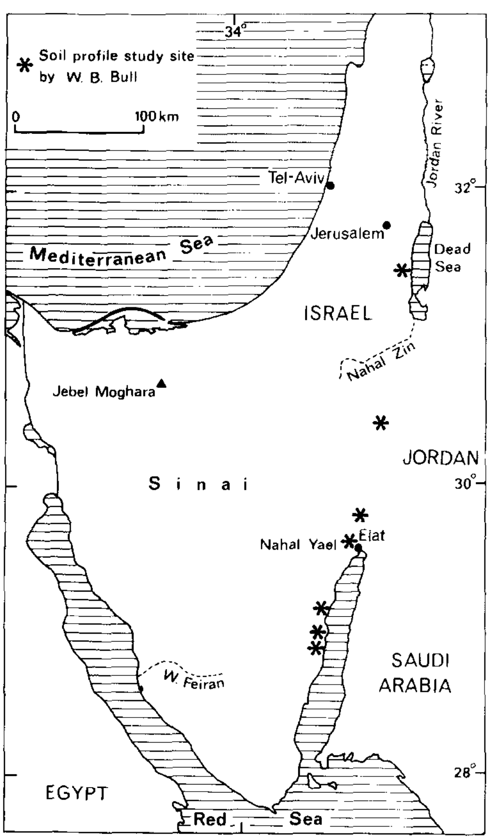

FIG. 1. Map of Sinai Peninsula and adjacent areas showing soil study sites.

Nahal Yael research watershed in the vicinity of Elat (Fig. 1). We assume that a change to a drier and/or warmer climate occurred in the Elat area too, but it should be emphasized that the time, type, or magnitude of the climatic change cannot be quantified by using data from the study area only.[1]

It is interesting to study pedogenic indicators of climatic change in the arid zone proper. Soil profiles on many alluvial terraces of the Dead Sea Rift Valley and in the eastern Sinai (Fig. 1) have dark desert pavements and calcic horizons consisting chiefly of minor amounts of calcium carbonate illuviated at depths of only 2 to 10 cm (Fig. 10B). Such soils are in accord with what one would expect from the limited amount and frequency of wetting in the present arid climate. Argillic horizons cannot form in the present extremely hot, dry climate, regardless of how much time may pass. Geomorphic surfaces associated with the thin calcic soils can be classified as Holocene in age (Bull, 1974). Higher terraces have bright reddish-brown argillic B horizons (Table 3) more than 30 cm thick, underlain by well-developed calcic horizons more than 0.5 m thick. The presence of argillic horizons and the much greater depths to the tops of the calcic horizons indicate that high alluvial geomorphic surfaces are older and have passed through a period of wetter climate than have low surfaces with only thin soils. We assume that geomorphic surfaces with argillic soils are Pleistocene. In this paper we are using the terms "Pleistocene" and "Holocene" in relation to this framework.

The purpose of this paper is to assess the impact of climatic change on the geomorphic processes in a fluvial system that is now extremely arid. We will discuss the hillslope, stream, and depositional subsystems, and will evaluate the types of time

[1] It is difficult to determine the relative importances of changes in temperature and precipitation on vegetation, soil-profile development, lake levels, and streamflow (Brakenridge, 1978).

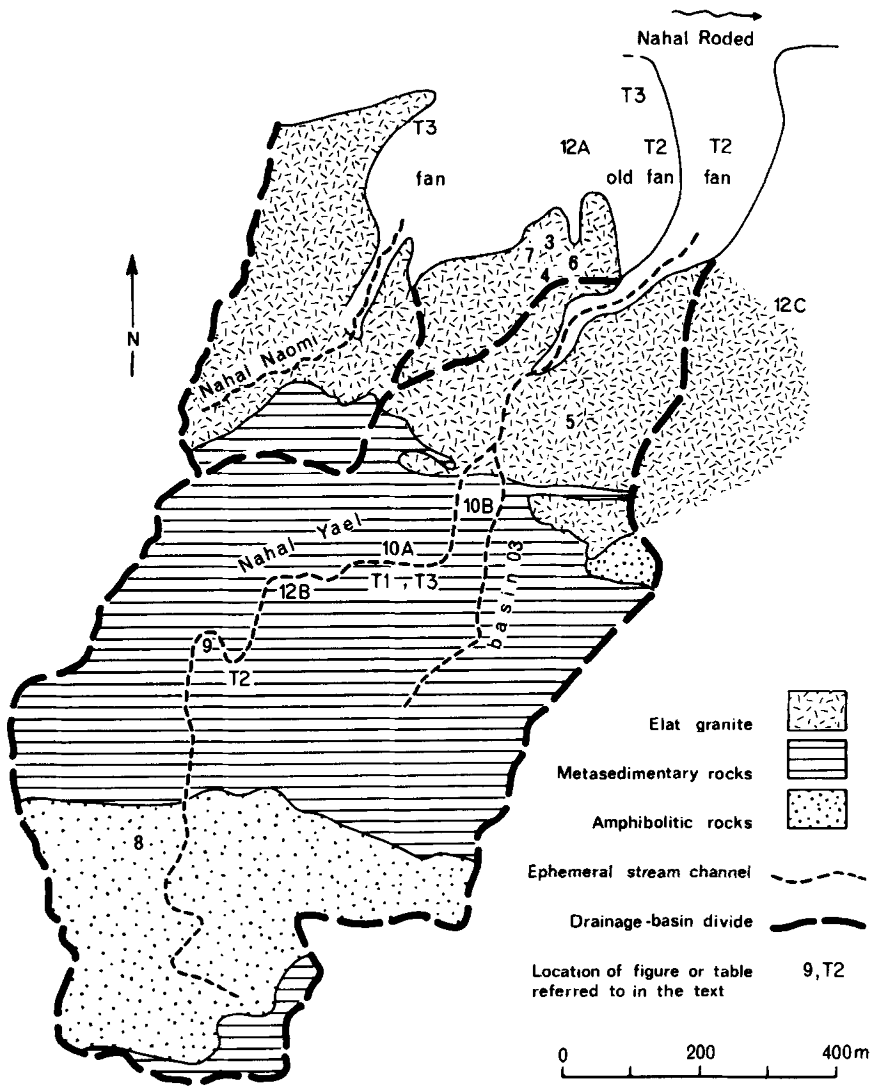

FIG. 2. Geology and location of study sites in the Nahal Yael research area. Geology chiefly from Shimron (Schick and Sharon, 1974, p. 104).

lags and changes for hillslopes underlain by different rock types.

THE NAHAL YAEL WATERSHED

The data were collected from the Nahal Yael drainage basin and from the adjacent small basin of Nahal Naomi (Fig. 2). Observations of precipitation, streamflow, erosion, and deposition have been made in Nahal Yael over the past 10 years (Schick, 1970, 1977; Sharon, 1970; Schick and Sharon, 1974). The drainage basin is about 4 km northwest of Elat, which has a mean annual rainfall of about 32 mm. Nearly all of the rain in this area falls between October and May, and rainfall has been insufficient in some years to cause streamflow. The winters are mild, and summer daytime temperatures commonly exceed 40°C. The hillslopes are almost barren of vegetation, and a sparse growth of trees, bushes, and grass is restricted to the stream channels.

The study area is underlain by Precambrian rocks of the Elat Massif (Fig. 2). Two of the three major rock types present have been metamorphosed. A sheared complex

FIG. 3. North-facing hillslope of Elat granite with contrasts in smoothness of outcrops. View along transect of Figs. 6 and 7.

of mafic rocks occurs in the headwaters of Nahal Yael. Biotite–plagioclase amphibolite, hornblende–plagioclase schist, and gabbroic rocks are common. The central part of Nahal Yael and the headwaters of Nahal Naomi are underlain by metasedimentary rocks, chiefly pelitic schists. Biotite–quartz schist, muscovite–biotite schist, and biotite–plagioclase schist are common. The downstream parts of both basins are underlain by the coarse-grained, jointed, and sheared pink porphyritic Elat granite, which intruded into the metasedimentary rocks. Dike swarms are present in all the rock units. Common dike lithologies are feldspar porphyry, lamprophyre, quartz porphyry, and pegmatite.

The two drainage basins have different proportions of underlying rock types. The Nahal Yael basin upstream from the fan apex is 0.54 km^2 and is underlain by 19% mafic rocks, 49% metasedimentary rocks, 13% granite, and 19% dike rocks. The 0.07 km^2 Nahal Naomi basin is underlain by 17% metasedimentary rocks, 70% granite, and 13% dike rocks. Although the basins are small, they are rugged. Nahal Yael has a relief of 180 m and Nahal Naomi, 135 m.

CHANGES IN THE HILLSLOPES

Climatic variation in arid regions affects rates of chemical weathering and erodibility of weathering products through changes in vegetation density. Erosion rates are also affected by changes in amount and intensity of rainfall. Each rock type in the study area has the potential to respond in a different manner to a change from a wetter to a drier

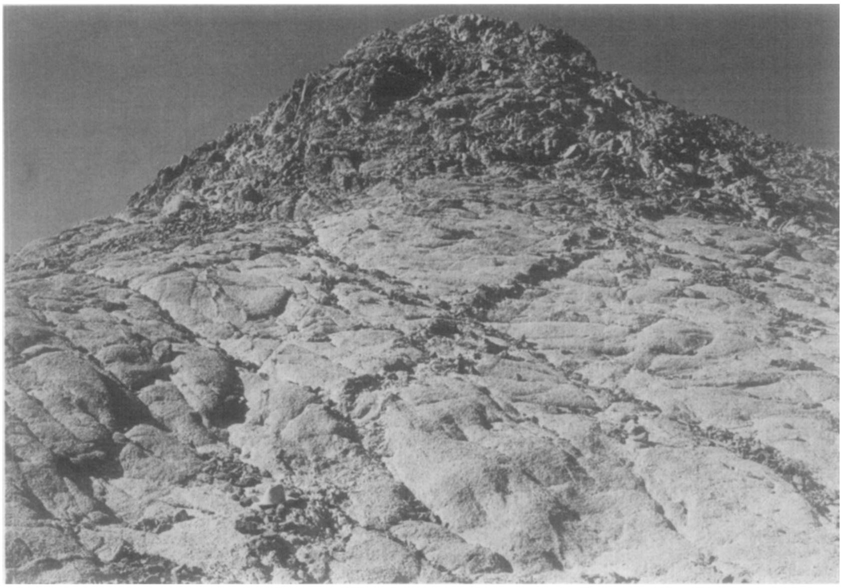

FIG. 4. North-facing hilltop of Elat granite with contrasts in smoothness of outcrops. Hat in left center foreground for scale.

climate. We assume that the study area was warm enough to promote chemical weathering during the Quaternary, but that adequate quantities of water to produce rapid chemical weathering were not always present.

Granite

An outstanding characteristic of the bare slopes of coarse-grained Elat granite is the marked contrast in smoothness of outcrops (Figs. 3 and 4). Rough, craggy exposures are coated with desert varnish, are little weathered, and ring when struck with a hammer. Smooth surfaces occur immediately adjacent to the rough outcrops, where there is no visible change in petrologic fabric, mineralogy, or fracture density (Fig. 7). The smooth slopes are not coated with desert varnish, are crumbly, and do not ring when struck with a hammer.

The two types of granite outcrops are the result of differences in weathering environments of the same rock type. Rough outcrops occur on topographic highs and in stream channels. The joint and shear fractures promote differential weathering of the granite where they are exposed to raindrop impact, sheetflow, and streamflow. Chemical weathering is slow in such a microenvironment, and the rock retains desert varnish except where subjected to abrasion by streamflow. Smooth exposures occur in topographic lows and under alluvium and remnants of colluvium. The coarse-grained nature of the granite promotes rapid weathering to smooth surfaces where a cover of colluvium provides a moist microenvironment after prolonged rains.

Much of the Elat granite is sufficiently massive to favor cavernous weathering. These tafoni form under conditions of subaerial exposure, as a result of variations in case hardening that affect rates of chemical weathering (Jennings, 1968). A moist subsurface microenvironment eliminates the differences in weatherability caused by case hardening, prevents the formation of new tafoni, and promotes the destruction of tafoni that have been buried. In Fig. 5 the upper part of the hillslope has abundant varnished outcrops and tafoni.

Although the hillslopes are bare, the weathering contrasts noted above are clear evidence that large portions of the slopes were previously mantled with grussy col-

FIG. 5. Contrasts in the abundance of tafoni on the upper and lower parts of a hillslope in the Elat granite.

luvium. The different weathering modes of the Elat granite allow mapping of the former extent of the colluvial cover. The weathering contrasts show clearly on aerial photographs and indicate that about two-thirds of the granitic hillslopes had a thin mantle of colluvium which has since been stripped. Most of the hillslopes that have been mantled and stripped have slopes of less than 30°. A map of stripped hillslopes is shown in Fig. 6, and a profile of a slope is shown in Fig. 7. Most of the area of rough granite outcrops is along a southwest-trending ridgecrest. Isolated outcrops of rough granite occur as small hills and as local high areas above the adjacent slopes. The boundaries between the areas of smooth and rough granite are commonly parallel to joints and shear zones.

Outcrop roughness and desert varnish were surveyed along transect A–A′ (Figs. 6 and 7) to determine the former extent and thickness of colluvium. Thicknesses of colluvium that have been removed by erosion were estimated by measuring heights to nearby small outcrops of rough dark granite (which are much too small to be shown in Fig. 6). These estimates are probably accurate to within ±20%. The lower part of the slope does not have any rough outcrops, because even the small ridges between two first order streams (swales) had been completely covered with colluvium. The heights of adjacent bare ridges provided a means of making rough estimates (±50%) of minimum thicknesses of colluvium in the

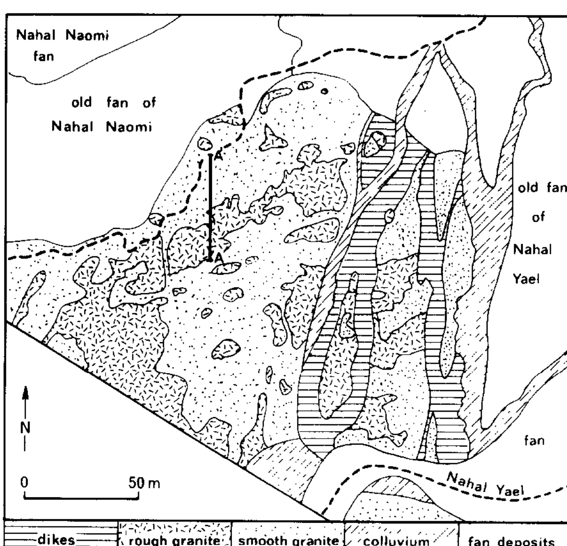

FIG. 6. Map of hillslopes of Elat granite that have been stripped of colluvium (the areas of smooth granite). Transect A–A′ is shown in Fig. 7.

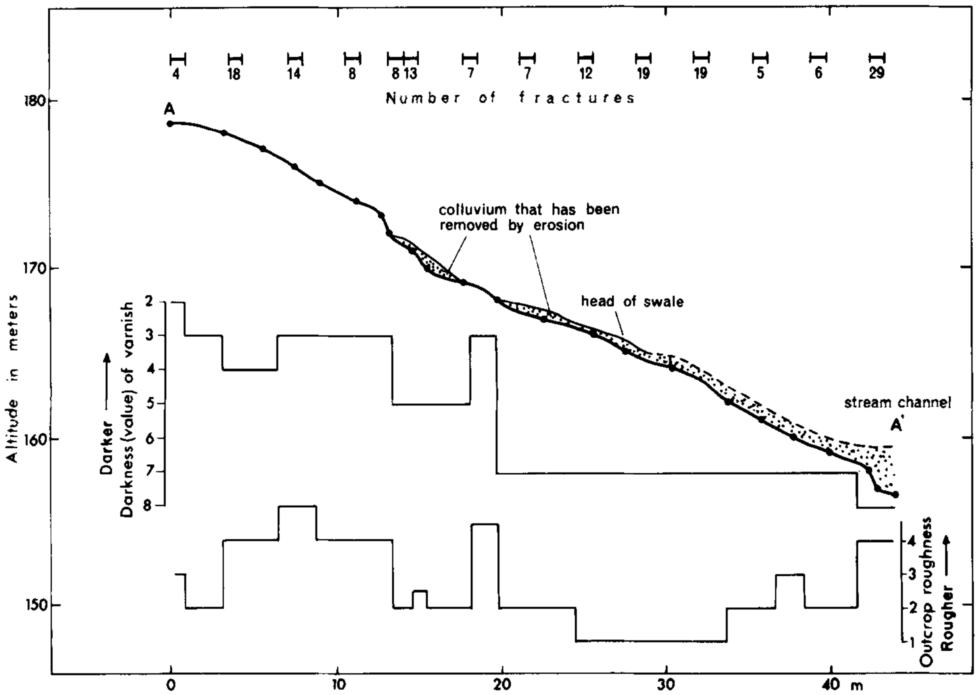

FIG. 7. Former thickness of colluvium, outcrop roughness, desert varnish, and fracture density in the Elat granite. The location of transect A–A′ is shown on Fig. 6.

swale. Minimum values of thickness of prior colluvium obtained by this method are shown by dashed lines in Fig. 7. The grussy colluvium was thin, and it thickened downslope. Most of the ridgecrest shows no evidence to suggest a former cover of colluvium. There is no relation between fracture density (shears and joints) and the smooth or rough weathering modes of the granite.

Roughness and degree of varnishing are markedly different for areas of weathered and unweathered outcrops. Outcrops along the line of transect were assigned relative roughness values. The roughest outcrops were assigned a value of 5, and the smoothest outcrops were assigned a value of 1. Intermediate roughness classes were assigned on a visual basis.

The rougher outcrops occur on the steeper parts of the ridgecrest. The smoothest outcrops (distances 25 to 33 m) occur downslope from extensive areas of class 2 roughness; this suggests that they have been uncovered more recently than the class 2 outcrops. Outcrop roughness increases between distances of 33 to 44 m because the first-order rill has eroded the weathered bedrock slightly, and because the trunk stream at the foot of the hill has downcut along fractures.

Desert varnish was measured by describing the color of the darkest outcrop along each part of the transect. The darkest ridgecrest rocks are brownish black, but the value of the varnish color decreases progressively downslope. Typical colors are as follows: for a value of 3 (5YR 3/4), dark reddish brown, and for a value of 7, (7.5YR 7/3) dull orange. The transect between distances of 14 to 18 m is darker than the lower slopes that were also covered by colluvium, suggesting longer exposure. Between distances of 20 and 44 m the granite is so weathered that disintegration rates exceed varnishing rates.

Mafic Rocks

In contrast to the uniform lithology of the Elat granite, extreme shearing of the

FIG. 8. East-facing hillslope of amphibolite that has been stripped of colluvium. Hat for scale in center foreground.

plutonic mafic rocks in the headwaters of Nahal Yael has resulted in diverse adjacent lithologies. Mapping the former extent of colluvium would be difficult because lithologic differences are partly responsible for differences in outcrop roughness and varnish.

Stripping of prior colluvium is apparent where the amphibolitic rocks are moderately uniform (Fig. 8). Massive mafic plutonic rocks weather in a manner similar to the granite, except that weathering rates are more rapid, the gruss is finer grained, and exposed outcrops varnish more rapidly. The slope shown in Fig. 8 consists of biotite–plagioclase amphibolite. Fresh rock in the stream channel is olive gray (10YR 5/2), but even a few meters above the channel the rock is varnished from dull brown (7.5YR 5/4) to dark brown (7.5YR 3/4). The outcrops are moderately smooth and show local spheroidal forms indicative of subsoil weathering. In contrast, the upper part of the hill has moderately rough outcrops varnished brownish black (7.5YR 2/2). The change in hillslope weathering characteristics coincides with the upper limit of a former debris slope, a remnant of which has been preserved downstream from the slope shown in Fig. 8.

Pelitic Schists

Slopes underlain by schist show a third type of weathering response to the climatic change. The intergrown small crystals, abundant joints, and foliation favor weathering to gravel instead of to gruss in the arid climate. In contrast to the stripped granitic

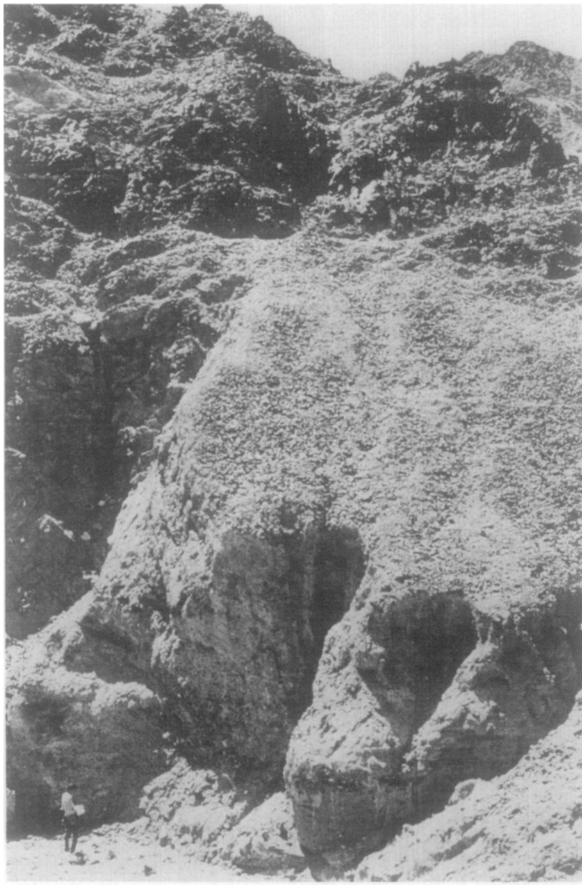

FIG. 9. Colluvium derived from metasediments, which has been incised by Nahal Yael. Note small source area for the colluvium and surficial sheet talus. Person for scale in lower left corner.

slopes, schist slopes have colluvium that occurs as dissected remnants of formerly extensive wedges that mantled slopes and partially filled valleys. Schist varnishes readily, jagged bedrock surfaces predominate, and no change in outcrop roughness is apparent on slopes that have been stripped of colluvium. The dark varnish and stable nature of the remaining debris slopes suggests that locally the bedrock–colluvium contact is roughly the same as during the latest Pleistocene (right side of Fig. 9).

Most of the colluvium has a matrix, and gully talus and beds of sheet talus are common. The variety of gravel sizes and matrix types suggest accumulation under a wide variety of conditions. Some beds appear to consist primarily of rock-fall debris, some of water-transported debris, and others of debris-flow materials, as indicated by a wide range of gravel sizes and poorly sorted matrices.

The presence of intertonguing colluvium and water-laid deposits and of colluvium that extends to the bedrock exposed in the stream channel demonstrates that colluvium accumulated during a period of minimal to moderate backfilling of the channel. The sequence of deposition of the valley fill was as follows: Deposition of colluvium occurred adjacent to the stream channel and continued during concurrent deposition of the micaceous water-laid sands. Incision by the stream allowed the formation of a thin argillic soil profile on top of the water-laid beds; deposition of colluvium continued, burying the water-laid deposits; then a pe-

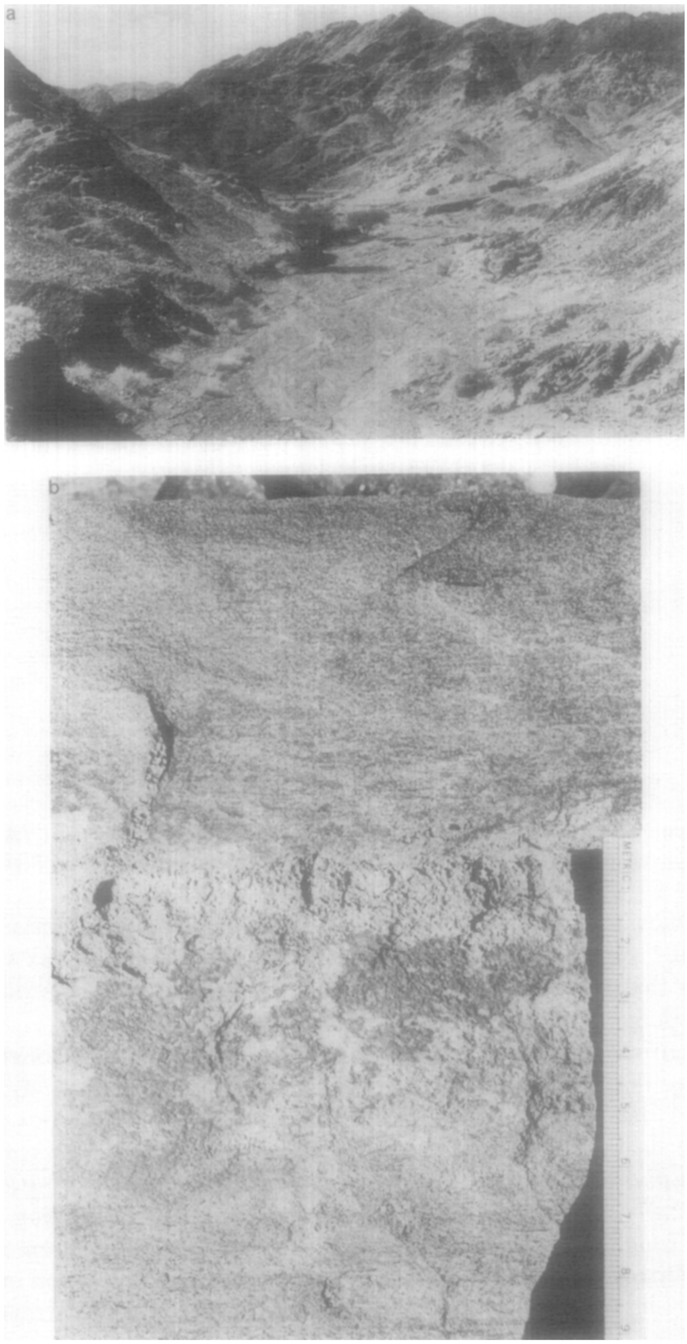

FIG. 10. A. Strath and fill terraces in Nahal Yael. B. Shallow depth of carbonate illuviation on schist boulder on early Holocene terrace. Ground level was at 0 cm. Foliation of schist is apparent above and below 6 cm band of $CaCO_3$ accumulation.

TABLE 1

SOILS AND TERRACE DEPOSITS OF NAHAL YAEL

Horizon	Depth (cm)	Description
A1	+2 to +8	Loosely packed desert pavement. Varnish varies with rock type. Quartz–biotite schist is gray (7.5YR 5/1), top is grayish brown (7.5YR 4/2), and bottom is orange (7.5YR 6/6).
A2	0–2	Light-yellow-orange (7.5YR 8/4) silt; vesicular; slightly hard, slightly sticky, plastic; abrupt wavy boundary.
C1ca	2–6	Light-yellow-orange (7.5YR 7/4) sandy gravel; massive; slightly hard, slightly sticky to nonsticky, nonplastic; clear wavy boundary. Thin incipient carbonate films on gravel particles.
C2	6–61	Brownish-gray (10YR 6/1) to dull-yellow-orange (10YR 7/3) sandy gravel, gravel, and sand. Bed thickness is 3 to 17 cm; most are 6 to 12 cm thick. Loose to slightly hard.
IIC3	61–180	Brownish-gray (10YR 6/1) to dull-yellow-orange (10YR 7/3) sandy gravel, gravel, and sand. Bed thickness is 3 to 17 cm; most are 6 to 12 cm thick. Loose to slightly hard.
IIIB2tb	180–186	Bright-brown (7.5YR 5/8) to orange (7.5YR 6/8) silty gravel; massive; hard to very hard, slightly sticky to sticky, plastic; clear wavy boundary.
IIIC1cab	186–217	Dull-yellow-orange (10YR 7/4) sandy gravel; massive; hard to very hard, nonsticky, nonplastic; gradual, wavy boundary. 0.5 to 3 mm thick carbonate coatings on bottom of pebbles and cobbles. Horizon extends horizontally more than 4.5 m under active channel where it is buried by 10 to 45 cm of loose gray sand and gravelly sand.
IIIC2b	217–405+	Yellowish-gray (2.5YR 5/3) and grayish-yellow (2.5YR 5/2) to dull-yellowish-brown (10YR 5/3) sand and sandy gravel; beds are 2 to 25 cm thick, most are 8 to 12 cm thick. One weathered amphibolite cobble was cut by the shovel.

riod of net channel downcutting to the present stream level was accompanied by stripping of much of the colluvium from nearby hillslopes. Winnowing of the surficial silt and sand and varnishing of the rocks were the chief processes on the remnants of stable colluvial surfaces.

STREAM TERRACES

Excellent strath and fill terraces are present in the Nahal Yael (Fig. 10A) and Nahal Naomi basins. The straths occur beneath the fill terraces, and thus are older. The strath surfaces may be related to a base-level control, but the processes of back-filling and reincision which are responsible for the fill terraces may be regarded as changes in the operation of the fluvial system that caused the stream to cross the erosional–depositional threshold. The Nahal Yael terraces also have been evaluated by stochastic studies of runoff (Schick, 1974).

Four meters of deposits and associated soil profiles are described in Table 1 for the lower of two fill terraces in Nahal Yael. The surficial soil profile is typical of a Holocene geomorphic surface (see Introduction). A varnished desert pavement is underlain by an incipient soil profile with no hint of an argillic horizon. The calcic horizon is only between depths of 4 and 6 cm, and the thin carbonate films on the gravel are difficult to see or feel.

The upper fill terrace also has minimal carbonate illuviation, which is illustrated dramatically by examination of carbonate that coats partially buried boulders. The

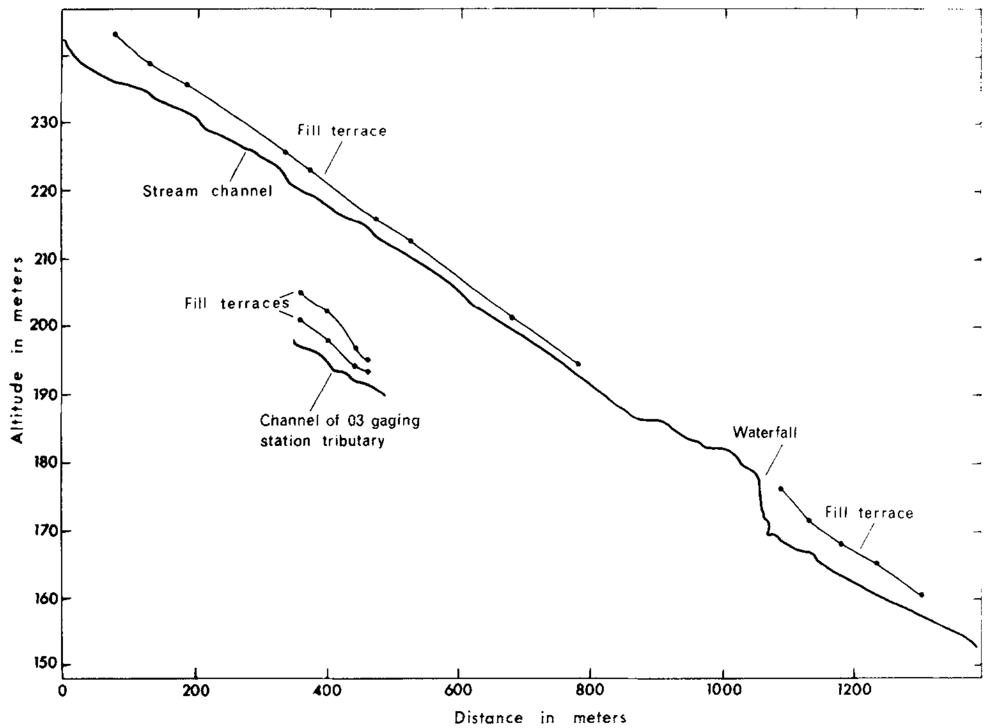

FIG. 11. Longitudinal profiles of fill terraces and stream channels of Nahal Yael.

schist boulder shown in Fig. 10B has a brownish-black varnish (7.5YR 2/2), but the carbonate coating extends to only about 5 cm below ground level. Fresh grayish-green schist is present below a depth of 6 cm. Infrequent prolonged rains may infiltrate several decimeters, but the shallow depth of carbonate illuviation indicates that most wettings are shallow.

The type II deposits described in Table 1 may be buried deposits of the older of the two Holocene fill terraces in Nahal Yael. The deposits are slightly siltier and more poorly sorted than the overlying type I deposits, suggesting that either a decrease in the availability of silt, or increased winnowing of silt, occurred during the Holocene.

A buried soil profile is present 1.8 m below the terrace surface. The A horizon and part of the B horizon were eroded prior to the deposition of the overlying deposits, but the color and plasticity clearly reveal the presence of an argillic horizon above a C_{ca} horizon. In contrast to the Holocene soil profiles, which are less than 10 cm thick, the buried soil is 37 cm thick. The buried soil appears to have formed during a period of wetter climate, as indicated by the presence of a 20 cm thick argillic horizon and a 31 cm thick calcic horizon, although the thicknesses and morphologies of both soil horizons suggest that the soil is not older than late Pleistocene. Only remnants of the Holocene fill remain, so it is unlikely that terrace deposits older than late Pleistocene in age have been preserved. Pleistocene terrace surfaces are not present within the erosional parts of the fluvial system. This indicates that maximum late Quaternary backfilling of the valleys occurred during the Holocene.

Longitudinal profiles of the Holocene fill terraces and stream channels of Nahal Yael are shown in Fig. 11. Prominent fill terraces start immediately downstream from the area of mafic rocks and converge with the present channel upstream from the top of the waterfall in the granite, which constitutes a local base level. The fill-terrace deposits did not bury the entire waterfall, so a plunge pool remained at the foot of the fall. The stream gradient downstream from the waterfall tends to have a slope sufficient to transport the imposed sediment load under the existing magnitudes and durations of discharges. The much steeper slope of the previous channels, indicated by the terrace gradients, suggests that steeper gradients were required to transport the sediment load during the time of maximum valley backfilling. Both Holocene paired terraces in the largest tributary of Nahal Yael (the tributary of the 03 gauging station) converge downstream.

The location of the area of maximum backfilling indicates that the perturbation responsible for valley backfilling was a climatically induced increase in hillslope sediment yield. The terraces are not the result of tectonism. Neither the Holocene terraces along the stream channels in the mountains, nor the Pleistocene alluvial fan at the mountain front are ruptured by faulting. Even if uplift had occurred at the mountain front during the Holocene, the effects of such a base-level change would not be transmitted upstream past the waterfall.

CHANGES IN FLUVIAL DEPOSITION

The time of valley backfilling was also a time of increased frequency of debris flows. Modern debris flows occur on hillslopes in the Elat area and in the eastern Sinai, but debris flows are not presently found along the active stream channels. In Nahal Yael, and elsewhere, water is the present mode of sediment transport. The Holocene terrace deposits of Nahal Yael contain debris-flow deposits; although they comprise less than 10% of the deposits, they represent a process that appears to have been more common during the late Pleistocene and Holocene than at present.

Gravel lithologies in deposits of different ages provide a means of comparing changes in hillslope sediment yield composition upstream from a given point on a stream. Therefore, we described the lithologies of alluvial gravels in the headwaters and on the alluvial fan of Nahal Yael.

The headwaters site consists of stream deposits that interfinger with hillslope deposits (Fig. 9). At this point the stream drains one-third of the watershed, which is

TABLE 2

CHANGES IN THE ALLUVIAL OUTPUT OF THE NAHAL YAEL BASIN

	Lithology of 16- to 64-mm gravel (%)			
Sample size	Schist	Amphibolite	Pegmatite	Red quartz porphyry and other dike rocks
Headwaters				
Pleistocene stream deposits that interfinger with colluvium (Table 1)				
211	37	9	17	37
Deposits in present stream				
208	36	25	16	23

Alluvial Fan

	Lithology of 64- to 256-mm gravel (%)				
	Schist	Granite	Pegmatite	Other dike rocks	Mafic
Surface deposits of Pleistocene fan					
224	62	4	14	9	11
Surface deposits of present fan					
200	43	30	8	8	10

TABLE 3

WEATHERING CHARACTERISTICS OF PLEISTOCENE (P) AND HOLOCENE (H) MATERIALS

Location	Material and age	Lithology	Color	Wet consistence
Nahal Yael Valley	Terrace deposits (H)	Sandy gravel	Light yellow orange (7.5YR 7/4)	Nonsticky, nonplastic
Nahal Yael Valley	Terrace deposits (P)	Silty gravel	Bright brown (7.5YR 6/8)	Slightly sticky, plastic
Nahal Yael alluvial fan	Water-laid alluvium (P)	Sandy clay	Bright reddish brown (5YR 5/8)	Sticky, plastic
Nahal Naomi hillslope	"Saprolite" on Elat granite (P)	Silty gruss	Dull reddish brown (5YR 5/4)	Slightly sticky, plastic
Nahal Naomi alluvial fan	Water-laid deposits (H)[a]	Sandy gravel	Dull yellow orange (10YR 7/3)	Nonsticky, nonplastic
Nahal Naomi alluvial fan	Water-laid deposits (P)	Clayey, grussy gravel	Reddish brown (5YR 4/8)	Sticky, plastic

[a] The color noted here is for late Holocene deposits. Typical colors of early Holocene fan deposits are (5YR 5/4), (5YR 5/6), (5YR 6/4), and (5YR 6/6).

underlain by about 40% mafic rocks, 40% metasedimentary rocks, and 20% dike rocks. A size range of 16 to 64 mm was selected for the lithology counts in the stream channel and the outcrop of Pleistocene deposits because the outcrop contains few particles larger than 64 mm. Table 2 shows that the percentages of schist and pegmatite are roughly the same for the outcrop and the present stream deposits but that marked differences exist for the other dike rocks and for amphibolite. Most of the other dike-rock pebbles are red quartz porphyry, which is the rock type most resistant to chemical weathering. Amphibolite is the least resistant. The markedly lower amphibolite content of the gravel in the terrace deposit shows that the Pleistocene deposits were derived from hillslopes that were subject to more intense chemical weathering than that which occurred during the late Holocene. The terrace deposits have a high percentage of other dike rocks, which provide an index of relative resistance to chemical weathering. The higher percentage of dike rocks in the Pleistocene than in the present stream deposits, despite their low abundance in the hillslopes, suggests that schist and pegmatite, as well as amphibolite, were weathered more during the Pleistocene than during the Holocene.

The greater chemical weathering represented by the terrace deposits also explains the small size of the gravel and the extremely micaceous nature of the sand as compared to that of the present stream. Much of the biotite in the terrace sands resulted from the weathering of biotite–hornblende–plagioclase amphibolite and mica schist during a period of wetter climate.

The alluvial fan (Fig. 2) provides an opportunity to compare past and present total lithologic output of the Nahal Yael drainage basin. Lithology counts of coarse-grained gravel were made along randomly selected transects. Although the source area is underlain by only 13% Elat granite, 30% of the cobbles on the present fan consist of granite. This difference is in part due to the proximity of the area underlain by the granite to the fan apex. However, the surface of the Pleistocene fan has only 4% granite cobbles. The granite cobbles on the Pleistocene fan are fretted by weathering in place, but have undergone minimal reduction in size. The lesser amounts of granite cobbles produced by the fluvial system at the time of deposition of the Pleistocene fan probably coincided with the time of greater mantling by gruss of the hillslopes of the Elat granite, which resulted in more monomineralic weathering products.

CHANGES IN WEATHERING PROCESSES

Contrasts between Holocene and Pleistocene modes of weathering are summarized in Table 3. The presence of an argillic horizon was the chief reason for assigning a Pleistocene age to the old fan of Nahal Yael. The argillic horizon, although protected by the armor layer on the fan surface, is being eroded from the 4.5° fan slope; it is becoming discontinuous and its remnants are generally less than 5 cm thick.

The rate and type of weathering of granitic materials in the Nahal Naomi basin also changed markedly between the Pleistocene and Holocene. Holocene fan deposits become progressively looser and grayer in younger exposures. The late Holocene fan deposits are gray to dull yellow-orange, loose, sandy gravel. Reddish-brown, hard, clayey gravel underlies the Holocene fan deposits, and initially suggests an exceptionally thick argillic horizon. On closer examination it can be seen that soil-profile horizons are absent and that the clayey gravel contains fragments of fresh black biotite schist derived from the headwaters of Nahal Naomi. The material is a water-laid clayey gruss that was deposited during or shortly after a time of moderately intense chemical weathering of hillslope colluvium. The hillslope materials have been stripped from the granitic rocks, so it is difficult to assess the nature of prior weathering products over large areas. Local remnants of colluvium and weathered granite indicate the type of weathering processes during the less arid climate. The "saprolite" noted in Table 3 consists of interlocking crystals that resemble an outcrop whose surface has been cleaned by raindrop splash. But the "saprolite" can be cut with a shovel, revealing a dull to bright reddish-brown silty gruss. Weathering that produces visible amounts of clay and iron oxides from the granite does not occur now, even adjacent to stream channels. Apparently, reddish-brown soil and "saprolite" were sufficiently widespread on Pleistocene hillslopes to be the source of the reddish-brown fan deposits.

TRAILS

Trails are common in many areas of the Negev and the Sinai, including the alluvial and colluvial surfaces of Nahal Yael. Variations in the density of trails on geomorphic surfaces of different ages provide clues about possible changes in climate. Dense networks of trails occur on the remnants of the Pleistocene fan (Fig. 12A), on the remnants of Pleistocene? Colluvium derived from metasedimentary rocks (Fig. 12B), and on quartz–porphyry dikes in the Elat granite (Fig. 12C). Trails are much less numerous on Holocene and modern surfaces. The trails occur as gently sloping benches a few decimeters wide and commonly clear of cobbles and boulders. Origins such as solifluction seem implausible for surfaces that cross contacts between greatly different materials, dip as little as 4.5°, and for which no subsurface evidence of mass movements can be found.

Most of the trails are not currently in use, as is indicated by the failure of trails to continue onto surfaces presently undergoing erosion or deposition. Only three or four trails cross the small gullies that are incising the toe of the Pleistocene fan of Nahal Yael, and the best preserved trails are on the ridgecrests between the gullies. The trails on schistose colluvium tend to end abruptly at the small valley at the left side of Fig. 12B. Trails are well-preserved on the quartz porphyry dike (Fig. 12C), but do not occur on adjacent slopes where colluvium has been stripped from the Elat granite.

The above lines of evidence support the tentative conclusion that the trails were made chiefly by grazing animals, which were more abundant during times of increased vegetation. Although some ibex and gazelle live in the area, there are too

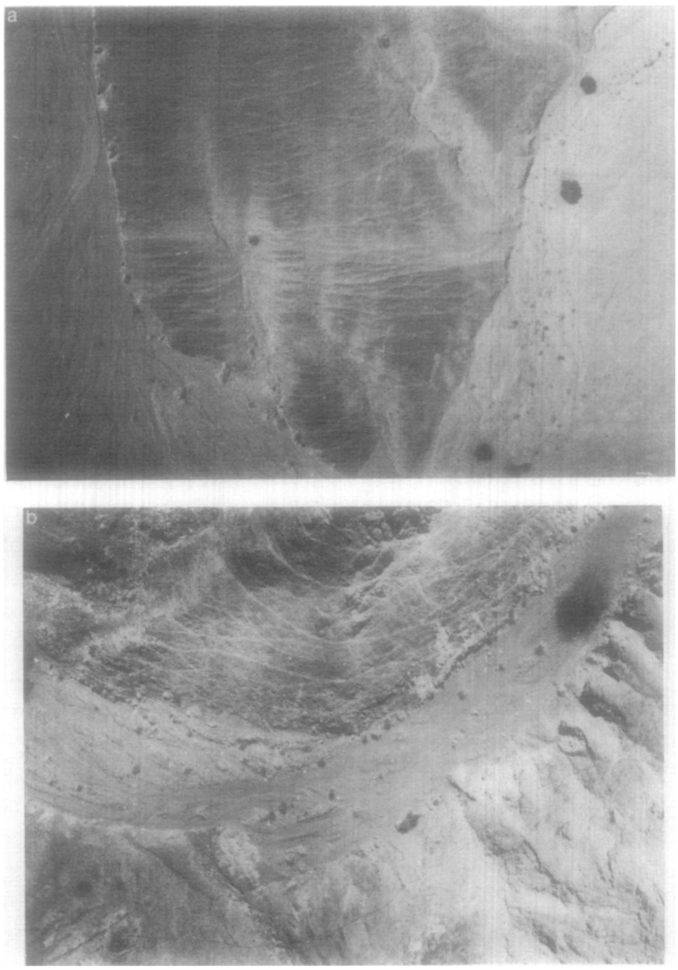

FIG. 12. Trails on surfaces that are relict from a time of wetter climate. A. The alluvial fan of Nahal Yael. B. Colluvium derived from metasedimentary rocks. C. Quartz porphyry dike in the Elat granite.

few to account for the abundant, well-defined trails. The presence of trails may be used to identify those parts of the landscape which have undergone minimal change since the time of change to a semiarid climate. Many of the trails may have been created initially during the late Pleistocene, but periods during the Holocene with conditions wetter than present may also have been times of plentiful grazing animals. At present, there is no need for many trails because the hillslopes are practically devoid of vegetation. Evidence of the effect of increased rainfall on vegetation occurred following the 65 mm of rain that fell in 12 hours on February 20, 1975—twice the mean annual rainfall. Within three weeks the north-facing slope shown in Fig. 12B was green with newly sprouted annual plants.

CONCLUSIONS ABOUT CHANGES IN THE OPERATION OF THE FLUVIAL SYSTEM

The Nahal Yael Research Watershed is excellent for studies of climatic geomorphology because the climatic change was sufficient to change the rates and magnitudes of geomorphic processes on hillslopes underlain by three rock types. Yair and Klein (1973) and Yair and Lavee (1974) provide data about the amounts and inten-

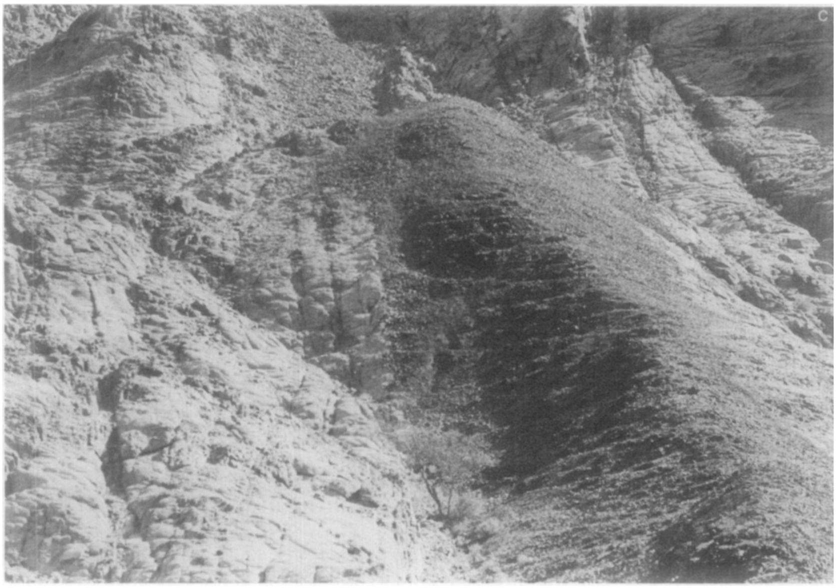

FIG. 12. *Continued.*

sities of rainfall needed to initiate overland flow on different rock outcrops and debris slopes. Outcrops of Elat granite generate runoff after only 2 to 3 mm of rain. Rainfalls of 10 mm are sufficient to erode gruss, thereby increasing the bedrock area that contributes to runoff in subsequent rainfall events. The lower threshold shear stresses needed to initiate transport of gruss have resulted in stripping of colluvium from slopes underlain by granite sooner than from other slopes. Angular blocks of varnished granite now remain as a lag gravel on the smooth surfaces of weathered granite (Fig. 4). The granite may therefore be regarded as the rock type that is most sensitive to climatic change. Re-establishment of the colluvium might occur on those granitic hillslopes that are less than 30°, but would require the stabilizing presence of vegetation to create conditions favorable for the accumulation rather than erosion of the gruss. This would require a climate sufficiently wetter and/or cooler than present to eliminate the extended droughts that kill most hillslope vegetation. When the slopes were mantled the climate was probably cooler and much wetter than the present climate in order to maintain such vegetation.

Rapid removal of colluvium from granitic slopes may have resulted in thicker, more extensive valley fills than those derived from the metamorphic hillslopes. Nahal Naomi has only one-fifth of the area of Nahal Yael, but it has equally thick fill terraces. Holocene alluviation in the downstream reaches of Nahal Yael filled the valley cut in the Pleistocene fan, but deposited less than 1 m of granite-rich alluvium on part of the fan apex. The granitic slopes of Nahal Naomi supplied sufficient debris to completely bury the Pleistocene fan.

The amphibolitic rocks in the headwaters of Nahal Yael reacted to the climatic change in roughly the same manner as did the granitic rocks. The amphibolitic outcrops are more deeply weathered and require more rainfall to initiate runoff—3 mm in 3 minutes (Yair and Klein, 1973, p. 17). More material is presently available for erosion than on the granitic slopes. The amphibolite weathering products have not been completely stripped from the slopes, and colluvium continues to supply sediment to the stream. Abundant dikes also provide coarse particles that tend to mantle and protect the sand produced by weathering of amphibolite.

Armoring by large particles is at a maximum on slopes of metasedimentary rocks. The high intensity rainfall needed to initiate runoff is about 4 to 8 mm. Both this large amount of requisite rainfall and the presence of angular blocks produced by schist and quartzite weathering have resulted in less stripping of colluvium from slopes underlain by metasedimentary rocks than from those underlain by other rock types. Colluvium is quickly stripped from granite hillslopes, but there may be insufficient time between periods of wetter climate to remove it completely from the metasedimentary rock terrains.

The large amount of colluvium adjacent to some schist hillslopes may cause the operation of the slope subsystem to cross a threshold. Continued erosion and concurrent burial of outcrops by colluvium reduce the area of exposed bedrock and decrease runoff to the colluvium. Some of the smaller ridges (Fig. 9) have been sufficiently buried so that the remaining outcrop area generates less than the minimum discharge needed to erode the colluvium, even though the vegetation density has decreased nearly to zero. Thus, the time needed to strip colluvium after a climatic change varies not only with lithology, but also with local outcrop areas.

The impact of the change to a drier climate affected Nahal Yael in the same manner as it did in the arid areas of the lower Colorado River region (Bull, 1974). Decrease in vegetation cover caused increases in sediment yield and valley backfilling, followed by incision of valley fill when hillslope sediment yields decreased with concurrent increases in the area of bedrock exposed on the hillslopes.

Climatically induced increases in sediment yield differ with watershed size and lithology; therefore, different times are needed to attain maximum thicknesses of valley alluviation, or to erode through valley fill to bedrock, after a given climatic perturbation. Because the component basins of a fluvial system may have different time lags, dissimilar local base-level controls may exist where smaller streams join larger streams. The two Holocene terraces of the 03 tributary of Nahal Yael (Fig. 11) show that locally valley backfilling during the second period of Holocene was much less thick than during the first. Along the main channel of Nahal Yael, the second backfilling was thicker than the first, buried the first fill terrace (Table 1), and resulted in a single compound Holocene fill terrace. Figure 2 indicates that the 03 basin is underlain almost entirely by metasedimentary rocks, whereas the Nahal Yael basin upstream from the site of Table 1 is underlain by roughly equal proportions of metasedimentary and amphibolitic rocks.

It is generally recognized that climatically induced changes in vegetation affect the production, erosion, transport, and deposition of sediment. However, the above conclusions underscore the importance of lithologic controls, which affect changes in the rates and magnitudes of geomorphic processes after a change to a markedly drier and/or warmer climate.

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REFERENCES

Ben-Arieh, Y. (1964). A tentative water balance estimate of the Lisan Lake. *Israel Journal of Earth Sciences* **13**, 42–47.

Bowman, D. (1974). Geomorphology of river terraces on the western bank of the Dead Sea—

Geomorphology of the shore terraces of the Late Pleistocene Lisan Lake. *In* "Field Study Program for the International Symposium on Geomorphic Processes in Arid Environments" (R. Gerson and M. Inbar, Eds.), pp. 40–51.

Brakenridge, G. R. (1978). Evidence for a cold, dry full-glacial climate in the American southwest. *Quaternary Research* **9**, 22–40.

Bull, W. B. (1974). Effects of Holocene climate on arid fluvial systems, Whipple Mountains, California. American Quaternary Association Biennial conference discussant paper, 64.

Butzer, K. W. (1975). Patterns of environmental change in the Near East during late Pleistocene and early Holocene times. *In* "Problems in Prehistory: North Africa and the Levant" (F. Wendorf and A. E. Marks, Eds.), pp. 389–410. SMU Press, Dallas.

Gerson, R., and Yair, A. (1975). Geomorphic evolution of some small desert watersheds and certain paleoclimatic implications (Santa Katherina area, southern Sinai). *Zeitschrift fur Geomorphologie N.F.* (Supplementband 19), 66–82.

Horowitz, A. (1971). Climatic and vegetational developments in northeastern Israel during upper Pleistocene–Holocene times. *Pollen et Spores* **13**, 255–278.

Jennings, J. N. (1968). Tafoni. *In* "Encyclopedia of Geomorphology (R. W. Fairbridge, Ed.), pp. 1103–1104. Reinhold, New York.

Kaufman, A. (1971). U-series dating of Dead Sea basin carbonates. *Geochimica et Cosmochimica Acta* **35**, 1269–1281.

Neev, D., and Emery, K. O. (1967). The Dead Sea, depositional processes and environments of evaporites. *Geological Survey of Israel Bulletin* **41**, 147.

Schick, A. P. (1970). Desert floods—interim results of observations in the Nahal Yael research watershed, southern Israel, 1965–70. *In* "Symposium on the Results of Research on Representative and Experimental Basins, Wellington," IAHS Publication 96, pp. 478–493.

Schick, A. P. (1974). Formation and obliteration of desert stream terraces—a conceptual analysis. *Zeitschrift fur Geomorphologie* (Supplementband 21), 88–105.

Schick, A. P. (1977). A tentative sediment budget for an extremely arid watershed in the southern Negev. *In* "Geomorphology in Arid Regions" (D. O. Doehring, Ed.), pp. 139–163. Publications in Geomorphology, Binghamton, New York.

Schick, A. P., and Sharon, D. (1974). Geomorphology and climatology of arid watersheds. U.S. Army European Research Office Report DAJA-72-C-3874, London.

Sharon, D. (1970). Topography-conditioned variations in rainfall as related to the runoff-contributing areas in a small watershed. *Israel Journal of Earth Sciences* **19**, 85–89.

Vogel, J. G., and Waterbolk, H. T. (1972) Groningen radiocarbon dates, geological samples, Dead Sea series, Israel, Lisan. *Radiocarbon* **14**, 46–47.

Yair, A., and Klein, M. (1973). The influence of surface properties on flow and erosion processes on debris-covered slopes in an arid area. *Catena* **1**, 1–18.

Yair, A., and Lavee, H. (1974). Areas contributing to runoff on scree slopes in an extreme arid environment, a simulated rainstorm experiment. *In* "Field Study Program for the International Symposium on Geomorphic Processes in Arid Environments (R. Gerson and M. Inbar, Eds.), pp. 81–87.