Chapter 19

EROSIONAL PATTERNS OF THE GILF KEBIR PLATEAU AND IMPLICATIONS FOR THE ORIGIN OF MARTIAN CANYONLANDS

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ABSTRACT

The relict fluvial topography of the Gilf Kebir plateau provides ample evidence for previous episodes of running water, with present-day domination by an active eolian environment. The caprock of the plateau is composed of quartzarenite, which locally has been recemented into extremely hard quartzite by silica overgrowths and vein fillings most likely accompanying adjacent Tertiary intrusions. Orbital photographs and images show both light- and dark-toned caprock, as well as eolian sand transported from the Great Sand Sea to the north, and redder sand that may in part be locally derived. Incised into the plateau are numerous wadis 10-40 km long that exhibit broad mouths with extensive alluvial fans. The upstream portions of the wadis are narrow canyons with flat floors, bounded by 100 m cliffs of sandstone. Within Wadi El-Bakht and Wadi Ard El-Akhdar, sporadic discharge of the wadis has apparently been blocked by dunes formed in the lee of south-facing slopes, which resulted in periodic damming of the channels and deposition of lacustrine silts and muds upstream from the dunes. More than 10 m of lacustrine sediments was deposited in Wadi El-Bakht, and in both wadis, interbedded mud and eolian sand are exposed where eolian and fluvial erosion has stripped away the recent playa deposits. Because of the absence of tributaries on the plateau surface, the linearity of wadi segments, and the evidence for structural control of Wadi Ard El-Akhdar, it is hypothesized that subsurface drainage, perhaps in the form of piping, has been responsible for the headward erosion of the wadis. This method of canyon development may also apply to several runoff channels on Mars, such as Nirgal Vallis, where tributary canyons in the upstream portions are similar in both scale and form to the blunt-shaped, abrupt headcuts of the Gilf Kebir wadis. Several of the martian canyons terminate at the location of scarps and ridges on the upland plains, suggesting structural control. These similarities in morphology and proposed origin provide justification for future investigations into the origin of the wadis of the Gilf Kebir.

INTRODUCTION

The Gilf Kebir consists of a broad elliptical plateau capped by extremely resistant sandstones of the Nubia Series (Peel, 1939b). Since its first sighting in 1909 by W. J. Harding King (see discussion in Bagnold, 1931), the Gilf Kebir and surrounding region has been the destination of several expeditions to southwestern Egypt, although the remote setting and harsh environment have not allowed extensive field work. Many of the early expeditions concentrated on mapping the extent of the plateau, exploring the many archaeological sites, and finding ways to go around it. Legendary accounts of the lost city of Zerzura, reported to be in the interior of the plateau (Bermann, 1934), no doubt were responsible for several of these trips. Serious investigation of the geomorphic history of the Gilf, however, began in 1938, and was due primarily to the efforts of Ronald F. Peel.

The massive, steep cliffs and extensive wadi networks that characterize the Gilf Kebir were of interest to the early explorers. In 1933, P. A. Clayton noted that the wadis commence at the scarps, yet have no drainage on top of the plateau. This suggested to him that the canyons must be the remains of an older system of drainage (Clayton, 1933). Studies by Peel (1939b) resulted in the first detailed interpretations of wadi and cliff morphology. The major unanswered questions of drainage pattern origin, channel incision and cliff retreat were raised by Peel, and still suffer today from lack of quantitative information.

Recently, photographs from the Gemini and Apollo missions, and images from Landsat spacecraft have greatly improved our view of this part of southwestern Egypt. The geographic division between the northern and southern Gilf Kebir discovered by Penderel in 1933 (see below) is well-documented on earth-orbital pictures, as are the extensive wadi systems that are cut into the plateau (Fig. 19.1). Consequently, although field studies are still sparse, there is much new data available on the large-scale relationships within the plateau.

The intent of this paper is to present both the field and orbital data in light of existing theories for the geomorphic development of the Gilf Kebir. New field data include profiles of Wadi El-Bakht and Wadi Ard El-Akhdar, and observations on the sandstones that make up the caprock of the plateau. In conjunction with previous maps of Peel (1939b), several volcanic hills can be tentatively identified on Landsat images. If the association between volcanically modified sandstones and early human settlement sites (El-Baz and Maxwell, 1979b) holds up under further field studies, then Landsat images may provide a useful means of predicting potential archaeological sites in this region.

In addition, orbital images of this region provide us with the large aerial view necessary for interplanetary comparisons. As on Mars, landforms of the southern Gilf Kebir show the effects of previous episodes of running water, yet are now dominated by an eolian environment. Fluvial canyons on both planets have been ascribed to

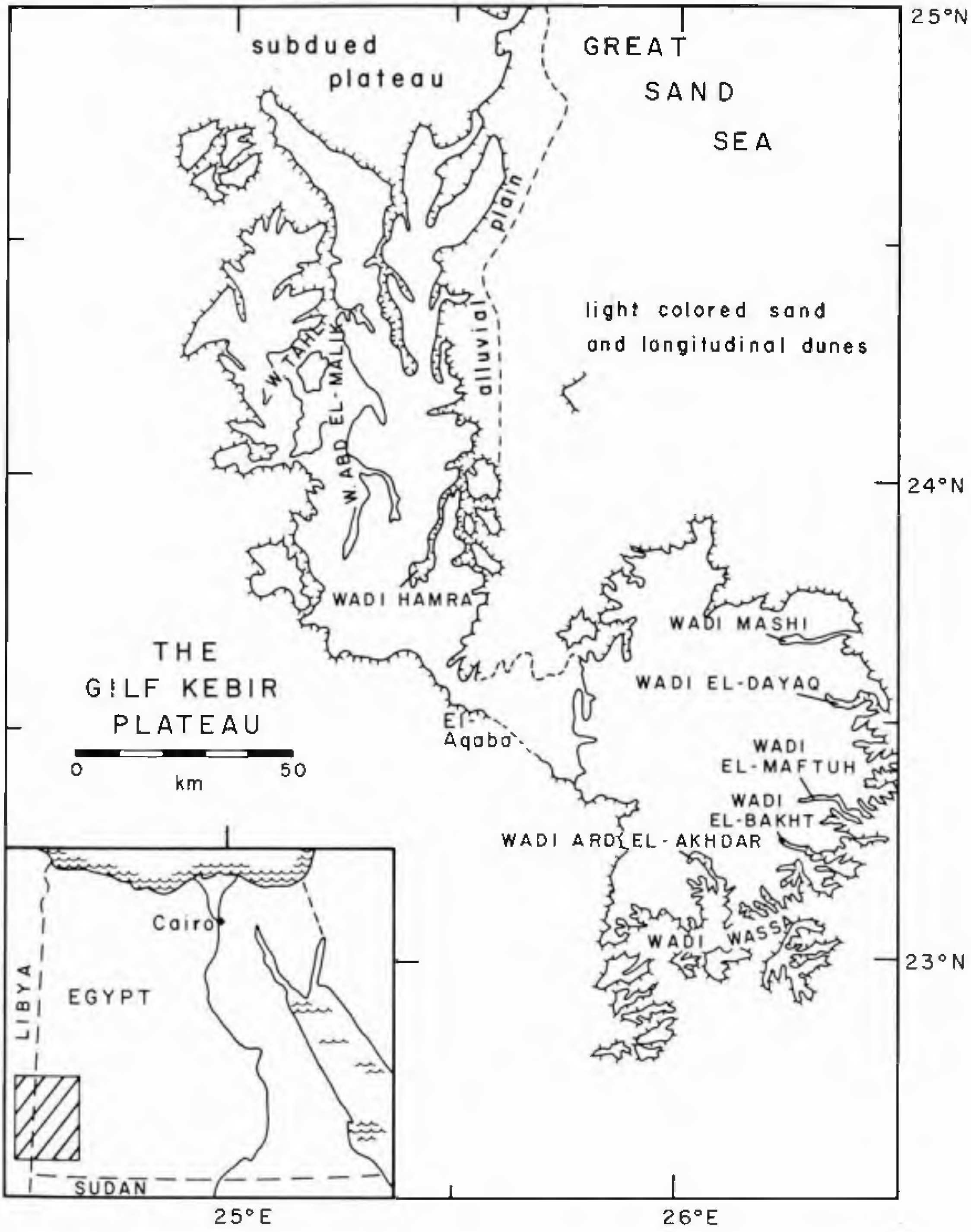

Figure 19.1 Map of Gilf Kebir region showing major named features and locations of wadis discussed in text.

the action of subsurface drainage and cliff retreat (Maxwell, 1979a), and the wadi systems of the Gilf Kebir provide a viable terrestrial analog for the results of these processes.

PHYSIOGRAPHY

In early 1933, while on a reconnaissance flight for the Royal Air Force, H. W. G. J. Penderel flew northwards over the western escarpment of the Gilf Kebir, and discovered the separation between the northern and southern parts of the extensive plateau. The gorge separating the northern and southern Gilf Kebir Plateau is 25 to 30 km wide, and is floored by numerous longitudinal dunes that have migrated southward from the Great Sand Sea (Fig. 19.2). Consequently, east-west passage is extremely difficult, although P. A. Clayton was able to cross the area later in 1933.

The most notable feature of both the northern and southern Gilf is the prevalence of steep-sided wadis that deeply incise the edges of the plateau. In some cases, wadis have completely separated portions of the plateau. This is especially true in the northern Gilf, where Wadi Abd El-Malik penetrates nearly the entire north-south length of the plateau, and on the southern edge of the plateau, where dissection has left several outliers. With the exception of the Clayton-Almasy expedition of 1932, there has been little work done on the wadis of the northern Gilf, although drainage dissection is more complete here than in the southern Gilf. In addition, the existence of trees and bushes in the wadis of the northern Gilf suggested to Clayton (1933) that water was either more plentiful here, or that it could have existed for longer periods of time.

In contrast, much more is known about the wadis of the southern Gilf, resulting mainly from the work of Bagnold's expedition of 1938. The southern Gilf occupies an area of 5800 km^2, and is penetrated by 5 wadis more than 15 km long. Wadi dissection appears to have progressed primarily from East to West, and the extreme southern portion of the plateau has been completely isolated by the east-west trending Wadi Wassa. The western side of the southern Gilf differs from the eastern side in that it has steeper cliffs (Bagnold, 1939; and Haynes, pers. comm.) and only minor incursions into the relatively straight walls of the plateau. East of El-Aqaba (Fig. 19.2), the few wadis that penetrate the plateau are elongate in a north-south direction.

Knowledge of the plateau surface of the southern Gilf comes from transverses made by Peel and Bagnold in 1938. The surface was described as rough and hilly by Peel (1939b), and nearly 50 exposures of basaltic hills were mapped. As can be seen from orbital images, the surface of the western half of the plateau is covered with reddish sand, similar in tone to the longitudinal dunes on the plains northeast of the plateau. In the northern part of the Gilf Kebir, inundation of the plateau is nearly complete; remnants of the dark, plateau-forming sandstone are barely visible through the haze of sand drifting southwards from the Great Sand Sea.

Figure 19.2 Mosaic of Landsat images of the Gilf Kebir plateau. Caprock of northern plateau disappears to the east under sand from the Great Sand Sea to the north (note the numerous longitudinal dunes). The northern plateau is more completely dissected than the southern part, primarily by north-south oriented wadis.

GEOLOGIC SETTING

The sedimentary series comprising the southern Gilf plateau consists primarily of sandstones, although individual beds may range from siltstones to conglomerates. The sandstone of the northeastern part of the plateau is believed to be conformable with the Jurasic-Cretaceous age Nubia Sandstone exposed south of the Kharga depression (Issawi, 1980), supported by the existence of upper Cretaceous fossils in the northeastern part of the plateau. The name "Gilf Sandstone," proposed by Issawi (1980), is reserved for that part of the section that unconformably overlies the Paleozoic rocks south of the plateau, and extends upsection to the dark, siliceous caprock of the northern Gilf. In contrast, Klitzsch (1978) proposed the name "Gilf Kebir Formation" for the sandstone section best exposed in El-Aqaba, where it consists of a cyclical cross-bedded silt to fine sandstone. Regardless of which stratigraphic model is preferred, the relatively soft siltstone cliffs of the Gilf Kebir are capped by layers of hard, siliceous sandstone that may range from several meters to tens of meters thick. These resistant ledge-formers create a stepped appearance to the scarps on the southeastern edge of the plateau, but appear to be thicker in the plateau interior where exposed in the wall of the wadis.

Samples of caprock and prominent ledge-formers from six locations on the edge of the plateau consist of quartzarenites (or orthoquartzite), although there is a great variation in texture, cementation and porosity of the sandstones. At the northeastern edge near Wadi Mashi, for example, the caprock consists of a bimodal mixture of coarse- to fine-sand-size quartz grains with almost no porosity. Almost 40% of this sandstone consists of a microcrystalline quartz and calcite matrix, with quartz slightly more abundant than calcite. Near a basalt intrusion in the same wadi, however, the caprock consists of a mottled white and brownish-red mixture of well-rounded medium sand (.20 mm) and angular medium- to coarse silt size grains. The matrix of both white and red portions is composed of microcrystalline quartz, with the reddish stain probably made up of iron oxides. Numerous bright red specks of hematite, 10 μm in diameter are present. The porosity of this rock is 10-15%, but has been somewhat reduced by late-stage precipitation of calcite as vein fillings.

In the upstream portions of Wadi El-Bakht (approximately 15 km from the mouth), the caprock consists of a unimodal, fine quartzarenite with abundant grain-to-grain contacts that pre-date quartz overgrowths in some cases (Fig. 19.3A). Although the rock is fairly strongly foliated, it is difficult to tell whether this fabric resulted from deposition, or later diagenesis. A primary stratification is favored, however, since quartz extinction is not related to the direction of foliation, and there is no other evidence for pressure-related phenomena. The rock is cemented by a mixture of microcrystalline quartz and hematite. For comparison, a resistant ledge-forming sandstone from near the mouth of Wadi El-Bakht is composed of a bimodal mixture of subangular silt to fine-sand and well-rounded coarse sand (0.60 mm) grains. This sample exhibits much higher porosity (10-15%), and similar to the other Gilf sandstones, is

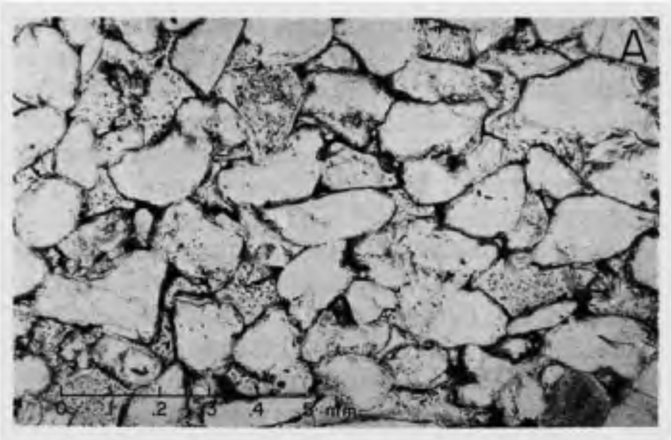

Figure 19.3 Photomicrographs of sandstone from the eastern edge of the Gilf Kebir plateau. A) Caprock sample from Wadi El-Bakht showing fairly strong (original?) foliation of angular grains.

cemented by microcrystalline quartz with minor calcite as the latest stage authigenic mineral. A sample of unimodal fine-sand size quartz-arenite from the caprock at the eastern edge of Wadi Wassa also suggests late-stage carbonate deposition in the form of narrow (20 μm) veinlets filled with microcrystalline calcite.

As shown by these analyses of caprock samples from locations scattered on the eastern edge of the plateau, there is an abundant source for silica both in detrital grains and in the matrix. The numerous Tertiary basalt intrusions mapped by Peel (1939b) provided a source of heat that aided local precipitation of silica as grain overgrowths and vein fillings. An example of this process is apparent at the constricted part of Wadi Ard El-Akhdar. Here, the hill on the northern side of the wadi consists of a basalt intrusion, whereas the southern hill is composed of an almost pure quartzite. The sandstone consists of an extremely siliceous mosaic of interlocking grains (0.08 mm; very fine sand) cemented by quartz overgrowths up to 50 μm wide (Fig. 19.3B). The porosity of this rock is much less than 5%, and where pores are present, they are bordered first by chalcedony, and then by calcite filling the center of the void. Since there are very few original grain-to-grain contacts, it is not likely that pressure solution played an important role in diagenesis. Instead, remobilization of silica was most likely due to the proximity of the intrusion, which reduced porosity and locally produced an extremely resistant caprock. An archaeological reduction site on top of the quartzite hill suggests that early man took advantage of the local geologic conditions, and used this material for production of implements (El-Baz and Maxwell, 1979b).

Surficial Deposits

As seen on Earth-orbital images and photographs, the surficial deposits of the Gilf Kebir consist primarily of exposed caprock, and eolian sand alluvial deposits within the wadis. Variations in degree of cementation and possibly even composition of the caprock make it

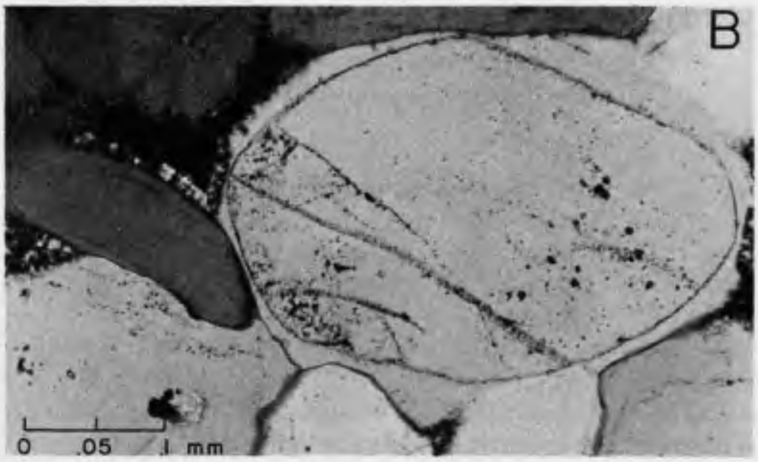

Figure 19.3 B) Extensive quartz overgrowths in a sample from Wadi Ard El-Akhdar adjacent to a basalt hill.

possible to distinguish a dark-toned and light-toned caprock. The dark-toned caprock is most prevalent on the surface of the northern Gilf Kebir, although it is also present on the northwestern and southern edges of the southern Gilf. It is possible that this tonal distinction is solely the result of covering by recent eolian deposits, but investigation of cliff heights in Wadi El-Bakht suggests that stratigraphically different units may also be responsible. The light-toned caprock on the north side of Wadi El-Bakht varies from 70 to 96 m above the wadi floor, whereas the dark-toned caprock on the south side of the wadi occurs at elevations of 115 to 140 m. Consequently, exposure of a stratigraphically higher sandstone unit (20-70 m thick) should not be discounted as a possible cause for tonal variations within the caprock. Locally, some circular patches of dark caprock most likely result from low grade metamorphism of the sandstone surrounding basalt intrusions.

Based on an Apollo 7 color photograph of the southern Gilf and numerous false-color Landsat images, it is also possible to divide the sand into two color zones. Relatively white sand similar in color to that of the Great Sand Sea surrounds the northern part of the plateau, and forms longitudinal dunes and linear chains of barchans within El-Aqaba. Reddish sand occurs in the middle of the plateau, as an extensive deposit off the southeastern edge of the plateau, and as a group of longitudinal dunes that have spilled over a short wadi on the western edge of the plateau. It is possible that part or all of the reddish color may be due to the addition of sand grains from the Gilf Sandstone, although the influence of a possible lag surface on the deposits cannot be discounted.

WADI MORPHOLOGY

Although only two wadis were investigated in detail, it is possible to make some generalizations on the overall morphology of several wadi canyons based on the experience gained from Wadi El-Bakht and Wadi Ard El-Akhdar, and the appearance of other wadis in orbital images. Minor tonal variations near the mouth of Wadi El-Bakht are the result of an extensive fan deposit shed off the south wall of the canyon, forcing the stream channels to the north side of the valley (Fig. 19.4). A similar process is also affecting Wadi El-Maftuh, where light-toned alluvial deposits occur only in the northern half of the valley.

In contrast to the wide mouths of the wadis, the upstream portions are narrow, linearly segmented box canyons characterized by flat alluvial floors. Channel incision ranges from less than a few tens of centimeters in Wadi El-Bakht to more than 3 m in Wadi Ard El-Akhdar, and the steep cliffs bounding the wadis rise to more than 100 m above the floor (Fig. 19.5). The investigation of the upstream portions of wadis El-Bakht and Ard El-Akhdar indicate that eolian activity has locally had a major effect on the floors of these wadis, although not on the morphology of the canyons as viewed from orbit.

Figure 19.4 View to the southwest at the mouth of Wadi El-Bakht. The relatively gentle slopes on the south side of the wadi are composed of coalescing alluvial fans and local deposits of eolian sand leading up to the sandstone cliffs.

Figure 19.5 Upstream portion of Wadi El-Bakht. Note the steep cliffs (approximately 100 m high), lack of extensive fan deposits and only minor channel incision.

Wadi El-Bakht

Approximately 15 km upstream from the mouth of Wadi El-Bakht, the effects of the comparatively recent eolian dominance can be seen in the valley floor morphology and sediments. Here, a 30 m high sand dune rests against the north wall of the wadi, and extends 200 m to the south, almost half way across the canyon floor. Because of its placement on the north wall of the wadi, and its north-south orientation, it is probable that this dune originated as a lee dune, formed from sand blown across the plateau surface. Although the position of the crest may have shifted to the east or west in response to (diurnal) up- and down-valley winds, the position of the dune itself has been remarkably stable as indicated by the presence of neolithic implements found on the upper dune surface (see McHugh, Chapter 20).

The presence of the dune has had a marked effect on both the stream profile and on the type of sediments found in the wadi floor. Upstream from the dune, more than 10 m of interbedded lacustrine mud and eolian sand was deposited, although these deposits are now exposed in a gorge at the present-day southern tip of the dune (Fig. 19.6). The valley floor above the dune is graded to the level of the playa surface (approximate channel gradient = 0.0028), suggesting that either channel incision was limited by the temporary base level imposed by the dune dam (Fig. 19.7), or that a significant thickness of alluvial valley fill has been deposited upstream from the lake bed. In either case, the continuous gradient of the wadi floor indicates a cumulative effect of fluvial erosion and deposition for more than the past 7000 years since man lived on the latest lake deposits (Wendorf and others, 1976). It is possible that once the initial lake sediments were deposited behind the dune, they may have provided a positive-feedback mechanism for the stability of the dune. Sand carried by the up- and down-valley winds would be deposited at the topographic break between the valley floor and lacustrine deposits, and thus would have aided dune growth during times of increased aridity. Near the present-day cliff of lake deposits, the bedding dips at low angles to the west (upstream), suggesting that at least during the latest episodes of playa formation, growth of the dune and consequent damming kept pace with formation of the intermittent lake.

Artifacts found within the top few meters of the lake deposits indicate that human habitation took place contemporaneously with the last stages of deposition of the lake. The single ^{14}C age of 7280 ± 90 BP of an eggshell in Wadi El-Bakht (Wendorf and others, 1976) suggests that the latest major periods of lake sedimentation took place as recent as the "Terminal Paleolithic-Neolithic Wet Phase" of Wendorf and others (1977), although more youthful lake sediments may have been stripped by wind erosion. The detailed topographic survey of the archaeological sites on the playa sediments indicates a minimum of 1 m of deflation from the highest hummocks of lacustrine semi-consolidated mud to the level plain consisting of the most recent mud-cracked playa surface.

Figure 19.6 View looking upstream from the crest of the dunes in Wadi El-Bakht. Recent playa deposits are in the foreground, and present-day channel and gorge are at lower left.

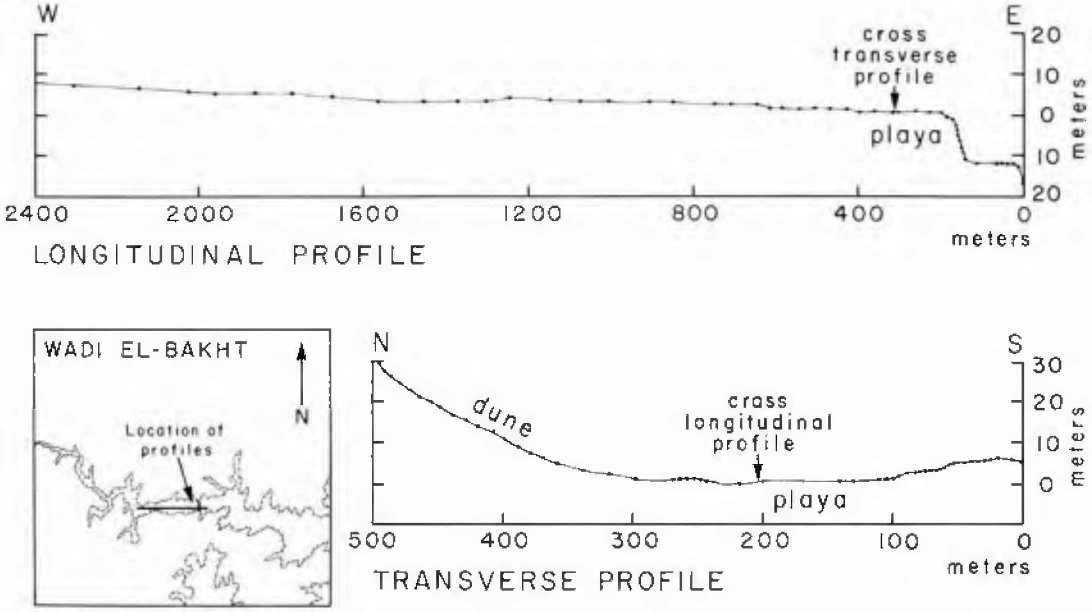

Figure 19.7 Longitudinal and transverse profiles of Wadi El-Bakht. Longitudinal profile was surveyed by pace and hand level and transverse profile by tape and level.

Wadi Ard El-Akhdar

As can be seen in orbital images, the upstream ends of Wadi Ard El-Akhdar abruptly terminate in circular, amphitheater-like depressions, with no evidence for channelized flow over the surface of the plateau (Fig. 19.2). Similar to Wadi El-Bakht, the downstream (southern) portion of Wadi Ard El-Akhdar is 10 km wide and is characterized by broad alluvial fans sloping down from the base of the steep cliffs of the plateau. The 2 km wide circular depression at the head of Wadi Ard El-Akhdar was investigated by Peel (1939b), who noted the presence of numerous basalt hills surrounding the depression. In addition, scree slopes of extremely hard, silica rich sandstone make up the southern side of the narrow mouth of the amphitheater, and a basalt hill forms the northern side of the wadi (Fig. 19.8). Although wadi formation by headward erosion versus inherited drainage remains an open question, it seems plausible that the incision of the canyon was here controlled by the bedrock. Whether inherited or headwardly eroded, the stream channel most likely took advantage of the highly fractured and metamorphosed sandstone at the contact with the Tertiary intrusion.

Within the gorge at the mouth of the amphitheater, a sharp crested dune is present, stretching from the basalt hill on the north approximately 2/3 of the way across the wadi (Fig. 19.8). On the south side of the constriction, channel incision has exposed a a 3.4 m section of sediments, composed primarily of poorly-sorted pebbles and cobbles set in a matrix of silt and clay. However, alternating with these structureless beds are well-sorted red sand lenses with low-

Figure 19.8 Canyon constriction and dune in Wadi Ard El-Akhdar. View from quartzite hill on south side of wadi. Hill on opposite side is basalt. Note jeep in lower right corner for scale.

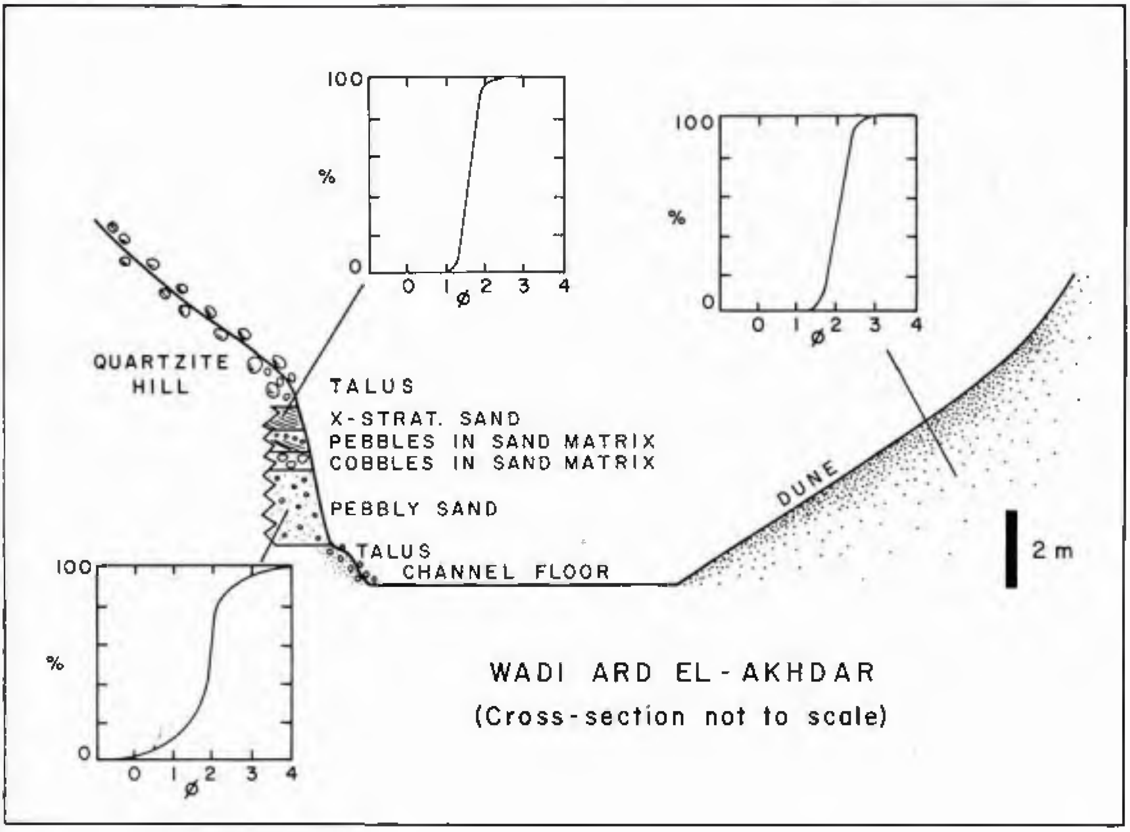

Figure 19.9 Vertical section and grain-size distributions for sediments in the constriction of Wadi Ard El-Akhdar. Note similarity in size distribution of modern dune sand and planar cross-stratified sand exposed on the south side of the wadi.

angle (6-14°), planar cross stratification dipping to the west (Fig. 19.9). As evidenced by a comparison of the modern dune sand with that exposed on the southern wall of the wadi, and the stratification observed in cross-section, it is most likely that this dune has experienced several episodes of growth across the wadi, resulting in the damming of the channel, and consequent playa mud deposition upstream from the dune.

In contrast to the limited extent of the playa deposits at Wadi El-Bakht, those at Wadi Ard El-Akhdar cover the entire floor of the amphitheater, and are extensively eroded by later periods of channel incision (Fig. 19.10). The main channel is incised up to 3 m into the lacustrine sediments, and secondary channels, now choked with sand, are perched 0.5 to 1.0 m above the level of the main channel. This lack of adjustment of drainage within the amphitheater is consistent with highly localized rainfall on the upper part of the basin. Although the pace and hand-level survey of the constriction of Wadi Ard El-Akhdar is not as long as that of Wadi El-Bakht, it is evident that the gradient of the main channel is much steeper in Wadi Ard El-Akhdar (Fig. 19.11).

Figure 19.10 Incised playa sediments of Wadi Ard El-Akhdar; view to the northwest. Dark hill on north side of the amphitheater (upper right corner) is composed of basalt intrusions.

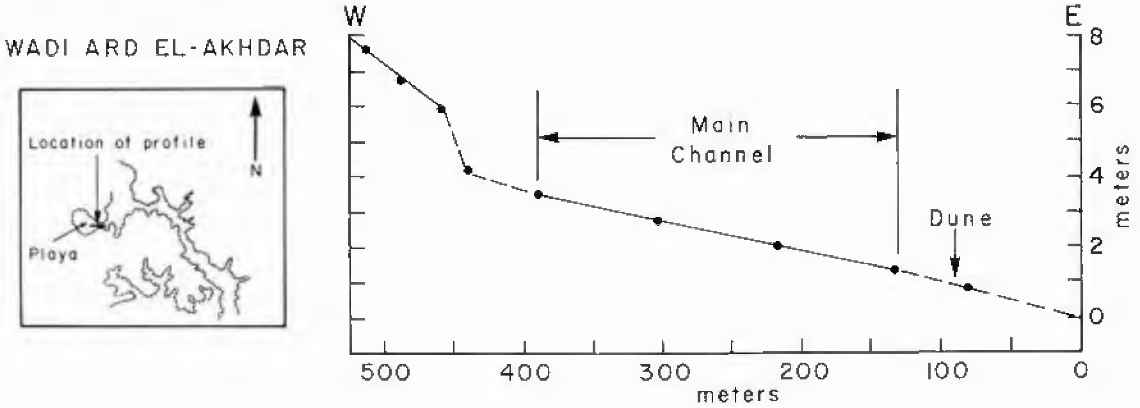

Figure 19.11 Longitudinal channel profile of Wadi Ard El-Akhdar near the constriction in the canyon.

DRAINAGE EVOLUTION

The conflict between the absence of surficial drainage patterns on top of the plateau, and the presence of the extensive wadi systems was explained by Bagnold in 1939 (in Peel, 1939b) as the result of subsurface drainage forming the wadis from rainfall seeping through the plateau surface. This hypothesis is supported by the observation of a discolored, friable sandstone alcove found midway up the southern cliffs of Wadi Ard El-Akhdar. However, the record of interbedded dune sand and lacustrine deposits found in both Wadi Ard El-Akhdar and Wadi El-Bakht suggests sporadic, high magnitude floods that were able to breach the dune dams in recent times (<6000 years).

An alternative model for the development of the wadis has been suggested by Haynes (pers. comm., 1978). Since less resistant shales (e.g. the Lingula Shale of Klitzsch, 1978) once covered the surface of the plateau, it is possible that the present-day canyons of the southern Gilf Kebir represent inherited channels from pre-existing drainage networks on the surface of the plateau. According to this theory, any evidence for pre-existing integrated drainage has been swept away by eolian planation of the surface of the plateau. Drainage patterns that are present in dark-toned portions of the northern plateau (Fig. 19.2) may support this hypothesis, if they are incised into stratigraphically higher units than the caprock on the southeastern edge of the plateau. However, considerable modification of the wadi headcuts must have occurred since the destruction of possible pre-existing drainage, as evidenced by the abrupt cliffs that are not at grade with the top of the plateau.

The lack of extensive widening of the wadis incised into the southeastern edge of the plateau, and the preservation of interfluve ridges south of Wadi Wassa (Fig. 19.2) indicate the importance of headward erosion in the geomorphic development of the plateau. However, the occurrence of the canyons as linearly segmented reaches, with short, stubby tributaries often joining the main canyon at right angles (Peel, 1939b) suggests the influence of structural control on headcutting. Consequently, it is possible that subsurface, channelized flow occurred through piping, a phenomenon that occurs in several arid regions of the earth (Parker, 1964). However, more field work needs to be done on the surface of the plateau in order to test this hypothesis, with particular attention paid to the nature of the plateau surface at the heads of the major wadis. Playa lakes may have formed on the plateau where the water table reached the surface. If so, then these areas would have been attractive to the early inhabitants of this region, and thus may be opportune sites for future archaeological investigations.

MARTIAN CANYONS

The interpretation of erosional processes and their results in the canyons of the Gilf Kebir plateau are particularly suited to the martian problems of canyon erosion in stable headlands, cliff retreat by possible subsurface drainage, and eolian modification of fluvial valleys and channels. In addition, the climatic change from a relatively humid to an extremely arid environment in southwestern Egypt is similar to the change experienced on Mars, where liquid water could have existed on the surface earlier in the planet's history (Pollack, 1979; Cess and others, 1980). Analogous features include flat upland surfaces with no integrated drainage, the abrupt, blunt-shaped headcuts, and the prevalence of straight channel segments possibly controlled by regional structure. Although several types of channels exist on the surface of Mars, these characteristics are typical of those classified as "runoff" channels by Sharp and Malin (1975). The spectacular outflow channels of the martian equatorial region generally do not share these attributes (Baker and Milton, 1974; Baker, 1978b), but terminate in chaotic, slumped terrain suggestive of a catastrophic release of water (Carr, 1979).

As viewed on orbital images, the stubby, linear segmented canyons of the southeastern Gilf Kebir resemble the tributary canyons on the south side of Ius Chasma on Mars (Maxwell, 1980), although there is a major difference in valley morphology. Instead of the characteristic flat floors of the canyons in the Gilf Kebir, the Ius Chasma tributary canyons are dominantly V-shaped, and very little floor is visible in the upstream portions of the canyons. Here, smooth surfaced talus slopes form the valley sides, extending to the base of the canyon (Fig. 19.12). However, the absence of tributaries on the surrounding upland plains, and the termination of the canyons is subcircular, amphitheater-like depressions are suggestive of erosion by drainage of

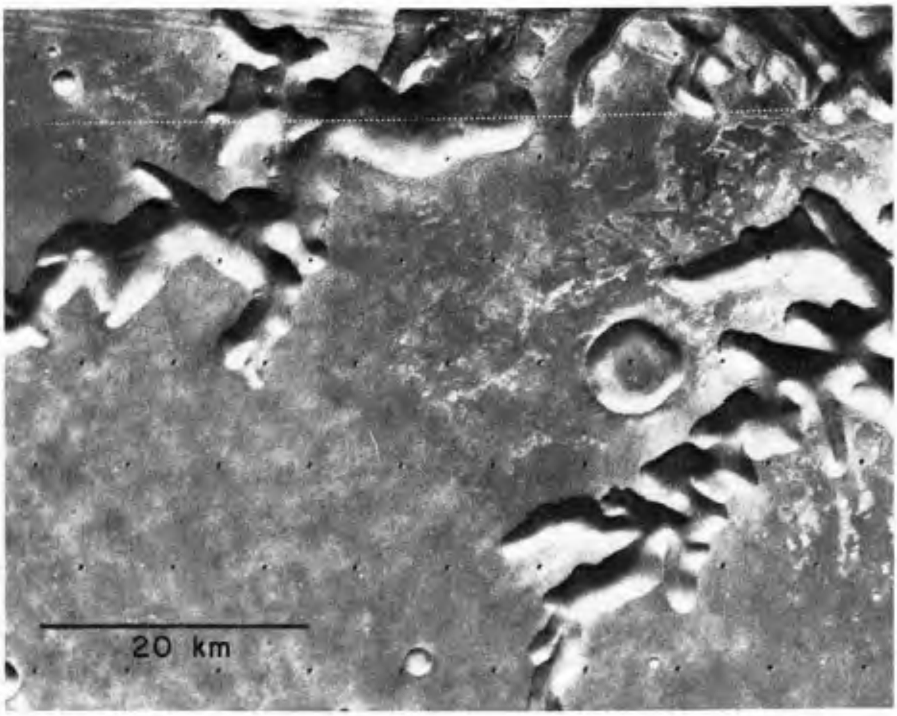

Figure 19.12 Tributary canyons on the south side by Ius Chasma on Mars. Note lack of low order channels on surrounding plains and abrupt termination of canyons in amphitheater-like depressions.

subsurface water (Sharp, 1973). It is possible that the differences in valley morphology may result from a less resistant "caprock" layer in the Ius Chasma region, which combined with the previously active tectonic formation of Vallis Marineris (Frey, 1979), would create conditions that favor unstable valley walls.

In the tectonically stable plains 500 km southeast of Vallis Marineris, the canyons of Nirgal Vallis display an outline similar to the wadis of the Gilf, and are also characterized by flat floors. This 700 km long canyon in the Mare Erythraeum region is characterized by abrupt headcuts of numerous tributaries, widening of mid-valley reaches, and an increase in width downstream, which led Sharp and Malin (1975) to suggest sapping and runoff as the principal mechanism for formation of the channels. Aided by Viking Orbiter images, it is possible to see finer details within the canyon than were evident in Mariner 9 images, which provide further evidence for subsurface drainage.

Near the upstream end of the valley, small tributaries are much more subdued than the main canyon possibly the result of mantling by eolian material. Sharp and Malin (1975) noted that the upstream portion of Nirgal Vallis exhibits a darker floor than the surrounding plains, which could result from the trapping of dark, mobile material. Consequently, the absence of low order tributaries to Nirgal Vallis may be in part due to infilling by eolian debris, although the similarities of canyon outlines to those in southwestern Egypt support an origin by subsurface drainage rather than by surface runoff (Fig. 19.13).

The effects of structural control on the location of canyons is evident in both the Gilf Kebir and Nirgal Vallis. In Wadi Ard El-Akhdar, the location of the constriction of the upper channel at the boundary between the basalt intrusion and the quartzite suggests that headward erosion took advantage of this weakness in the bedrock. In addition, the predominant north-south alignment of wadis in the northern Gilf Kebir may have resulted from drainage localized by fractures that originated during uplift and eastward tilting of the plateau (Maxwell, 1979b). Structural control on the location of tributaries to Nirgal Vallis is represented by north trending ridges and scarps that terminate at the headcuts of several tributaries, and continue on the opposite side of the canyon (Fig. 19.14). Assuming that these ridges represent folding or faulting of the local bedrock, it is possible that the flow of subsurface water was localized along these discontinuities resulting in an enhanced zone of headward erosion. Of the four tributary canyons that exhibit this phenomenon, three are incised into the south side of Nirgal Vallis, possibly suggesting a more abundant source of water to the south.

As shown by our field investigations in the southern Gilf wadis, the relatively recent eolian regime has had a great effect on the type of sediments deposited on the wadi floors, but has done little to mask the effects of the original fluvial processes that created the canyons. Instead, the location of wind-blown deposits has been controlled by pre-existing forms (such as south-facing cliffs),

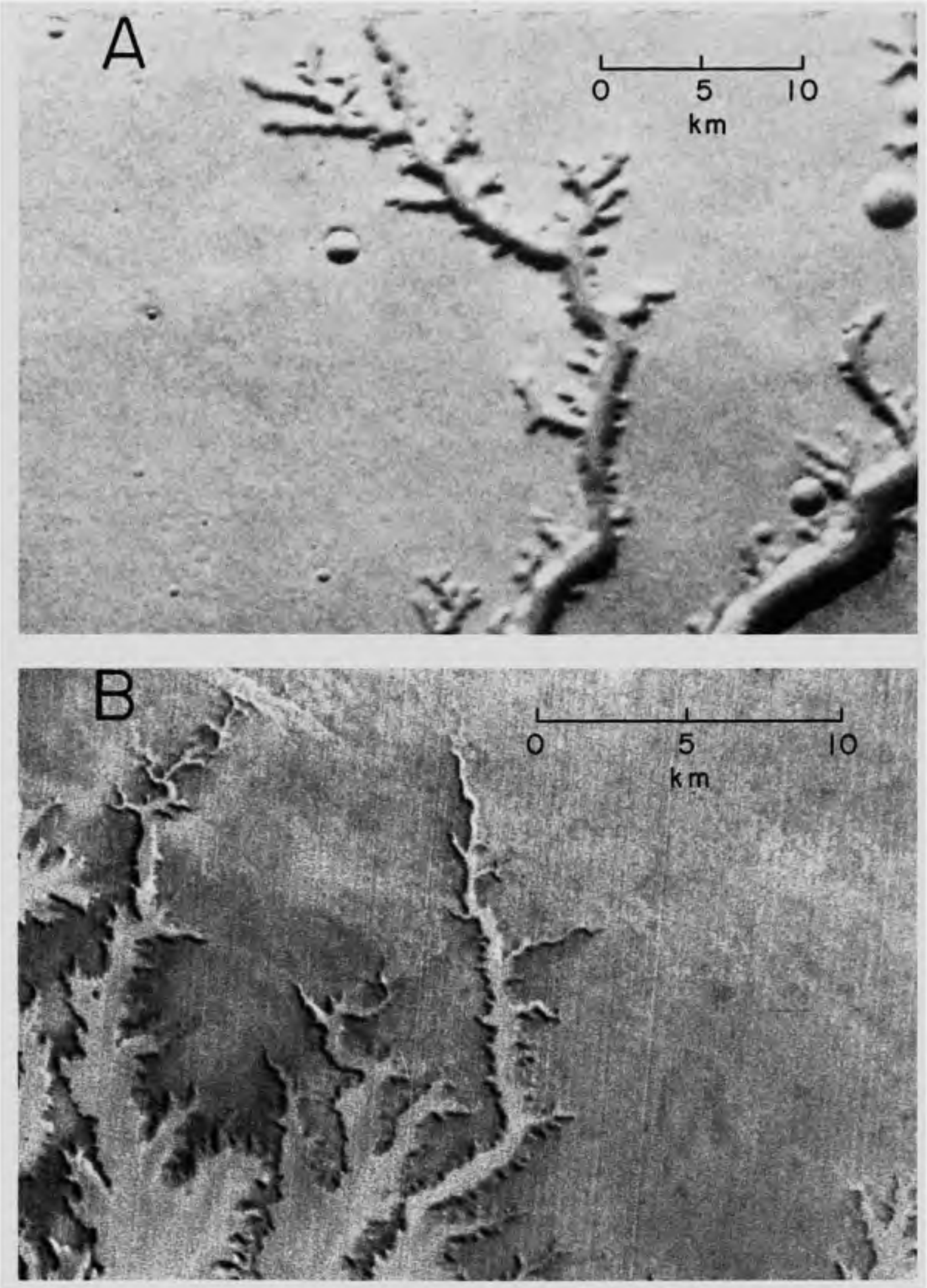

Figure 19.13 Tributary canyons to Nirgal Vallis on Mars (A) and drainage canyons of the southeastern Gilf Kebir (B). Canyons in both places abruptly terminate in subcircular depressions, and are dominantly flat floored.

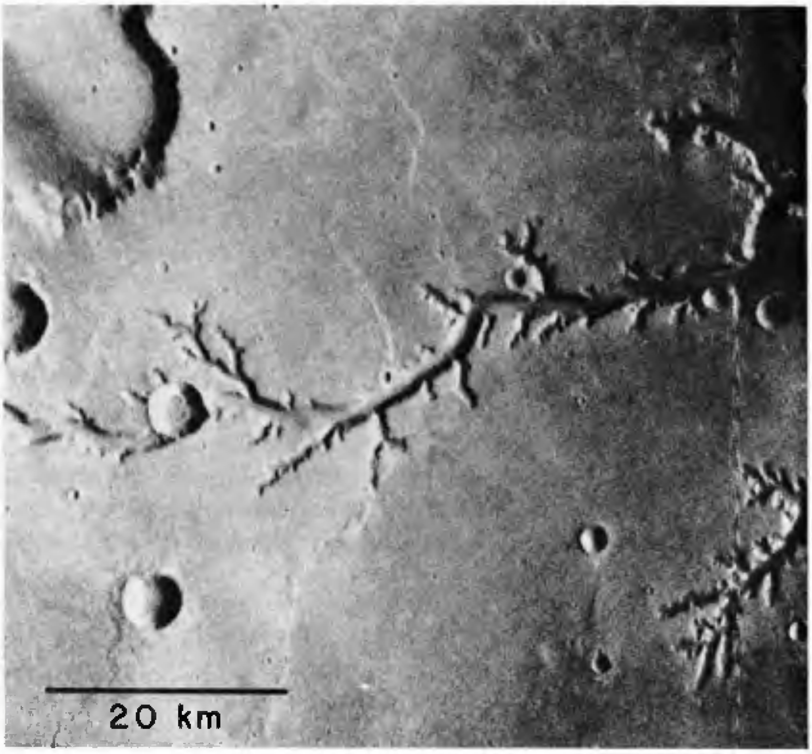

Figure 19.14 Tributary canyon on the south side of Nirgal Vallis that is suggestive of structural control. Canyon terminates at location of ridge in the upland plains.

resulting in the formation of lee-side dunes in Wadi El-Bakht and Wadi Ard El-Akhdar. Since they are transient features, the dunes have imposed temporary base levels, locally affected the gradient of the wadi channels, but have not caused any change in canyon outline or in the dominant flat-floored character of the valley floors. These observations thus suggest that many of the morphologic characteristics of martian canyons may truly be relict fluvial topography, with relatively little recent modification.

CONCLUSIONS

Erosion patterns of the Gilf Kebir plateau provide evidence for previous fluvial activity, which has now been taken over by the eolian regime of the present-day hyperarid climate. The extensive systems of wadis that are carved into the resistant quartzarenite and quartzite caprock of the plateau are dominantly flat-floored, and terminate in abrupt headcuts in the plateau interior. In the upstream reaches of Wadi El-Bakht and Wadi Ard El-Akhdar, lee dunes have dammed the channels, resulting in extensive deposits of playa mud. It is apparent that early man took advantage of these geologic conditions, the lakes for storage of intermittent rain water, and the quartzite for the production of implements.

Both field investigations and observations of orbital images support Bagnold's early hypothesis of subsurface drainage of the plateau.

The absence of surficial drainage networks and the steep cliffs that characterize the upstream ends of the wadis may best be explained by eastward drainage of water trapped beneath the caprock of the plateau. Headward erosion of the wadis took advantage of the pre-existing structure, as shown by the location of the constriction of Wadi Ard El-Akhdar at the contact between basalt and quartzite, and by the north-south alignment of wadis in the northern Gilf Kebir. It is suggested that subsurface water may have been channelized by piping in the siltstones of the plateau, thus accounting for the linear segments of the wadis.

The similarities in canyon outline and valley shape between the Gilf Kebir wadis and the tributary canyons of Nirgal Vallis on Mars suggest that similar mechanisms may be responsible for their formation. Subsurface runoff, perhaps in the form of piping may have substantially contributed to headward erosion on both Earth and Mars (Baker, 1978b), resulting in the abrupt headcuts and amphitheater-like terminae of the canyons.

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