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THE QUATERNARY EVOLUTION OF WADI BISHA (SAUDI ARABIA):

A MORPHO-CLIMATIC INTERPRETATION

By

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ABSTRACT

THE QUATERNARY EVOLUTION OF WADI BISHA (SAUDI ARABIA):
A MORPHO-CLIMATIC INTERPRETATION

By

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An attempt has been made to study the effect of climatic changes during the Quaternary Period on various geomorphic systems of Wadi Bisha and the Uruq Subay' Basin of southwestern Saudi Arabia. The four geomorphic systems which are believed to have evolved as a direct response to Quaternary climatic changes are: river terraces, conglomeratic duricrusts, Khabrat (playas), and eolian forms.

The investigation involved fieldwork, arial-photo interpretation, and litho-stratigraphic analysis, and the study of relevant literature on arid-zone morpho-climatology.

The study led to the recognition of three alluvial terraces, the distinction between two types of conglomeratic duricrusts, a tentative establishment of the presence and extent of Khabrat, and a genetic interpretation of eolian forms in the study area. On the basis of these findings, three Quaternary pluvial phases, interrupted by two interpluvials, have been recognized. A correlation of the form and material sequences in Wadi Bisha with established time-stratigraphic schemes of the Near Eastern and the European Quaternary reveals only partial agreement and calls for a great deal of further site work in Saudi Arabia.

To Jawahir

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER I

INTRODUCTION TO THE GEOMORPHIC PROBLEMS OF WADI BISHA

Terrain evolution in any given natural region depends mainly on the character and intensity of geomorphic processes and geologic structure; both are subjected to changes over time. Geomorphic processes are controlled by the prevailing climatic conditions. Most arid regions of the subtropics, however, exhibit landforms and other physical features that are not in harmony with the current climatic regime.

There is ample evidence that the subtropical deserts possess land features which are inherited from a moister climate. In the Arabian Peninsula, the most striking phenomenon is the presence of a fluviatile drainage network, or a wadi system, in areas presently under fully arid climatic conditions.[1]

Most of the Arabian wadis exhibit certain characteristics which are indicative of strong fluvial influences in the formation of a landscape, which today, is of the desert type.

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[1]The term wadi is an Arabic equivalent for valley which is widely used to describe arid region water courses, especially those of the Sahara and Arabia. In Saudi Arabia the term is used for a well-developed valley. Maseel is used to describe a gulley or narrow channel that is occupied by torrents waterflow.

The drainage system, most conspicuous even on small-scale maps, but particularly on aerial photographs, has a fairly high channel density in most of the interior basins, especially on the broad slopes which are drained by the wadis of Asir and the Hijaz Plateau. This dense drainage network can only be explained by a much larger runoff rate, compared to that of today. Moreover, the drainage system has an integrated arrangement: small valleys terminate in larger ones, which in turn terminate in a few master wadis, some of which reach the sea. Increasing valley size indicates that at some previous time discharge also increased downstream. Wadi al Rummah, for example, was continuous in the past from the eastern slope of the Hijaz Plateau through Central Arabia (Dahna Desert) and reached the Arabian Persian Gulf, a distance of more than 700 km from its source. Today's flow in the Wadi al Rummah dissipates in Najd, well "upstream" of Al-Dahna.

Most of the wadis of the peninsula are deeply entrenched into bedrock and have thick alluvial fills. Such characteristics reflect coarse bed load and cutting power with large discharge. In Wadi ad Dawasir, for instance, the alluvium reaches 100 m in thickness (Italconsult, 1969a).

The presence of well-rounded gravels in various wadis indicates transport by streams of considerable transporting capacity. Studies of gravel samples indicate that, in most cases, the gravels were transported long distances from upstreams of their current positions. Wadi al Batin, for example, contains channel gravels that must have been transported from the igneous and metamorphic rock complex of the Hijaz Plateau over a distance of at least 300 km (Powers et al., 1966). Today, Wadi al Batin is almost completely covered by the sands of the Al-Dahna desert.

The wadis of the arid zones exhibit certain form elements which are similar to valleys in humid regions. Cross sections in the upper reaches are V-shaped, the middle courses are box-shaped, and the amount of alluvium increases downstream. Headwater and middle sections of wadis display evidence of "active erosion," while extensive alluvial plains characterize their lower reaches (Petrov, 1976). There are, however, indications of recent fluviatile dissection: small channels (arroyos) have been cut into the soft materials of the wide channel floors. This shows that the current "underfit" discharge that occurs sporadically is not morphologically insignificant; it is strong enough to form a new set of low terraces in older alluvium.

Statement of Problem and Research Objectives

This research was aimed to investigate the geomorphological effects of known climatic changes that took place during the Quaternary Period in the subtropical zone in a selected site of the Arabian Peninsula.

The Study Site

Wadi Bisha, known to the author from previous brief visits, was chosen as representative for exhibiting a fluviatile history alternating between erosion and deposition. To prove that changing environmental conditions were the major cause for Quaternary landform evolution in the wadi, certain landform systems were given particular attention.

River Terraces.--Various aspects of a clearly defined river terraces system were investigated, such as the types and numbers of terraces, type and size of materials or each terrace, sorting, bedding and stratification of the materials, and the position of each terrace relative to others. Such study will help in drawing a fairly clear picture of the fluviatile regime that led to the deposition of the massif wadi alluvium and the alternation between deposition and erosion.

Conglomeratic Duricrusts.--The mere existence of duricrusts is indicative of climatic change. Duricrusts of the wadi were studied in terms of lithologic type, sources of calcareous matter, associated materials, and the positions of the conglomeratic accretions in the alluvial profile of the wadi. Conclusions about the environmental conditions that led to the deposition and encrustation of the wadi duricrusts are correlated with other previously active and current geomorphic processes.

Khabrat (playas).--Playas are interpreted in the literature as the legacies of Pleistocene (pluvial) lakes (Neal, 1969). One of the research objectives is to study, with the help of airphotos, the possible existence and the distribution of Khabrat over the study area. Moreover, the relationships between Khabrat and other landform systems of the study area are to be investigated.

Eolian Forms.--About 50 percent of the study area is covered by eolian landforms, mainly sand dunes and almost relief-less sand sheets. The main research objective, here, is to study the development and distribution of, as well as the relationships between, eolian forms and other landform systems of the study area. To an extent, it is also possible to reconstruct former wind directions in fossil dune fields and compare them to the current wind transport pattern.

The need of this study arises from the lack of systematic morpho-climatologic and geomorphologic studies of Arabia. Aside from Wadi Hadhramout of south Arabia, which underwent several morphological investigations, the Arabian Peninsula's morpho-climatology and geomorphology are only presented in scanty reports or articles. These are generally descriptiove of the existing landform types. Holm (1960), for example, wrote about the desert geomorphology of the Arabian Peninsula, devoting the main discussion to the distribution and types of sand dunes. A similar report by Brown (1960) was written about the geomorphology of western and central Arabia. Several other studies concentrated on one landform types, such as that of Chapman (1974) who wrote on the calcareous duricrusts of the Eastern Province of Saudi Arabia. Only in 1978, however, while this research was well underway, the first part of a comprehensive morpho-climatologic study of Arabia was published. The study was conducted by members of both the Austrian Academy of Science (Vienna) headed by Zötl (1978) and the University of Petroleum and Minerals (Dhahran, S.A.) to investigate the climatology and geomorphology of the Quaternary Period of Saudi Arabia. Several conclusions concerning the climatic history of Arabia during the Quaternary Period were given in the mentioned study. These will be reviewed in the following chapter.

Research Procedures

In accordance with the stated research objectives, the investigation involved fieldwork, aerial photo interpretation, sample analysis, and the study of the relevant literature on morphoclimatology of the arid zone and on the study area.

Fieldwork

Fieldwork was carried out in the area between El Madarah and al Junaynah (Figures 1, 3). The area was chosen, mainly, because the geomorphic systems of the wadi, such as river terraces, duricursts, and floodplain are conspicuous and accessible. They are not totally masked by eolian sands as is the case in the lower courses of the wadi. Moreover, the area has been studied geohydrologically (Italconsult, 1969b), so that base maps, as well as geohydrological maps and accompanying reports are available; the rest of the wadi is devoid of any intensive geomorphic and geologic studies.

Fieldwork was carried out during the summer of 1976. It included an inventory of the geomorphic systems near the town of

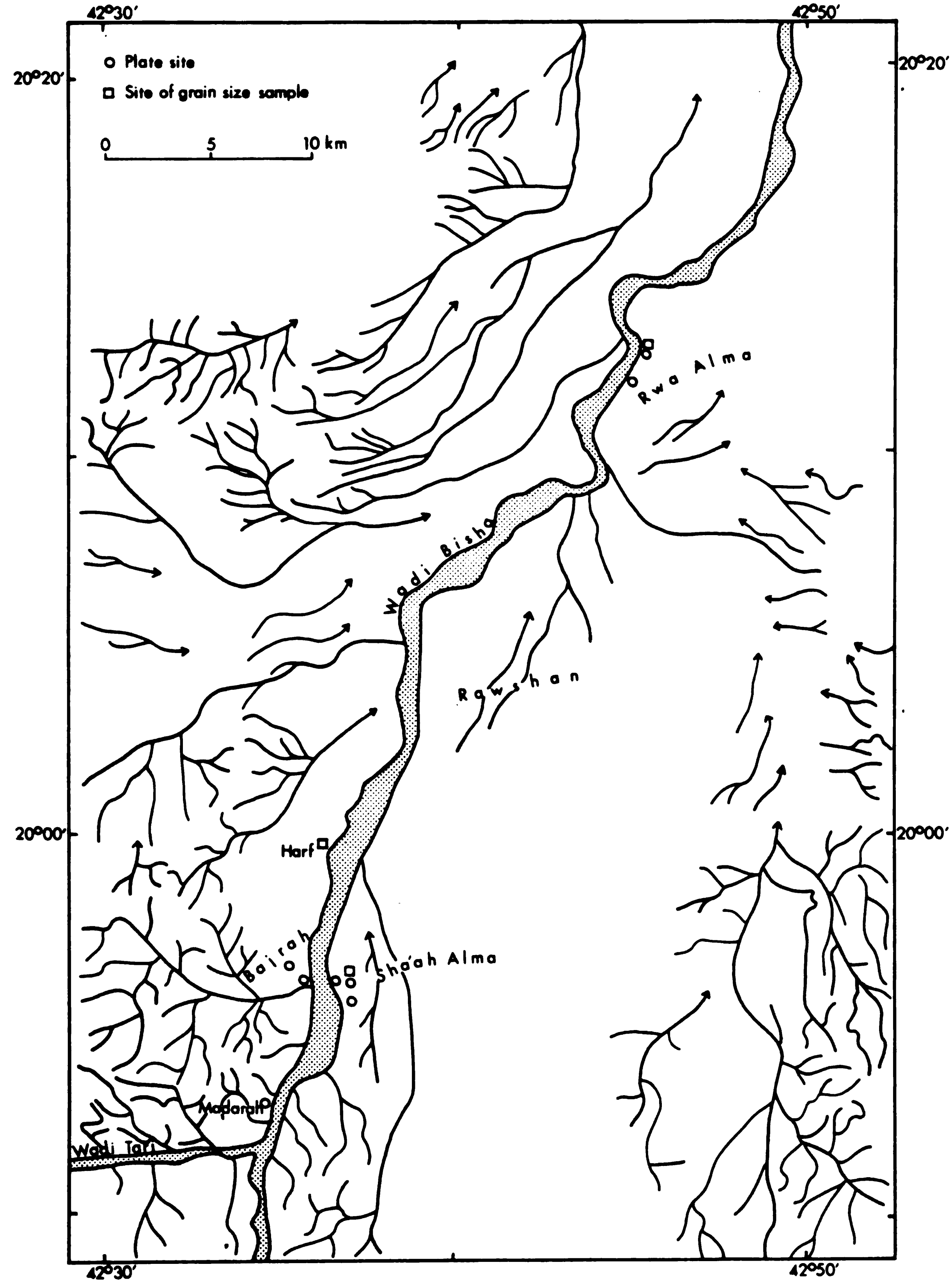


Fig.1 Main field sites in the middle course of Wadi Bisha.
(source: Italconsult, 1969c)

Bisha by site documentation, sketching, lithological sampling, and ground photographs. Surveying and leveling terraces were also executed. The fieldwork also included a reconnaissance trip from Bisha town to the upper reaches of Wadi Bisha. It was aimed to observe form systems and materials in the wadi in the Hijaz Plateau and Asir Highlands.

Aerial Photographs

A major source of data were some 270 airphotos that were purchased from the Ministry of Petroleum and Mineral Resources with the cooperation of King Abdulaziz University. The airphotos were taken by Western Shield Agency over the middle and lower courses of Wadi Bisha, Uruq Subay' basin, and Wadi Ranyah. Considering the problems of surface transportation in the study area, allowing direct access to only a very limited portion of the wadi, the rendition of the form complexes in the aerial stereomodel proved to be of great value.

Data Analysis

Post-fieldwork processing of the data and samples included cartographic, aerial-photographic, and laboratory analysis. Although the size of both the intensively studied field stie and of the collected samples is small, it is believed that the conclusions reached in this study rest on firm evidence.

CHAPTER II

EFFECT OF CLIMATIC CHANGES ON ARID LANDFORMS

Climatic changes of the Quaternary Period were characterized by phases of long-term rainfall or pluvials and temperature decrease. The term "pluvial" was introduced by Hull (1884) after he recognized evidence of moist phases in lower latitudes (Butzer, 1961). A pluvial may be defined as time-stratigraphic period of widespread, long-term rainfall during the Pleistocene, of sufficient duration and intensity as to be of stratigraphic and geomorphic significance (Butzer and Twidale, 1966; Butzer, 1958, 1961, 1963).

Pluvials are believed to be multi-phased, and not uninterrupted moist periods. In the subtropical zones, several interpluvial periods have been found separating the pluvials. Such interpluvials were characterized by dry climate, as proved in the Sudanese Sahel and southern Africa (Butzer, 1958). The pluvials of the Quaternary period are associated with Pleistocene epoch. Pluvials of the Pleistocene epoch are believed to have coincided with the continental glaciations of middle and high latitudes.

The Correlation Between Glacials and Pluvials

The concept of pluvials being associated with the Pleistocene glacials was not being thought of until the recognition of glacio-eustatic sea level fluctuations. During each of the glacial phases of the Pleistocene, large amounts of water were withdrawn from the world's oceans and locked up in the continental ice masses. This resulted in lowering of the world sea level by at least 100 m (Butzer, 1958). The association of pluvial continental deposits and marine regression has been proven in the Mediterranean and other low latitude areas (Butzer and Twidale, 1966). The geological evidences that correlate the Pleistocene glaciations and sea level changes (marine regressions) with the Near East pluvials, are based upon palaeoclimatic, geologic, and geomorphic studies in the Aegean, Black, and Caspian Seas, the Coast of Lebanon, and the Coastal Plain of Palestine. One of the most convincing studies in this respect is that of Pfannenstiel (1952) concerning the Coastal Plain of Palestine. As reviewed by Butzer (1958), the study concentrated on the analysis of bore hole profiles taken in the area. Pfannenstiel reconstructed five lithostratigraphic profiles from the present coastline inland. They rest on the Lower Pliocene bedrocks and contain a series of marine and terrestrial horizons. The position of terrestrial horizons (gravels) on top of the marine sediments suggests that the former had been deposited by running water after the exposure of new land during regressive phases which must have been in phase with the major Pleistocene glaciations.

In the study of the alpine Quaternary geology, Penck and Brückner (1909), who first suggested four major glacial phases during the Pleistocene, observed transitions and interfingerings of terrace and plateau gravels with glacial morainic deposits. They attributed that to the coincidence of glacial epochs with phases of alluviations (Cotton, 1945). A similar conclusion had been reached by Bryan and Ray (1940) in their geomorphic study undertaken to determine the age of archaeological sites east of the Rocky Mountains of Colorado. They admit no possibility other than the correlation of downstream gravels with substages of glacial advance. They observed that alluvial stream terraces "can be traced continuously along the major streams into mountains where each terrace ends at the moraine left by an ancient glacier" (Bryan and Ray, 1940, p. 27).

Evidence of Climatic Changes in Arid Landforms

The pluvials and interpluvials of the Quaternary left their imprints on the landforms and other physical features of the arid regions of the subtropics. A brief description of the major geomorphic features whose origin must be associated with the Quaternary climate changes is presented here.

Khabrat (Playas)

Khabrat is an Arabic term for inland saline or clay-silt flats known as playas in western terminology. These occupy the lowest areas in closed desert drainage basins. They are mostly vegetation-free surfaces of finely grained sediments. Most of the world's playas are believed to be the relics of Pleistocene lakes. In southwestern United States, at least 120 of the known 300 playas are believed to have been pluvial lakes during the Pleistocene. Most evident are lakes Bonneville and Lahontan (Cooke and Warren, 1973;

Butzer, 1961). In the Sahara, the site of a vanished lake is found in the "Pays-Bas" of Bodele Depression (Peel, 1966).

Khabrat contain sediments of clastic and non-clastic origin. The clastic sediments are usually clay, silt, and fine sand that were transported by surface runoff and deposited, in most cases, into standing water bodies. Non-clastic sediments come mostly from ground water and are mainly saline deposits or evaporites (Cooke and Warren, 1973). The size and shape of a playa is dependent on the drainage basin's morphometric properties. Cooke and Warren (1973) found that in 38 playas of the Mojave Desert in California the playa size correlates positively with the drainage basin area. In Saudi Arabia, khabrat are widely distributed over the major four deserts. For instance, a group of khabrat are occupying an area of about 130 km by 75 km near the center of the Najd Pediplain (Brown, 1960). At Wadi ad Dawasir there is an extensive khabra between Kabkabiyah and Sulayyil extending over 180 km (Powers et al., 1966). In the southwestern Ar Rub Al Kahli, a series of low terraces of lacustrine origin is present. They represent fresh-water sediments. They are interbedded, white, tan, and brown, fine-grained, quartzose sands with micaceous, silty, and, rarely, gypsifereous clay and fossiliferous silt. A number of fragments of vertebrate teeth and bones were found within or were associated with the lacustrine deposits. The age, based on these fossils, is considered to be late Pleistocene to early Recent (Powers et al., 1966).

Alluvial Deposits

Semi-rounded and polished gravels are widely distributed over channels and flood plains of Arabia's and the Sahara wadis. Their present occurrences confirm that greatly increased discharges occurred in the wadis and resulted in the transportation of the gravels for great distances from their sources. Large portion of ad Dibdibah Plain, for instance, is covered by alluvial gravels that represent the remnants of a wide floor of rock debris derived from the basement complex for at least 300 km, and funneling out through the Ar Rummah-al Batin channel system, covering a surface of about 60,000 km^2. The gravel is chiefly composed of quartz pebbles, with varied admixture of carbonate, igneous, and metamorphic grains (Powers et al., 1966; Hötzl, Kramer, and Maurin, 1978). In south-eastern Arabia, large coalescing delta-like surfaces of gravel sheets are found pouring out of the Wadi as Sahba-ad Dawasir-Najran drainage system. The present distribution of this gravel sheet indicates that prior to the formation of Ar Rub Al Khali and al Jafurah sand deserts, a vast part of the area west of 51° E was covered by alluvial materials emanating from thse channels (Powers et al., 1966; Hötzl, Kramer, and Maurin, 1978).

Duricrust

Duricurst has been described as a concentration of siliceous, aluminous, ferruginous, and calcareous materials that originated as a product of soil forming processes. Such processes are the repeated wetting and drying of the soil under a climate of increasing aridity or strong seasonal moisture contrasts. During more humid periods, a saturated alkaline solution can rise either by capillary action or as a result of a rising groundwater table. $CaCO_3$ is precipitated as the water evaporates, during drier periods, thus leaving an indurated crust in and on the soil (Miller, 1937, Chapman, 1971, 1974). Duricrusts have been investigated in Saudi Arabia in several areas. Chapman (1974) studied duricrusts in the Shedgum area which includes Scribner's Canyon between Abgig and Hofuf. According to this source, duricrusts overlie surfaces of erosion of different ages. Subsequently, duricrusts of different stages were recognized. Scribner's Canyon is a Pleistocene valley that cut its course through sandy limestone at the eastern edge of the Shumman Plateau. Four bedrock terraces have been recognized in Scribner's Canyon. Duricrusts developed throughout the Shedgum area which includes the plateau surface, the top of erosional outliers, wadis walls and gullies, and all of the four recognized terraces. As Chapman pointed out, duricrusts over the Shedgum area are of different characteristics. Those developed over the plateau surfaces, which presumably are the oldest topography in the area, are the thickest and most thoroughly developed. The thinner and less thoroughly developed duricrusts rest on successively younger surfaces; these are the four terrances and the present channel of Scribner's Canyon. One may conclude that duricrusts on the oldest surfaces are older and more mature than those on the younger surfaces. More important is the implication of a time lapse along with climatic changes. After the development of duricrusts on the oldest (Plateau) surface, a phase of wet climate folowed which resulted in the incision of Scribner's Canyon and the development of the first terrace. A subsequent drier phase followed and was marked by the development of a duricrust on the new stream-eroded topography. The alternation of wetter and drier phases continued until the thinnest, least developed duricrust was formed on the present channel of Scribner's Canyon.

There are other non-geomorphic features that are indicative of past humid phases in the arid regions of the subtropics. These include the following.

Paleosols

Fossil soils are found in the Sahara and the Mediterranean region. Birot, Capot-Ray, and Dresch (1955) found a fossil red soil associated with joint cavities in the Hoggar massif, suggesting a hot, seasonal-rainfall type of climate (see also Peel, 1966). A wide-spread occurrence of *terra rossa* soils in the Mediterranean region has been interpreted by Kubiena (1963) as a product of wetter conditions in the past.

Organic Fossils

In the field of paleobotany, Quezel (1963) and his associates found fossil woods of oak and cedar types in the Tibesti Mountain of the Sahara. These are estimated to be 20,000 years of age. This proves that some 20,000 years ago the climate of the Sahara was avorable for the growth of oak and cedar forests which can survive only in humid regions.

Anthropogenic Remains

An abundance of archaeological evidence from ages back to palaeotithic and neolithic times are found in the Sahara and show that man then inhabited regions of the Sahara which are now completely uninhabited (Peel, 1966). In the Ar Rub al Khali desert, Palaeolithic and Neolithic sites have yielded arrowheads, fist hatchets, scrapers, and other stone implements--all such were found beneath river banks or associated with lacustrine deposits (Zeuner, 1954).

Evidence of Pluvials in the Arabian Peninsula

The Arabian Peninsula, according to recent geologic studies (Hötzl and Zötl, 1978), had experienced several humid phases between the late Pliocene or early Pleistocene and the Holocene. In the late piliocene/early Pleistocene, an intensive, long, humid (pluvial) phase took place, probably between 1.2 - 2.5 million years B.P. It resulted in the entrenchment of the wadi systems of Arabia. It also left its marks in the vast depositional landforms: most impressive is the alluvial plain of ad Dibdibah which had been deposited by the Ar Rummah-al Batin Wadi system. It covers about 60,000 km^2 of the north central part of Saudi Arabia. The Wadi ad Dawsir-Najran drainage system which originates in the southern Asir highlands, was responsible for the deposition of the alluvial plain of Ar Rub Al Kali which covers vast areas of southeast Arabia (Hötzl and Zötl, 1978).

During the entire middle Pleistocene, the Arabian Peninsula according to the mentioned source, is believed to have been under arid conditions, with minor humid phases of little geomorphic and stratigraphic significance. Most of this period was marked by strong eolian deposition that resulted in the formation of the great deserts of Arabia. Discharge over wadis of Arabia probably were similar to that of today, except for short humid periods that caused the filling, by eolian sand and alluvial materials, of the wadis channels (Hötzl, and Zötl, 1978).

During the period between 25,000 - 30,000 years B.P., a period which corresponds to the late Würm stage in formerly glaciated parts of the earth, the Arabian Peninsula had substantial amounts of precipitation. This is evidenced by sinter formations in terraces, caves, and soils, and weathering horizons. Carbon-14 measurements made from calcite crusts collected from gravels below the surface of terraces in Wadi Shibah (a tributary of Wadi Ar Rummah) revealed ages of 28,900 ± 1,300 and 30,200 ± 1,300 B.P. (Hötzl and Zötl, 1978).

In the Mugabil loam pit of Wadi Ranyah, samples collected from the limy crusts at depths of 0.7 and 1.0 m below the land surface have carbon-14 ages of 26,400 and 29,840 years B.P. for the origin of these calcite horizons. Such results lead to the conclusion that there was enough precipitation to produce soil caliche for this period (Hötzl, Lippolt, Maurin, Moser, Rauert, 1978).

Relics of late Pleistocene pluvial lakes in Ar Rub al Khali speak in favor of a longer humid phase that matches the entire Würm Glacial. A series of lake beds were found in the lee of Seif dunes in southwestern Ar Rub Al Khali with C^{14}- dates ranging from about 36,000 years B.P. to about 17,000 years B.P. (McClure, 1978). The period between 17,000 - 9,000 years B.P. was characterized by arid conditions, with strong deflation and eolian deposition. McClure (1978) termed it a hyperarid period in Ar Rub Al Khali.

A humid subphase between 9,000 - 8,000 years B.P. is recognized in several areas of Arabia. There are shells collected from limnic sediments at the base of the young terrace of Wadi al Luhy in central Arabia. Their age is 8,400 ± 140 years B.P. In recent times, this species has been found in warm humid climates, such as in the Sudan, and Zaire (Hötzl and Zötl, 1978). In Al-Hasa region (east Saudi Arabia), peat and charcoal were found on flat hills and C^{14}- dated at 8,290 ± 120 years B.P. (Felber et al., 1978).

A subpluvial lake with radio carbon dates ranging from 9,000 - 6,000 years B.P. is found separating red, eolian sand depositions in southwest Ar Rub Al Khali (McClure, 1978). The rest of the Holocene is believed to have had similar arid conditions to those that prevail today over Arabia, with some intervals of minor increase in precipitation (Hötzl and Zötl, 1978).

Wadi Hadhramout had been under investigation by Caton-Thompson and Gardner (1939) for paleo-climate and archaeology. According to these authors, the history of the evolution of Wadi Hadhramout can be divided into distinct phases. There is evidence of a major erosional phase that can be witnessed in the major channels of the Wadi and its tributaries. Whether we deal with one phase or repeated entrenchment, is not known, but a great amount of erosion is obvious. The time of cutting may be as early as late Tertiary or early Pleistocene. This phase indicates the availability of a large water surplus, as shown by similar erosive activity in the Near East, such as the Kharga Oasis in Egypt and the Jordan Valley in Palestine (Butzer, 1958; Canton-Thompson and Gardner, 1932). A major depositional phase is indicated by deposits of considerable depth that fill Wadi Hadhramout. The exposed part of these deposits consists of fine-grained material. Caton-Thompson and Gardner (1939, p. 29) termed it "eolian silt." Structurally, it shows the prominent vertical jointing characteristics of loess deposits. In areas of the Wadi, this fine-grained material is overlying a gravel layer. Such stratification clearly reveals a two-phase sequence: a fluviatile phase, followed by a dry phase that is characterized by active wind deposition. Three minor erosional phases are represented by the gravel terraces at 10 m, 5 m, and 3 m. All three terraces contain man-made tools of chert.

Perhaps the best known morpho-climatic sequence is that of the Jordan Valley. Picard (1932, 1933, 1937), as outlined by Btuzer (1958), recognized three pluvial phases based on valley morphogenesis. Pluvial A was evidenced by the deposition of boulders, and fresh-looking gravels that overlie the base loam of earlier dry phase. Semi-arid conditions followed Pluvial A and was indicated by the formation of terra rossa. It coincided with a period of active vulcanism. Another prevalence of moist conditions (Pluvial B) followed and was marked by the deep incision of the resistant Rukkard lava of the preceeding stage, and the revival of Jordan inland sea. A phase of dry conditions followed Pluvial B, leading to a shrinkage of the Jordan inland sea. A weak phase of erosion (Pluvial C) took place in the upper reaches of the valley, marking the end of the Pleistocene.

CHAPTER III

THE EVOLUTION OF WADI BISHA

The Study Area

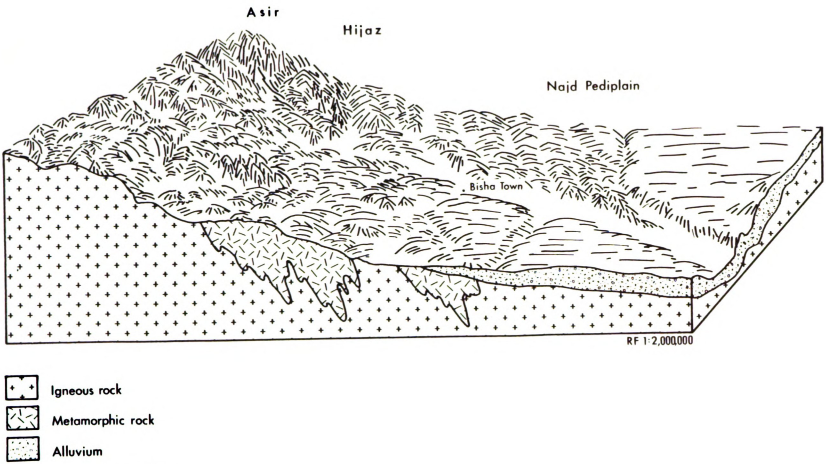
Wadi Bisha is one of the longest and most active drainage systems in southwestern Saudi Arabia. It trends in a southwest-northeast direction. It originates in the highland of Asir and empties into the accumulation plain of Bisha-Ranyah in the Uruq Subay' basin of the Najd pediplain (21° 15' N, 43° 20' E; Figure 2).

Physiography

The Wadi and its main tributaries (Tabalah, Tarj, and Harjab) run across formations of a Precambrian basement complex. The main rock types of these formations are as follows: granite (gneissic granite) and granodiorite, greenstone (schistose, with minor slate and phyllite), schistose greenstone (sericite and chlorite schist derived from the basic igneous rocks), and granodiorite formation interbedded with amphibolite schist (Figure 3; Jackson et al., 1963).

Wadi Bisha is about 500 km long. It has its origin in the vicinity of the town of Khamis Mushayt at an elevation of 2,237 m a.s.l. The altitude and ruggedness of the Hijaz Plateau decrease gradually in an easterly direction. The Wadi reaches the town of Bisha at the eastern border of the Hijaz Plateau at an elevation

Fig. 2 Wadi Bisha; general topography and structure.



Source: Jackson, et. al., 1963

Legend, fig. 3

QUATERNARY

Eolian sand; unstable

Lacustrine deposits, clay to sand

Alluvial materials; unconsolidated silt, sand, and gravel

TERTIARY

Basalt, olivine rich, and titaniferous

PRE-CAMBRIAN

Halaban formation (andesite)

Igneous rock, mainly granite, diorite, granodiorite

Metamorphic rock, chlorite, sericite schist, and greenstone

Fault

0 10 30 50 Km

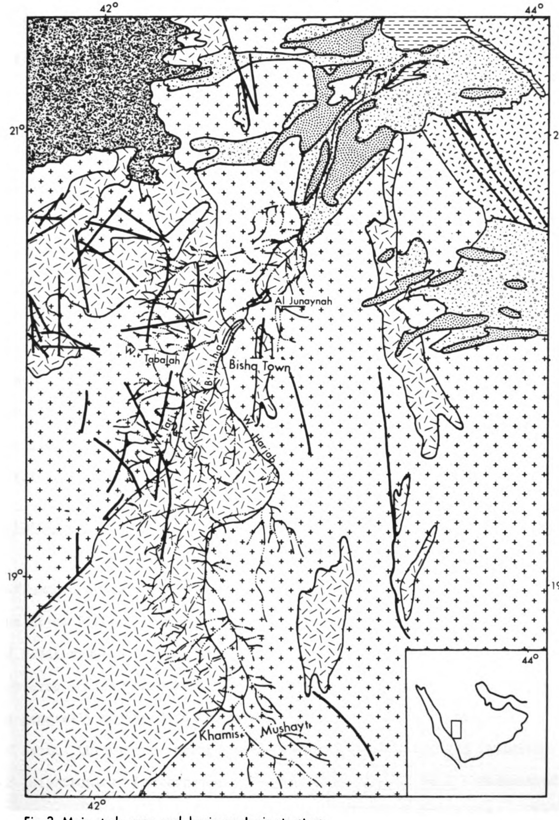


Fig. 3 Main study area and basic geologic structure.
(source: Jackson, et. al., 1963)

of 1,122 m. Further northeast, Wadi Bisha crosses its alluvial plains through the Najd pediplain, a vast area with typical inselbergs of crystalline rocks protruding through the alluvial deposits.

The Wadi Bisha channel is divided into two distinct sections. In the highlands of Asir and the northern Hajaz Plateau gorges are frequent. In this section, the Wadi channel is confined to the weak structure, resulting in a steeper gradient than that of the alluvial plains' section.

The alluvial plain begins in the transitional area between the Hijaz Plateau and the Najd pediplain near Heifa. It extends for about 300 km through the Najd pediplain, until it loses its definition under the eolian sands in the Bisha-Ranyah accumulation plain. There are 22 oases in the alluvial sections of the Wadi. These rely on the availability of the groundwater of the Quaternary alluvial aquifer (Italconsult, 1969a).

Climatic Aspects

The catchment area of Wadi Bisha and its tributaries is influenced by two different air masses. During the winter months, the Hijaz Plateau comes under the influence of westerly air masses of Mediterranean origin, usually associated with depressions that traverse northern Saudi Arabia. Rainfall from the westerly air masses is generally confined to the western escarpment and the Highlands of Asir. During the spring season the area comes under the influence of Intertropical Convergence. The ITC gives rise to fairly widespread rainfall over the upper portion of the Wadi Bisha drainage shed. The southerly monsoon becomes stronger and more frequent during the summer months; however, its rain is restricted to the southern and western regions and does not appear to occur north of 20° N or east of 44° E (Italconsult, 1969a).

Wadi Bisha can be divided into three climatic zones. The mountain zone, generally above 1,500 m, has a mean annual temperature between 16° and 21° C, with a mean range of 10° C. Average relative humidity is above 50 percent. Low temperature, comparatively high humidity, and considerable cloudiness offset the high radiation encountered in the mountain regions.

The steppe zone lies between 1,000 - 1,500 m. It has a mean annual temperature of 22° - 25° C, with a mean range of 15° C. Relative humidity averages around 30 percent. Potential evaporation in the steppe region is greater than that of the mountain range.

The desert zone lies below 1,000 m. It borders the lower oases of Wadi Bisha. The mean annual temperature in this zone is above 25° C, with a mean range of 18° C. The relative humidity is less than 30 percent. The combination of high temperature, low relative humidity, a high incidence of radiation, and hot air advection all provide for high potential evaporation rates of up to 2.5 m per year (Italconsult, 1969a).

Runoff

The runoff of an area is a function of the amount and duration of the rainfall, evaporation, soil conditions (such as permeability and degree of saturation), vegetal cover, and the degree of slope.

In hot desert areas, the rainfall is of a heavy storm type, with a very short duration. The vegetal cover is very scarce or non-existent. The combination of these two factors usually gives rise to intensive runoff in the desert valleys in the form of turbulent torrents. The effect of other variables, such as water deficiency in surface material, infiltration capacity, local topography, and the intensity of soil conservation in the form of terracing, however, are all important variables influencing runoff and erosion (Cooke and Warren, 1973; Leopold, Wolman and Miller, 1964; Italconsult, 1969a).

In Wadi Bisha, the main runoff-generating areas are the highlands of Asir and the plateau region. The existence of man-made terraces, however, in the mountains decreases the amount of runoff. Generally, the total runoff in these regions is insignificant when compared with the amount of precipitation. The annual runoff in the highlands of Asir and the Hijaz Plateau regions is estimated to be in the order of only 2 percent of precipitation (Italconsult, 1969a). It rarely reaches as high as 8 percent of the total precipitation. This only occurs when the amount of rainfall is uncharacteristically high so that it leads to the overflow of conservation terraces and a complete saturation of surface materials, as in the case of the years 1966, 1967, and 1968 (Table 1) (Italconsult, 1969a, p. 30).

Having a considerable proportion of its catchment area lying within the 200 - 300 mm rainfall belt, Wadi Bisha is considered one of the most important watersheds in the southwestern region in terms of total discharge.

TABLE 1.--Summary of runoff data of Wadi Bisha ($10^6 m^3$) (Italconsult, 1969a)

Station	Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Heifa	1966	-	-	-	0.20	-	-	-	-	-	-	-	-	(0.40)
	1967	-	-	0.10	8.43	5.82	-	2.42	2.45	-	-	21.35	0.20	(41.47)
	1968	-	25.53	0.83	53.94	60.0	14.26	1.02	0.85	-	-			(156.17)
Sada	1966	-	-	-	-	-	-	-	-	-	-	-	-	(NIL)
	1967	-	-	-	5.91	3.80	-	1.27	0.50	-	-	15.88	-	(27.36)
	1968	-	12.52	-	39.59	49.10	10.00	0.06	-	-	-	-	-	(111.27)

Although the existence of man-made terraces is very limited in the middle and lower courses of the Wadi, the runoff is extremely low due to high infiltration rates. This, in turn, is a consequence of highly permeable alluvial materials underneath the middle and lower courses of the Wadi.

Differentiation of Active Geomorphic Processes

The presence and the degree of effectiveness of any geomorphic process depends on a set of variables to be recognized by inductive and deductive investigation. This section is aimed at the discussion of dominating geomorphic processes in the study area and their effect on the development of morphogenetic regions. The study area appears to be divided into two morphogenetic regions based on the predominance and intensity of certain morpho-climatic conditions.

Asir Highlands and the Hijaz Plateau Region.--It extends from the Asir mountsins (> 2,500 m) to the foothills of the Hijaz Plateau (1,000 - 1,250 m). The average rainfall over the region ranges between 250 - 350 mm annually. Most of the rain comes in March and April. At this time of the year, the temperature is still low, and the evaporation is at minimum rate. Vegetal cover is sparse throughout the region, providing little protection for the soil, expecially in areas of relatively steep slopes without man-made terraces. All these variables make running water the dominating geomorphic agent over the region. Because of the nature of desert rain--heavy accumulation in a short period of time--sheet wash and sheet erosion is as likely to occur as concentrated channel erosion (Plate 1). Evidence of linear cutting is provided by a very conspicuous drainage system entrenched throughout much of the area.

Another important process is frost action. It is confined to the mountains above 1,500 m where the temperature falls below the freezing point in the winter nights for a considerable length of time. In addition, sleet, hail, and occasionally, snow occur.

The presence of relatively steep slopes in the mountains and plateau region results in effective mass wasting: its main role is the forcing of weathered materials to fall, slide, or creep under gravitational stresses (Leopold, Miller, and Wolman, 1964). Talus is the feature most evident from mass denudation in this region.

Mechanical disintegration of rocks through the alternation of heating and cooling processes is possible. However, the magnitude and geomorphic effect of volume changes due to temperature changes is somewhat disputed in the literature (Thomas, 1974; Leopold, Wolman, and Miller, 1964). In the mountains and plateau region of the study area, the heating and cooling process seems to be of minor effect due to the relatively low and limited ranges of temperature. It is quite possible that it may have accumulative effect over a long period of time (Plate 2).

<u>The Pediplain Region</u>.--Over an extensive stretch the channel of Wadi Bisha is cutting through fossil erosion surfaces. The surfaces, which are covered by Wadi Bisha alluviations, are considered a part of Najd Pediplain (Italconsult, 1969a).

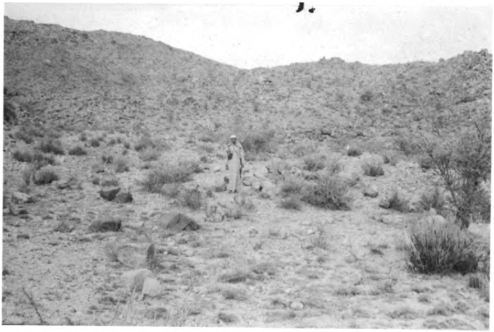


Plate 1

Sub-angular boulders that overlie a thin alluvial veneer at the eastern rim of the Hijaz Plateau northwest of Wadi Bisha. Sheet-wash is believed to have transported these materials after being broken by _in situ_ weathering.

Plate 2

Joint-controlled granitic boulder field, typical for the headwater areas of Wadi Bisha. In situ degradation and front action are believed to be the main denudational agents. Note sparse vegetation cover, rainfall is between 20 and 30 cm, and surface runoff has its influence on the microrelief.

The region lies northeast of al Junaynah, the northernmost oasis in Wadi Bisha. It extends from an elevation of 1,000 m near al Junaynah to 800 m at the mouth of the Wadi in the Bisha-Ranyah accumulation plain south of Uruq Subay' basin.

The region is a hot desert. The average temperature is above 20° C, with a mean temperature range of 18° C. The annual amount of rain is less than 100 mm. The vegetation cover is very scarce. Materials, consisting of sands over a large portion of the region, are incohesive. These surface conditions coupled with a strong southeastern wind system make eolian activities the most pronounced geomorphic agent over the pediplain region, both in the deflationary and depositional sense. More than half of the region is covered by sand dunes of several types.

Because the temperature is high during the summer days (reaching as high as 45° C), and because the ground is bare, the effect of direct insolation is believed to be important. Insolation weathering is based on the fact that rocks and minerals expand and contract differently when exposed to a large diurnal and/or seasonal temperature change.[1]

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[1]During the field work, two incidents strengthened the researcher's belief in the importance of insolation weathering in the mentioned region. For three consecutive nights we heard the cracking of rocks one hour after sunset. During the day, the temperature reached a maximum of 45° C in two of the three days, while night temperatures were about 20° C lower. At 4:35 - 4:45 p.m., August 9, a rain storm hit us during our field work near al Nagi Oasis. Five minutes after the rain had stopped, a nearby exfoliated granite rock cracked twice. Both indicents must be attributed to contraction cooling of the outer rock shells.

Besides the breaking of rocks and minerals, thermal variations are important in increasing the permeability of rocks, providing avenues for the penetration of chemically active water (Cooke and Warren, 1973).

CHAPTER IV

LANDFORMS AND MATERIALS OF WADI BISHA AND URUQ SUBAY' BASIN

Wadi Bisha cuts its channel through rocks of the Basement Complex. Sericite and chlorite schists are the predominant rocks in the area between El Madarah and Junaynah. They are characterized by several structural trends. The main trend strikes N 36° E. It controls the general direction of the course of Wadi Bisha and its main tributaries (refer to Figure 3, p. 24).

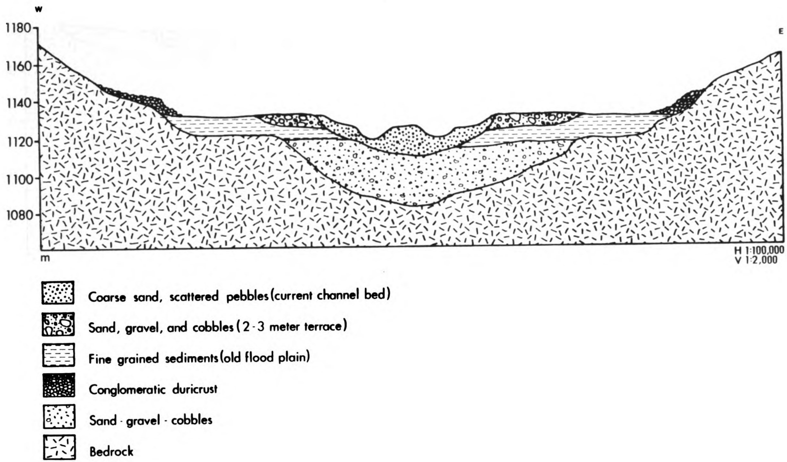
The Wadi bed is composed of the alluvial fill in which a set of erosional terraces can be recognized.

Lithostratigraphy of the Alluvial Fill

Five different layers comprise the Wadi alluvial fill (Italconsult, 1969b). At the base of the Wadi fill, there is a massive zone of sand, gravel, and some cobbles. It rests upon bedrock, ranges between 10-40 m in thickness, and is usually thicker below the Wadi channel (Figures 4 and 5). Groundwater is drawn from this zone in almost the entire floodplain (Italconsult, 1969b).

A transitional layer which ranges between 1-2 m in thickness is found overlying the coarse base beds in discontinuous distribution. It consists of fairly compacted beds of conglomerates cemented by calcium carbonates. These conglomerates, however, are not present

Cross Section of Wadi Bisha at El Madarah

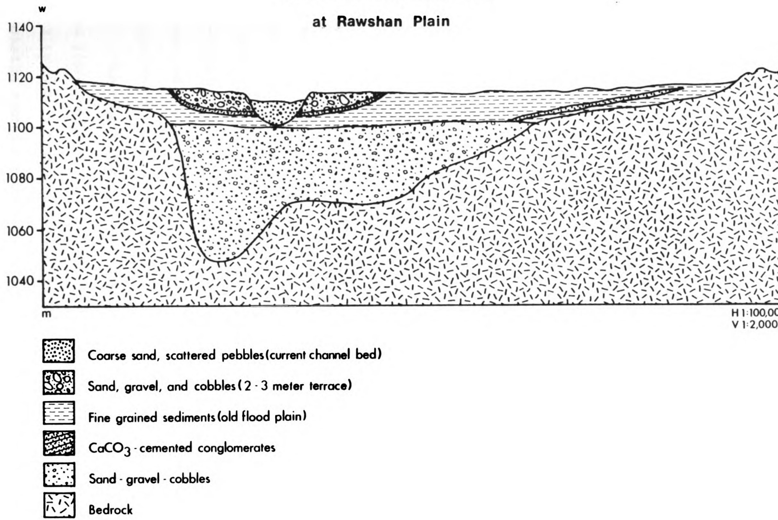


Source: Italconsult, 1969 b

Fig. 4

Cross Section of Wadi Bisha

at Rawshan Plain



Source: Italconsult, 1969 b

Fig. 5

below the Wadi channel. The reason for the non-existence of the $CaCO_3$-layer below the Wadi channel is, most probably, its destruction or dissolution after deposition. It might not have formed in the first place because of a continuously high groundwater table which prohibited the precipitation of the calcium carbonates in the Wadi channel.

The most extensive alluvial deposits are those forming the present surface of the floodplain at the margin of the active channel. They overlie the calcium carbonate layer and the base sand-gravel-cobble beds. All the Wadi oases are situation on the floodplain. The surficial floodplain deposits range between 2-12 m in thickness (Italconsult, 1969b). The floodplain will be discussed in more detail in connection with the terrace morphology of the Wadi.

With respect to the inner margin of the floodplain deposits, the mentioned source refers to a bed of sand and cobbles that is somewhat cemented by calcium carbonates and is less than two meters in thickness (Italconsult, 1969b, p. 7). There is no mention in what localities the $CaCO_3$-cemented beds were found. It is certainly not noticeable at the surface between the deposits of the 2-3 m terrace and the floodplain deposits in the area between El Madarah and Junaynah investigated by the author.

The recent channel bed is composed of coarse sand and scattered gravel and cobbles. Deposits of the channel bed range from 1-2 m to over 15 m in thickness (Italconsult, 1969b). These are reworked by sporadic floods that occur once or twice every three to five years (Italconsult, 1969b; and personal information obtained during field work).

The Alluvial Terraces

Three terraces have been recognized in the main field work area between El Madarah and Junaynah. Differentiation of these terraces is based on relative terrace position, and elevation, differences in material composition, texture, roundness of coarse materials, sorting, stratification and bedding.

The Conglomeratic Duricrust Terrace

This terrace is formed by remnants of indurated gravel sheets of indurated gravel sheets which are believed to have once covered the entire Wadi channel. Two types of conglomeratic duricrusts were recognized in the area between Wadi Harjab mouth and Junaynah.

Lateral Indurated Gravels.--These are thin bands that range between 1-4 m in thickness and spread discontinuously along the sides of the Wadi. The indurated gravels are most conspicuous at El Madarah and Sha'b Alma on the west side of the Wadi (Plate 3), and at Barjrah and Harf on the east side of the Wadi (Plate 4). Field measurements of their positions place them between 10-13 m above the actual wadi floor. The gravel and cobbles within the indurated conglomerate are composed of sericite and chlorite schists, the same which form the country bedrock. The gravel and cobbles are angular, indicating little transport by running water, and they also have a limited degree of bedding. The matrix of the terrace crust, however, is a mixture of quartz sand and other rock fragments which must have been

Plate 3

Remnant of conglomeratic duricrust on the wadi-sides of El Madarah. They are positioned at 10-13 m above the actual wadi floor.

Plate 4

Remnant of the wadi-sides conglomeratic duricrust at Harf, 10-13 m above the wadi bed. The gravels are mainly chlorite and sericite schists. The terrace shows some banking, but no obvious bedding.

transported from upstream probably by waters of low velocity. The coarse materials (gravels and cobbles) were deposited by local denudation processes, most probably by gravity and colluvial action.

Laboratory analysis of the duricrust indicates that it is predominantely calcite. Both calcite nodules and powder are present throughout most of the indurated Wadi-side gravels. The outer layers of the duricrust exhibit weathering zones in the calcite cement while deeper within the duricrust the calcite cement is quite hard.

The Conglomeratic Wadi-Channel Duricrusts.--They were observed at three localities: Raw Alma, Bajrah, and the mouth of Wadi Harjab. They contain sand, gravel, and pebbles of varying rock types, most of which were transported from the upper areas of the Wadi basin. The gravel and pebbles within the duricrusts are fairly rounded, showing long-distance water transport.

The conglomeratic duricrust of Raw Alma (Plate 5) was superimposed on the country granite (Figure 6). The duricrust contains stratified horizontal beds of sand, gravel, and pebbles. The base layer rests on bedrock and is composed chiefly of gravel and pebbles whose fabric shows an imbricated or horizontal structure. This complex is cemented by a thick and hardened coating of calcium carbonate which actually forms skins or shells around every pebble and sand grain.

The conglomeratic duricrust of Bajrah (Plate 6) is very similar to that of Raw Alma in composition, thickness, and hardness.

Plate 5

Remnant of the wadi-channel conglomeratic duricrust at Rwa Alma. It is resting on granite bedrock. The unconformity represents the pre-Quaternary erosional surface. Horizontally bedded materials of the conglomerates are sand, gravels, and pebbles of varying rock types.

Cross Section of Wadi Bisha at Rwa Alma

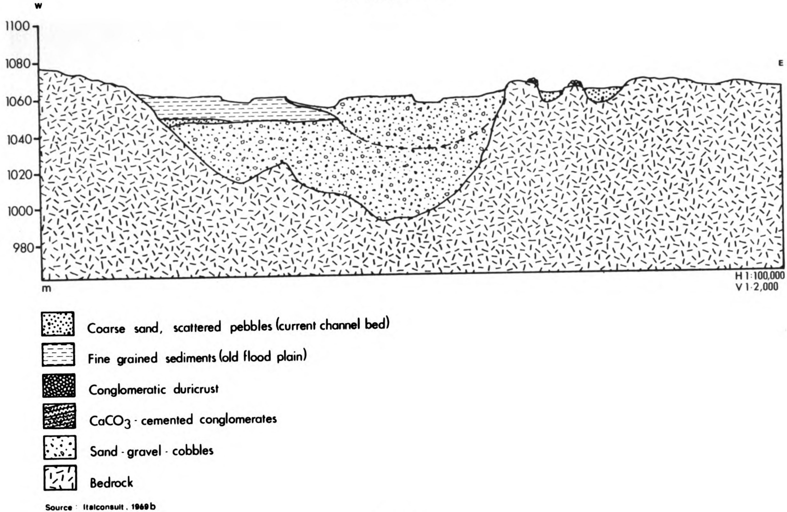


Fig. 6

Plate 6

Residual of the conglomeratic duricrust at Bajrah. The complex is broken into conglomeratic boulders due to the weakness of the underlying materials which are (unconsolidated) less resistant to erosion.

However, it does not rest on bedrock but on the coarse base layer of the Wadi fill. The duricrust has been broken into conglomeratic boulders which blocked part of the Wadi channel and obstruct current runoff.

The most extensive of the three Wadi channel conglomeratic duricrusts was found at the mouth of Wadi Harjab which is one of the main tributaries of Wadi Bisha (Plate 7). The conglomeratic duricrust of Wadi Harjab covers much of the floor and the sides of the Wadi, except in the middle of the channel where it was eroded by recent floods. It exhibits, as the other two, horizontal as well as a certain degree of cross-bedding. Gravel and pebbles are of varying rock types and are fairly rounded. Interstitial material is chiefly composed of quartz sand; the calcite matrix is as hard as in the other two Wadi-channel duricrusts.

Origin of Wadi Bisha Duricrusts.--The calcareous duricrusts that cement the gravel terrace and the channel gravels are composed mostly of calcium carbonate, and they may thus be termed of the calcrete type.[1]

The environment of formation of calcretes--and duricrusts in general--has been the subject of much debate. Some authors take them as evidence of a humid phase (Twidale, 1968). Others believe that they are products of dry stages (Chapman, 1974). Butzer (1971),

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[1]Laboratory analysis was completed under the direction of Dr. D. Sibley, Department of Geology, Michigan State University.

Plate 7

Wadi Channel remnants of conglomeratic duricrust at the mouth of Wadi Harjab. They are composed of sand, pebbles and cobbles cemented by calcite. They are dipping slightly toward the center of the Wadi Channel. Cross-bedding seems to show, indicating considerable change in flow regime.

however, suggested that their occurrence may indicate either moister or drier palaeoclimates, depending on the situation.

Reeves (1976, p. 84) pointed out that "the ideal environment for caliche formation to be neither excessively arid or excessively humid. Too much precipitation or water availability, as in the tropics, causes leaching of soil solubles, and too little water, as in the arid deserts, allows only thin surficial accumulations of salts." Goudie (1973) described different models of the development of duricrusts. These are the fluvial models, the lacustrine models, the _in situ_ models, the capillary goundwater models and the pedogenic models.

The fluvial model seems to best fit the duricrusts of Wadi Bisha. The fluvial model attributes duricrusts to the deposition or precipitation of suitable materials in valleys or channels. Support for this model comes from the association of duricrusts with valleys and alluvial materials; among the best-described are the valley calcretes of western Australia and southern Africa (Goudie, 1973).

Calcareous duricrusts of Wadi Bisha contain well-rounded gravels of fluvial origin. The calcite cement is thick, hard, and thus, probably could not have been precipitated from groundwater by capillary action. They, most certainly, could not have developed _in situ_ because of the absence of local bedrock or materials that are rich in calcite. Consequently, the calcium carbonates must have been brought to the site in solution in chemically charged waters from wider ranges within the Wadi Bisha basin. The precipitation and induration of calcium carbonates most probably occurred during equilibrium changes in the stream of Wadi Bisha, presumably due to climatic changes that resulted in less discharge. This matter will be discussed more thoroughly in the discussion of Wadi Bisha's morphogenesis.

The Five-Meter Sand and Fine-Grained Sediment Terrace

This terrace is formed in the 10-12 m thick deposits of sand, silt, and clay that comprise the floodplain of the Wadi. It overlies the coarse base layer (Figures 4 and 5). The terrance is apparent along the sides of the Wadi (Plate 8). It is also found on various surfaces of the Wadi channel where it is partially destroyed by recent alluvial action (Plate 9). The deposits which comprise the Wadi floodplain have horizontal to sub-horizontal bedding. They have no apparent dip. The sediments are predominantly sand (grain size > 0.05 mm), especially near the Wadi channel[1] (Table 2).

High silt and clay concentrations seem to occur only sporadically in the terrace sediments. Clay percentages increase in "pocketed" areas of the Wadi floodplain, such as at Sha'b Alma. The deposits lack any kind of sorting which might indicate that the rate of deposition was relatively constant, rather than episodic.

The terrace deposits and the floodplain, in general, are believed to be the results of flood deposition during a pluvial

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[1]Laboratory analysis of grain size was executed with the Buoyocus hydrometer method.

Plate 8

A portion of the 5 m fine-grained terrace at Rwa Alam. The texture is predominantly sand. (Fro grain size analysis, see Table 2.)

Plate 9

Remnants of the old wadi floodplain at Bajrah. The floodplain has been partially destroyed by recent erosional downcutting. The surface of remnants is consistently 5 m above the channel bed.

TABLE 2.--Grain size data

	Location	Sample size (gm)	Sand (> .05 mm)		Silt (.05-.002mm)		Clay (< .002 mm)	
			Weight	%	Weight	%	Weight	%
1	Rwa Alam depth of 1.5 m (Plate 8)	50	15	30	25	50	10	20
2	Rwa Alma depth of 3 m (Plate 8)	50	30	60	8	16	12	24
3	Rwa Alam depth of 5 m (Plate 8)	50	25	50	14	28	11	22
4	Harf (surface)	50	23	46	21	42	6	12
5	Sha'ab Alma (surface)	94	42	44.6	11	11.7	41	43.7

NOTE: The samples were collected from the floodplain and/or the 5 m terrace at random locations.

period, to be discussed later. The floodplain extends laterally between 2-10 km along the Wadi sides. It also can be traced back up to the mouths of Wadi Bisha's main tributaries (Wadi Harjab, Tarj, and Tabalah) where the terrace is preserved at three meters above the Wadi channel (Italconsult, 1969b).

Evaporites, particularly gypsum, have been confirmed on different parts of the floodplain generally at a depth of one meter (Italconsult, 1969c). An incipient calcareous duricrust was found cementing blocks of floodplain deposits at Sha'b Alma (Plate 10). It is mostly of a powdery type, with few nodules and, unlike the calcareous duricrusts of the indurated gravel terrace, its outer layers do not exhibit weathering zones. The calcite cement also is not as hard as that of the indurated gravel terrace. Both hardness and the lack of weathering zones prove that it is considerably younger than the duricrusts of the gravel terrace.

The 2-3 Meter Terrace

It consists of coarse sand and cobbles that range between 10-15 centimeters in diameter. These materials are typically cross-bedded and lack any kind of sorting, most probably because they were deposited by strongly turbulent flows. The cobbles and gravel are smooth and fairly rounded. They contain a mixture of rock types (Plate 11; Figures 4 and 5). The terrace accompanies the entire course of the Wadi; it is continuous for a maximum length of 1 km, but usually for no more than 200 m at a time (Figure 7; Plate 12).

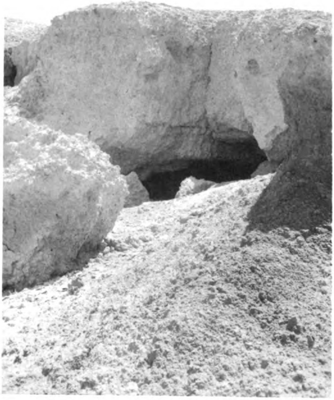

Plate 10

Blocks of fine-grained sediments of the old floodplain at Sha'ab Alma; they are cemented into a young duricrust.

Plate 11

Closeup of a portion of the 2-3 m sand, gravel and cobbles terrace at El Madarah. The cobbles and gravels are smooth-surfaced and sub-rounded.

Legend, fig. 7

Current channel beds, unconsolidated sand, scattered gravel, and cobbles

Old wadi channel (sand, pebbles, and cobbles)

Old bedrock controlled floodplain overlain with sand veneer

Three meter terrace (coarse sand and cobbles)

Evaporites (salt crust)

Conglomeratic duricrust

Bedrock, (igneous and metamorphic rock)

Agricultural areas (oases)

Inactive discharge channels

Entrenched channel

Active (episodic discharge channels)

Dyke

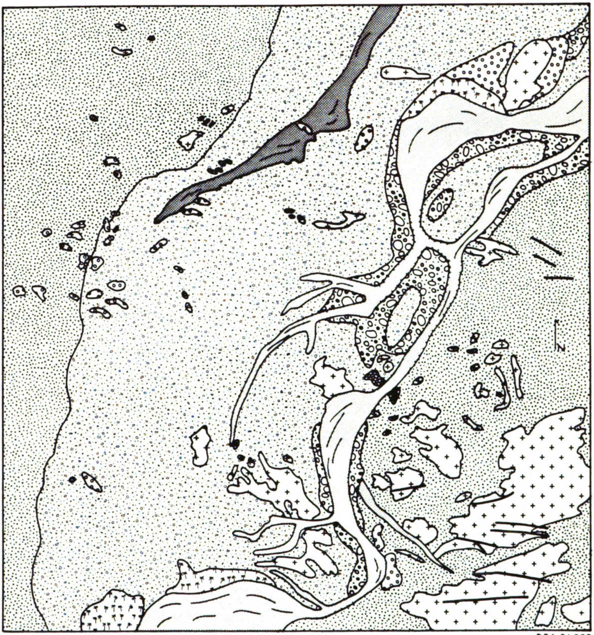

Fig. 7 Channel system of Wadi Bisha north of Bisha Town.
(airphoto by Western Shield Agency)

Plate 12.--The aerial photo covers an area northeast of Bisha Town in the middle course of the Wadi. Elevation of the area is approximately 1000 m above sea level. Bedrock appearing at the surface and also underlying the alluvial deposits is of pre-Cambrian age, and consists mostly of granits and diorites. The current Wadi channel is well-defined and its course is determined by bedrock obstructions; abandoned older channels are also recognizable on the west half of the image.

Scale: 1:60,000

Plate 12

Field measurements place the terrace between 2 m and 3 m above today's wadi floor. The terrace actually was carved out of the active floodplain. Often, the terrace thins out to merge with the floodplain.

Khabrat (Playas)

Khabrat of the study area occur over the enclosed basin of the Uruq Subay'. The creation of the Uruq Subay' basin is related to the precambrian tectonic movements that were responsible for the Madinah-Muwayh Fault System. The basin has an elongate shape in response to the mentioned fault system which has a southeast-northwest trend (Figure 8). The mid-Tertiary tectonism that caused the rifting of the Red Sea, the uplift of the Arabian Shield's west part, and a steeper eastward dipping of the Arabian platform established the present regional gradient and trends, in correspondence to the old fault system (Hötzl, 1978). The basin lies between 21°05' - 22°30'N and 43° - 43°35' E. It borders the Hijaz Plateau to the east (refer to Figure 3, p. 24). Three major wadis debouch into the basin. Wadi Bisha, which traverses through the Asir Highlands and the Hijaz Plateau, reaches the basin from the wouthwest. Wadi Ranyah, which drains the east section of the Hijaz Plateau and Harrat Nawasif, enter the basin from the west. The system of Wadi Subay' which today has its channel completely covered by sand dunes, formerly reached the basin from the north.

Khabrat of Uruq Subay' basin are associated with depressions in the basin. The main khabrah is located north of the Wadi Bisha mouth (Figure 8). It is bordered by the alluvial fan of Wadi Ranyah to the west and south, and by a field of transverse and oblique sand dunes to the north. Due east, the depression is controlled by Umm Matirah andesite outcrops.

Both materials and landform types of Uruq Subay' basin khabrat are well-displayed on the aerial photographs. Considering the difficulty of ground access to Uruq Subay', aerial-photo interpretation is extremely useful for drawing inferences on the processes which were responsible for the khabrat. Indeed, this technique is often the only mean to discover the patterns and interrelationships of the landform complexes. As the overlay over photo 1750 (Figure 9) shows, a large part of the depression floor is covered by dark-toned materials. These are believed to be fine grained clastic sediments that have been deposited in standing water. The materials appear--in the photos--to be firm and compact. They also did not give in for wind erosion or deflation. Sand dunes of barchan and transverse type cover about 20 percent of the depression floor. The source of the sand usually is in the alluvial fans of Wadi Ranyah and Bisha, which are swept quite frequently by strong southeasterly winds. About 10 percent of the depression floor is covered by white to medium gray materials. They are interpreted as evaporites.

The khabra floor generally is semi-flat, except for the eastern half where several small wadi channels dissect the depression floor. The exhumed khabra floor is best explained by the former existence of a body of standing water, either a perennial lake, or a

Legend, fig. 8

Eolian sand, both sand dunes and sand blankets

Unconsolidated surficial deposits of silt, sand, and gravel

Fine grained sediments, associated with evaporites in depressions and depression outlets

Bedrock

Remnants of greenstone schist pediplains, dissected by fossil dendritic drainage system

Fault

Thrust fault

Wadi system

0 10 20 30 Km

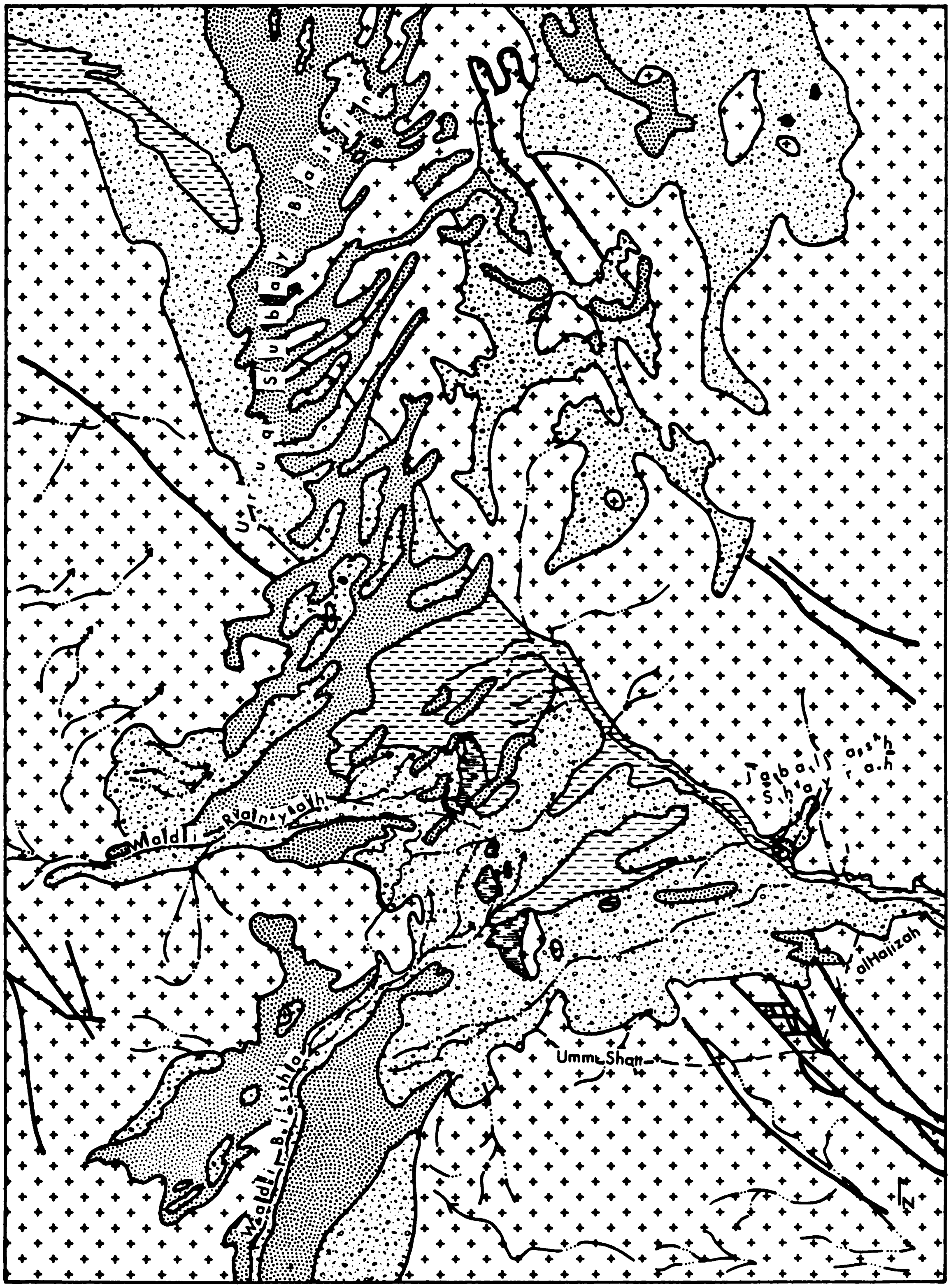

Fig. 8 Surface formations at the junction of Wadi Bisha with the Uruq Subay Basin.
(source: Jackson, et. al., 1963)

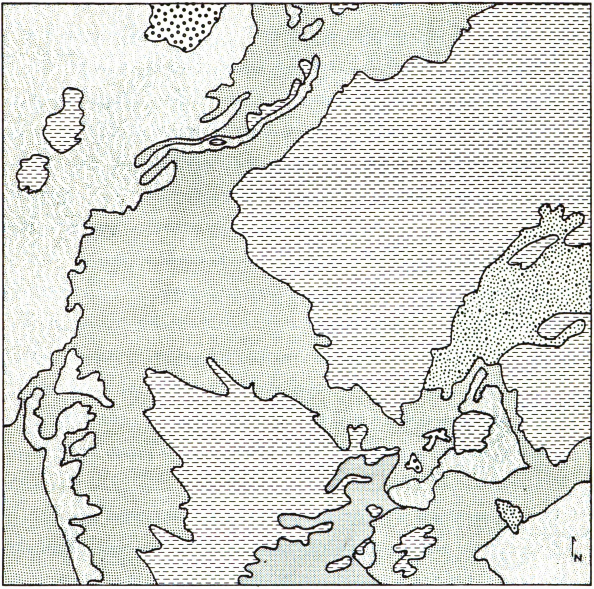

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Fig. 9 Khabra depression bordering Wadi Ranyah and Wadi Bisha mouths.
(airphoto by Western Shield Agency)

- Sand dunes
- Sand veneer and ripples
- Fine grained sediments
- Evaporites
- Blown sand associated with fine grained sediments (lacustrine)
- Evaporites associated with alluvial material (channel), and fine grained sediments (lacustrine)

succession of ephemeral lakes. With even distribution of suspended sediments in standing water, the depositional unit at a given point would be directly proportional to the water depth. And each unit would decrease regularly in thickness from deeper to more shallow water. It is in this fashion that the pre-lake surface with considerable initial relief should approach flatness, given sufficient time and sufficient sediments (Smith, 1969).

It must be borne in mind, however, that it is unlikely for the depression floor to be consisting only of fine-grained sediments. The (suggested) former body of standing water must have been affected, quite frequently, by the alluviation of coarser materials transported by the former streams of the three major wadis mentioned earlier. Also, sand dunes bordering the khabra depression must have been reworked by water, thus contributing to the formation of the khabra floor.

The depression has an outlet bordering the khabra to the east. The outlet starts at a channel that runs southeast until it joins what is called the lower reaches of Wadi Bisha, which cuts its channel through the Al Hajizah and Ash Shayrah mountains (Figure 8). As shown on various airphoto sets covering the area, the whole outlet channel is covered by a white to medium gray material. Here, salt crusts or evaporites, in general, have precipitated in greater frequency, undoubtedly because of higher probability of subaerial salt crystallization in the shallow channel.

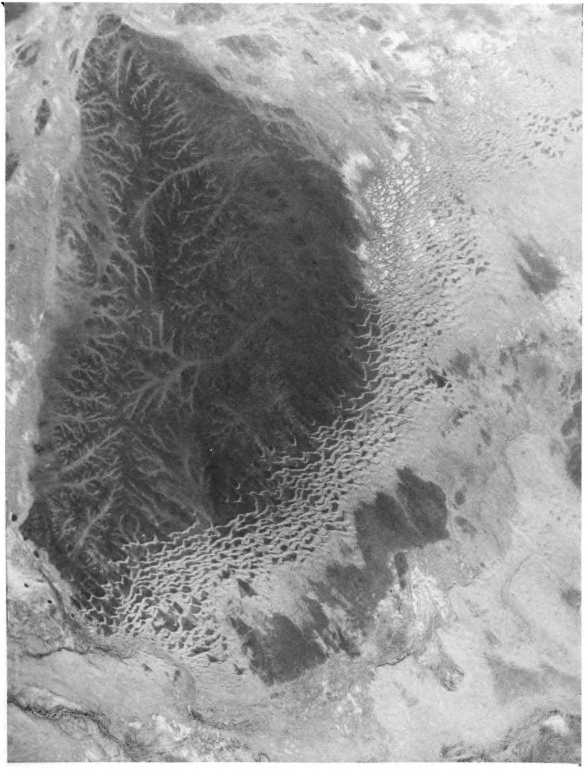
The southern portion of the depression is bordered partially by a dissected greenstone schist that comprises the northern end of

Umm Shatt pediplain (Figure 8). As can be seen in photo 4354 and its overlay (Plate 13; Figure 10), the erosional channels of the dissected schist are sharp, except for the lower reaches of the channels where they appeared merged at an almost even level with the adjacent dissected schist. It is possible that the blurry looking portions of the channels may have been modified by ephemeral standing water. The transition point between blurred and well-defined appearance of the channels is suggested as the high water line. Below the erosional channels there are dark, untextured surfaces. These are interpreted as the legacy of the (suggested) lake floor. Mixed with these surfaces are white to medium gray spots which are interpreted as evaporites that had precipitated during the lake dryout.

Considering the type of materials, their relationship to surrounding source areas, and the incongruence of this landform type with current morpho-climatic conditions, the Khabra is believed to be the site of ancestral Pleistocene "pluvial" lake. Since this interpretation has not been made before and may possibly be applied to a large number of similar khabrat in Arabia, the evidence here evaluated includes the following:

1. Three major valleys (Wadi Bisha, Ranyah, and Subay') converge in the khabra depression.
2. The depression is confined by impermeable precambrian bedrock.
3. Fine-grained clastic sediments are characteristic over most of the khabra floor.

Plate 13.--The image was taken over the central part of Uruq Subay' Basin. Elevation of the area is approximately 810 m above sea level. Bedrocks exposed in the western half of the photo are greenschists whose planated surface exhibits a fossil, dendritic drainage system. The eastern portion of the bedrock block shows very little channel dissection, which may be attributed to the occurrence of a former standing water body which protected it from subaerial erosion. Products of evaporation, especially salts, are conspicuous throughout the image, appearing between the sand deposits. Sand dunes of the Akle' type are seen bordering the bedrock to the south and east. Dark-toned, untextured (homogeneous) surfaces are seen throughout the image, most clearly to the southeast of the bedrock complex; they are interpreted as clay-rich of bottom deposits of a former (Pluvial) lake.



Scale: 1:60,000

Plate 13

Legend, fig. 10

Sand dunes

Sand veneer

Fine grained sediments

Evaporites

Alluvial materials(including unconsolidated deposits of silt, sand, and gravel)

Greenstone schist dissected by a fossil dendritic drainage system

Active drainage system(braided stream)

Old drainage system(inactive)

RF 1:92,000

Fig. 10 Dissected greenstone schist associated with alluvial and lacustrine deposits at the termination of W. Bisha (airphoto by Western Shield Agency)

4. Evaporites that had precipitated during the lake-dryout are ubiquitous.
5. The depression floor, generally, is flat. Flat floors of similar basin usually interpreted as a result of suspended sediments in standing waters.
6. The depression has an outlet bordering the Khabra to the east. The outlet starts at a channel that runs southeast to join what is called Wadi Bisha lower reaches. The outlet served, most probably, as the main drain of the suggested lake, as evidenced by the presence of salt crusts or evaporites on the shallow channel of the outlet.
7. Transverse, barchan, and parabolic sand dunes border the depression,particularly to the north and parts of the south; the location of these eolian deposits, i.e., their relationship to the Khabra,makes their interpretation as lake beach dune fields most plausible.
8. The dissected greenstone schist that borders the depression to the south has sharp erosional channels except for the lower areas where the frequency and sharpness of the channels decrease greatly. A suggestion for these marked differences is that ephemeral standing water modified the lower sections of the erosional channels.

Eolian Forms

Eolian deposits may cover as much as 50 percent of Wadi Bisha's valley trains and plains. They also cover a large portion of the Uruq Subay' basin. Sand dunes and sand veneers are the main forms created by winds.

The abundance of unconsolidated fine alluvium, coupled with a very sparse vegetal cover, and strong southeasterly winds led to the dominance of sand dunes over the alluvial plain of the middle courses of Wadi Bisha and the northern half of Uruq Subay' basin.

The largest sand dune fields accompany the middle courses of Wadi Bisha, as far as the Wadi mouth at the Uruq Subay' basin.

The largest sand dune fields accompany the middle courses of Wadi Bisha, as far as the Wadi mouth at the Uruq Subay' basin. Along this stretch, sand dunes cover more than two-thirds of the Wadi's alluvial plain. The main dune types are of the transverse type. These are both simple and compound dunes that lie transverse to the main wind. They also contain barchan dunes, especially in areas where sand sources diminish. Southeasterly winds are prevailing over the middle course of Bisha, as evidenced by the trend of crests of the dune chains (SW-NE), and the exposition of the gentle, windward and steep, leeward slopes, with is SE and NW, respectively.

The northern half of Uruq Subay' basin is covered by complex sand dune types that are present in large dune fields called <u>erq</u> (singular for <u>uruq</u>). As a matter of fact the basin takes its name (<u>uruq</u>) from these large features. <u>Erq,</u> in Arabic, refers to a "sea of sand dunes."

Over the southern half of the basin sand dunes occur only over relatively smaller areas. This could be attributed to the strong deflationary effect of southeasterly winds which would tend to denude the southeastern portion of the basin; the southern half of the basin is virtually a perfect plane, devoid of vegetation or any other kind of obstacles that might obstruct wind flow and lead to the deposition of shifting sand.

Several dune types occur over the northern half of the basin, such as transverse, barchan, oblique, and circular dunes. Those occur within draa-sized features[1] (Plate 14), such as draa-sized barchans, and irregular and elongated forms that lie transverse to the southeastern winds.

Several reasons could be cited for the distribution and diversity of dune types. The underlying topography is most important, particularly with respect to the trend of the oblique dunes and the draa-sized features.

Oblique sand dunes might have developed as a result of secondary seasonal winds that blow from the northeast.

Other sand dune fields of considerable interest to the objective of this research are located between Wadi Bisha and Ranyah mouths and the Khabra depression. The main sand dune field is a draa - sized Akle' dunes, that border the Khabra depression from the south (Figure 10; Plate 13). The Akle' dune field is composed of sinuous ridges

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[1]Draa, in Arabic, refers to the human arm. In desert terminology, it is the term of semi-stable or slow-moving large eolian features--that is covered by sand dunes and has a slip face like them.

Plate 14.--The airphoto was taken over the northern half of Uruq Subay' Basin. Elevation is approximately 850 m above sea level. Large sand dune complexes are seen throughout the image. Transverse and oblique dunes are predominant. A large source of sand, in the form of alluvial and lacustrine deposits, coupled with a consistent southeasterly winds, enchance the higher frequency of transverse dunes. Bedrock control, locally visible on the photo, or indicated underneath the sand deposits, appears to explain the presence of oblique dunes superimposed upon draa-sized features. Extensive deflation plains and smaller blow-out hollows occur, particularly in the middle part of the plate.

Scale: 1:60,000

Plate 14

that are transverse to the prevailing winds. The ridges are made up of crescentic sections, alternatively facing into and away from the wind. They are the result of relatively unidirectional southeastern winds that blow against a large source of sand (Cooke and Warren, 1973). Material sources of the Akle' field are fine sediments of alluvial valleys and fan origin. The entire sand dune field is advancing north and northwest, invading the Khabra floor and the old dissected greenschist remnants, clearly visible with their fossil dendritic channels (Figure 10; Plate 13). Various parts of the Akle' dune field are superimposed on salt crusts or evaporites and also on dark-toned untextured surfaces of the Khabra floor. Before it advanced, it is possible that the Akle' sand dune field had been marking the southern shorelines of the suggested "pluvial" lake.

CHAPTER V

THE ORIGIN OF WADI BISHA -- A MORPHO-CLIMATIC INTERPRETATION

Reconstruction of Wadi Bisha's physiographic evolution will be mainly based on alluvial stratigraphy, for it is in the channel deposits themselves where the best evidence of hydraulic regime, and, therefore, climate can be found. Before discussing the proposed stages of the Wadi, however, it is necessary to examine possible causes other than climatic changes, that could have affected the observed alluvial stratigraphy and the postulated sequence of erosion and deposition.

Base level changes in the form of sea level fluctuations do force a river to deepen or fill its channel in response to the new base level. A lower base level causes downcutting, and the remnants of the old channel will stand as river terraces. Eustatic fluctuations do not apply to Wadi Bisha simply because the Wadi does not reach the sea so it cannot be affected by sea level fluctuations.

Another possible factor that could renew a river's erosive power and leave the old floodplain as cut terraces is tectonic movement, either by warping or outright uplift. The last known major tectonic movement took place during the mid-Tertiary and resulted in the Red Sea rift (Powers et al., 1966; Chapman, 1978). Tectonism undoubtedly initiated the erosional history of Wadi Bisha by raising the Asir Mountains and the initial course and gradient were established during the middle and late Tertiary; however, the region is believed to have come to a standstill by the Pliocene (Powers et al., 1966; Chapman, 1978).

With tectonic movements abating by the beginning of the Pleistocene, and a primeval wadi channel in existence, all subsequent changes in the longitudinal and transverse profile must be explained by exogenic factors.

Reference to the importance of Quaternary climatic change in altering the morphogenesis in the arid zone of the old world has been made in Chapter II. The following discussion is an attempt to interpret the observations made in Wadi Bisha morpho-climatically, and to establish a first time-stratigraphic sequence for western interior Saudi Arabia. The proposed phasing is tentative, based on relative, rather than absolute dating of form systems and materials, but a first correlation of wadi evoution in Saudi Arabia with Quaternary stratigraphy in neighboring areas, seems justified.

Pluvial 1 (P-1)

An initial stage of intensive erosion resulted in the cutting of a deep V-shaped valley to at least 60 m below the present wadi surface. It is also believed that it was responsible for the deposition of the coarsest materials in the wadi bed, where these have been preserved at the surface, it was due to cementation by calcareous crusts.

This stage is believed to have been the longest and most humid phase during the Pleistocene.

The timing and duration of Pluvial 1 cannot be determined precisely. But, based on the dating of two different basalts in the vicinity of the neighboring Wadi Ranyah (Figure 11), a relative chronology can be established. The younger of the two basalt flows, dated at 1.1 ± 0.3 million K/Ar-years features very fresh surfaces, and shows few signs of intensive erosive activities or chemical alterations (Hötzl, Lippolt, Maurin, Moser, and Rauert, 1978). This may be a strong indication that since the erruptions of these lava flows, southern Arabia experienced arid climatic conditions.

The other basalts are in the area of Al-Jerthamiyah and between Mugabil and Rawdhah. These are cut by Wadi Ranyah. They are intensively weathered and broken up into blocks attaining diameters of up to 0.5 m. These blocks cover red clay of a few meters in thickness. The red clay had been formed by autochthonous weathering of basalts (Hötzl, Lippolt, Maurin, Moser, and Rauert, 1978). Such intensive lateritic alterations indicate humid tropic conditions, a climate that must have prevailed before the young, unweathered basalts were extruded. Samples that were collected for the age determination of the older basalts reveal an age of 3.5 ± 0.3 million K/Ar-years.

The last period of Pluvial 1 must have experienced a decrease in rainfall. This is evidenced by the deposition of the basal coarse sand, gravel, and cobbles, a consequence of the inability of the

Legend, fig. 11

Khashm Shayil lava flows

Remnants of greenschist pediplane, dissected by fossil dendritic drainage system

Eolian blanket, traverse dune formations

Sand and gravel of fluviatile origin

Evaporites

Episodic discharge channels

Entrenched channel

Inactive drainage systems

Wind direction

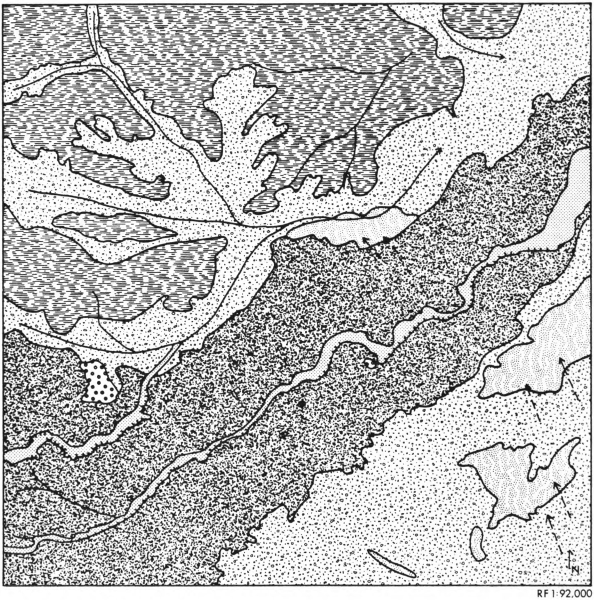

Fig. 11 Middle course of Wadi Ranyah entrenched into late Tertiary lava flow (Harrat).
(airphoto by Western Shield Agency)

stream to carry its bed load to the lower courses of the Wadi. These deposits range between 10-40 m in thickness. With rainfall decrease, a higher evaporation rate favored the precipitation of calcium carbonates and other salts. Crystallization was a result of either infiltration from underlying materials (capillary action) or evaporation at the surface. Most precipitation of the dissolved load took place in the middle course of the Wadi; here stream velocity decreased sharply due to considerable decrease of the gradient and occasional floodwaters were spread over a wide valley floor and evaporated easily. Farther downstream, in spite of still higher evaporation rates, discharge diminished almost completely and eolian action became dominant.

Interpluvial 1 (IP-1)

Pluvial 1 was followed by a stage of arid conditions. This is evidenced by further crystallization and induration of the precipitated solubles (mostly calcium carbonates). The indurated crust covered the entire Wadi channel, and was also observed as lying uncomformably over bedrock of the Wadi sides. The formation of duricrust was more extensive and led to a harder variety in the main channel, mainly because there was greater discharge in the Wadi channel and thus more precipitable load.

The thickness of the duricrusts varies greatly and most of them had been redissolved. Today, the lateral duricrusts of Wadi Bisha are found between 10-13 m above the channel floor, and they range in thickness between 75-250 cm. Channel duricrusts are found either superimposed on bedrock outcrops close to the present channel floor or their remains are encountered frequently within the channel fill as isolated conglomeratic boulders.

IP-1 is not known in terms of duration and intensity. As a matter of fact, the correlation of this stage with phases of the neighboring areas or with the European Pleistocene phases seems to present great difficulties, as evident from pertinent literature. Different workers of the Near East chronology seem to have different views on the climate of Early and Middle Pleistocene (Table 3). Butzer (1958), for instance, designated the longest and most pronounced Pleistocene pluvial to both the Riss and Mindel Glacials. That was based on the interpretation of the alluvial stratigraphy of the Jordan Valley, and also, on other findings in various areas of the Near East. Hötzl and Zötl (1978), on the other hand, concluded in their study of "The Quaternary Period of Saudi Arabia," that the Arabian Peninsula, since the Late Pliocene/Early Pleistocene, had been under arid conditions throughout the Pleistocene up to the Würm Glacial, with several short-lived moist phases. They based this conclusion on:

1. Strong eolian processes that overpowered the Late Pliocene/Early Pleistocene landscape, covering the Wadi channels.
2. The domination of deflation and dune accumulation in areas of the old fluviatile accumulation plains, such as in Ar Rub Al Khali and ad Dibdibah Plain

TABLE 3.--Suggested climatic stratigraphy in the Near East correlated with European Quaternary

	Late Pliocene/Early Pleistocene		
Europen Chronology (Alpine Scheme)	Günz	Günz/Mindel Interglacial	Mindel
Butzer (1958) (Near East)	Two suggested pluvials, separated by Inter-pluvial.		
Hötzl and Zötl (1978) (Saudi Arabia)	Long humid period; indicated by intensive chemical weathering, and deep entrenchment of Arabian Wadi systems.		
McClure (1978) (Rub Al Khali)	"Wet Pluvial" (!); witnessed plains of old alluvium		
Al-Otaiby (1980) (Wadi Bisha)	Pluvial 1, deep cutting of the primeval V-shaped valley of Wadi Bisha; massive deposition of sand, gravel, and cobbles.	Decrease in the discharge resulting in the precipitation of the constituents of the calcareous duricrusts.	

TABLE 3.--Continued

Middle Pleistocene			Late Pleistocene		
Mindel/Riss	Riss	Riss/Würm	Early Würm	The Gottweig Inter-stadial	Main Würm
The Great Inter-pluvial	The Riss Pluvial	The Last Inter-pluvial	Würm Pluvial I	Würm Inter-pluvial	Würm Pluvial II (25,000 -18,000 B.P.)
Mainly dry, with short humid phases; eolian deflation and deposition.			Humid (25,000 -30,000 year B.P.)	Extremely dry, eolian deflation and deposition (25,000 - 14,000 year (B.P.)	
Arid			"Wet Pluvial" (!) (36,000 - 17,000 year B.P.)		
Interpluvial 1, fully arid; Incrustation and Induration of the Wadi Conglomeratic duricrust.			Pluvial 2, cutting of the Wadi conglomeratic duri-curst and the formation of the old floodplain (5 m terrace). Beginning pre-cipitation of the younger duricrust.		

TABLE 3.--Continued

Holocene			
Alleröd	Latest Würm (Upper Dryas)	Recent	
Post-Pluvial (Arid) (18,000-11,500 B.P.)	Sub-Pluvial (11,500- 10,500 B.P.)	Arid stage 10,000 B.P. to present	
Humid (about 11,000 year B.P.)	Dry	Humid (8,000 - 9,000 year B.P.)	Dry; Eolian deflation and deposition
Hyper-Arid (17,000 - 9,000 year B.P.)	Wet Sub-Pluvial (9,000 - 6,000 year B.P.)	Hyper-Arid (6,000 year B.P. to present)	
Interpluvial 2, Incrustation of the younger duricrust. Precipitation of evaporiates (salt and gypsum) within the floodplain deposits.	Pluvial 3, Deposition of 5-8 m of coarse alluvia (2-3 m terrace)	Arid conditions of the present; episodic torrents that cut arroyo channel in Wadi Bisha; strong wind deflation at the middle and lower courses of Wadi Bisha, and in Uruq Subay' basin.	

3. Formation of fanglomeratic deposits and wadi khabrat sediments.
4. Ceasing of soil formation and the destruction of parts of the old soils either by gullying or wind deflation.

Although there is evidence for increasing aridity throughout the Middle Pleistocene, the conclusion that morphogenesis was entirely dominated by arid processes, is not acceptable to this writer. The point will be further elaborated in the concluding discussion of the chapter.

Pluvial 2 (P-2)

A stage of discharge followed IP-1 and resulted in the cutting of most of the Wadi conglomeratic duricrusts and the deposition of the old Wadi floodplain. It was also responsible for transporting the constituents of the younger calcretes that had been noticed on different parts of the floodplain. Pluvial 2 was less humid than Pluvial 1, even though it was able to destroy most of the conglomeratic duricrusts that had been deposited by Pluvial 1. That is evidenced by the inability of Pluvial 2 to reach and erode all of the lateral duricrusts of the Wadi, or to completely remove the P-1 gravel fill.

The intensity and duration of Pluvial 2 cannot be determined from the available information. It is, however, most likely to have coincided with the Würm Glacial. This inference is based on carbon-date measurements in several neighboring areas of Saudi Arabia.

For instance, calcareous weathering horizons 0.7 - 1.00 m below the surface in Mugabil Loam Pit in Wadi Ranyah showed an age of 26,000 and 29,000 years, P.B. (Hötzl and Zötl, 1978), and in a series of Pleistocene lakes that were investigated in Ar Rub al Khali. Their beds have radio carbon dates ranging from about 36,000 to about 17,000 years, P.B. (McClure, 1978). Such a period coincides with a maximum Würm Glacial.

It is believed that rainfall exceeded evaporation sufficiently during P-2 to lead to the formation of a fresh-water lake north of Wadi Bisha-Ranyah's accumulation plain in the southern portion of Uruq Subay' basin. Although this assumption could not be verified in the field, the presence of Khabrat deposits (see p. 60) has been established on aerial photographs of the area.

Interpluvial 2 (IP-2)

A stage of arid conditions with wind activities dominating is indicated over most of Arabia after P-2 (McClure, 1978, Hötzl and Zötl, 1978). In Wadi Bisha, Interpluvial 2 resulted in the incrustation and induration of the younger calcareous duricrust that has been located at Sha'ab Alma. It also resulted in the precipitation of evaporites, particularly salt and gypsum, on or within the old floodplain sediments. Gypsum is generally found at a depth of one meter (Italconsult, 1969c).

Interpluvial 2 is believed to have marked the beginning of the Holocene. Hötzl and Zötl (1978) suggest an arid stage from 25,000 to 12,000 years B.P. throughout Arabia. McClure (1978), however, places this arid stage between 17,000 to 9,000 P.B., based on radiometric data from Ar Rub Al Khali. The stage is characterized by the deposition of red eolian sand and extensive scattered gypsum deposits in Ar Rub Al Khali.

Pluvial 3 (P-3)

The arid conditions of Interpluvial 2 were interrupted by a weak moist phase (subpluvial) that resulted in the deposition of some 5-8 m of sand and cobbles. It also deposited the constituents (mainly $CaCO_3$) of a poorly cemented bed that is "sandwiched" between the old floodplain deposits and the sand and cobbles accumulations.

Radio-carbon dates from Wadi Ar Rummah, Ar Rub Al Kahli, Wadi Luhay and Wadi Ranyah confirm the dominance of this "subpluvial" phase over most of Arabia from the 10th millenium to the 6th (Hötzl, Felber, Maurin, and Zötl, 1978; McClure, 1978; Hötzl, Lippolt, and others, 1978).

The Arid Conditions of the Present

During the last 6,000 years, the Arabian Peninsula has been under the domination of arid conditions, with the wind and *in situ* denudation as most effective agents. Fluviatile discharge has been minimal and only in the form of episodic torrents. Over this period, storm floodwaters in Wadi Bisha have cut an arroyo channel into the sand and cobble accumulation of the preceeding subpluvial, leaving it as a 3 m terrace. Deposits of coarse sand and scattered gravel and cobbles have accumulated by the torrents; these deposits have a maximum depth of 15 m.

Eolian activities have been at maximum during this period, mainly due to the absence of vegetal cover, and the presence of a great amount of sand and silt in the alluvial plains of Wadi Bisha and Ranyah and also in Uruq Subay' basin. Added to that is the presence of a strong and consistent southeasterly wind flow, and an opposed minor northeasterly wind. Sand dunes of varying types have formed over the study area. These occupy as much as 50 percent of the study area, and cover practically the entire middle and lower Wadi Bisha and most of Uruq Subay' basin.

Discussion of the Results in Comparative View

A survey of existing schemes to order the morphoclimatic events in the Near East during the Quaternary indicates certain basic agreements, but discrepancies as well. An attempt is made here to review the chronostratigraphy presented in this chapter in the light of schemes on Quaternary morphogenesis suggested by other authors.

In Table 3, which summarizes the climatic changes of the Quaternary as given by Butzer (1958), Hötzl and Zötl (1978), and the geomorphic events in Wadi Bisha, are compared with those described by the above authors in neighboring areas.

Different workers of the Near East geochronology have different views on the physiographic stages of the region during the Quaternary period. These differences could be attributed to their preconception of the problem. Butzer (1958), who is clearly influenced by the concept of stronger correlation between the Quaternary pluvial phases of the subtropical regions with the glacial stages of

Europe, attempted to establish records of pluvial and interpluvial stages in total coincidence with the European (Alpine Scheme) Chronology. He went particularly far in his attempts of establishing the chronology of the Early and Middle Pleistocene. While the more intensive coverage of these older deposits in North Africa and the Levant may permit these correlations, the evidence from Arabia is still too sparse to allow more than tentative interpretations.

Hötzl and Zötl (1978), on the other hand, are impressed by the work of winds in arid regions to the degree that they concluded that Saudi Arabia had been under arid conditions throughout the Pleistocene with only few, short-lived humid phases. It is hard to accept such conditions, especially when considering the worldwide climatic deterioration during the Riss glacial which definitely must have been the result of a general shift of global circulation, specifically the equatorward expansion of the planetary westerlies. Nevertheless, they also suggested (Hötzl and Zötl, 1978) a very short pluvial phase (30,000 - 25,000 years B.P.) during the Würm Glacial, but they still consider the main Würm period as characterized by arid conditions, with a dominance of eolian deflation and deposition. The existence of a longer humid phase in Arabia during the Würm Glacial seems, however, clearly evidenced by radiometric data from Ar Rub Al Khali. These place the Würm Pluvial between 36,000 - 17,000 years B.P. (McClure, 1978).

CHAPTER VI

SUMMARY AND CONCLUSIONS

The major finding of this study with regard to the evolution of landforms of Arabia during the Quaternary is the decisive role of fluvial processes. The deep etching of the bedrock foundation with extensive wadi systems stands as the main proof of past moist conditions.

The main problem encountered by the writer was to investigate the landform systems and materials of Wadi Bisha, which included deep alluvial fill, terrace systems, duricrusts, khabrat, and eolian deposits. It is in these form systems and materials where lies the answer to the still unsolved question concerning the influence of climatic change on Quaternary surface evolution in Saudi Arabia.

Results of the investigation allowed the writer to reach the following conclusions:

1. Wadi Bish and its drainage basin had been influenced by three climatic changes leading toward three moister conditions ("Pluvials") and two intervening, less moist periods ("Interpluvials") during the Quaternary Period.

2. The first Pluvial (P-1) proved to be of particularly great geomorphic and stratigraphic significance, as can be witnessed by what must have been the first deep entrenchment of the original

V-shaped valley of Wadi Bisha, as well as the massive sand, gravel, and cobbles accumulation, both of which must be attributed to P-1. Both a cutting and depositional phase is indicated in these sequence of events during the first fluvial "cycles" at Bisha.

3. A dry period designed as an Interpluvial (IP-1) followed, details of which have yet to be worked out in Wadi Bisha; the effect of this first arid period is seen in the formation and induration of a cemented conglomerate in the Wadi gravels.

4. The second Pluvial (P-2) is indicated by the cutting of the conglomeratic duricrust and the development of an extensive floodplain. The intensity of P-2 is believed to be far less and its duration far shorter than P-1: this is indicated by the inability of P-2 to erode the lateral conglomeratic duricrust that had been deposited by P-1.

5. The second Interpluvial (IP-2) was marked by the incrustation and induration of the younger duricrust, and also, by the precipitation of gypsum and salt within the floodplain deposits.

6. A weak moist phase, or subpluvial (P-3), interrupted the arid conditions of IP-2. Of the three pluvials, P-3 had the least geomorphic and stratigraphic effect upon the study area. It was marked by the deposition of some 5-8 m of sand and cobbles. These deposits have very little lateral expansion.

7. Although current geomorphic processes in the study area are dominated by eolian activities, there is sufficient fluvial surface runoff to produce linear erosion in the P-3 Wadi bed in form of shallow channels.

8. While the relative time sequence of morpho-climatic events, presented above, can be considered as at least founded on directly observable evidence, the matter of absolute dating, i.e., the establishment of a Quaternary time stratigraphy scheme for the study area proved to be impossible with the research data presented at hand. To an extent it is still possible, however, to establish a chrono-stratigraphical scheme for Wadi Bisha for the Quaternary by extrapolation of time-marking data from neighboring areas in Arabia and the Near East. This, however, did not solve the problem of dating entirely, because there are considerable discrepancies between analysts of the Near Eastern geochronology themselves. The differences seem particularly obvious if it comes to the matter of climatic conditions of the Middle Pleistocene. Late Pleistocene and Holocene conditions seem to be better known in terms of climate, thanks to the availability of radiometric isotope analyses from lake beds in Ar Rub Al Khali, weathering horizons of Wadi Ranyah, stillwater sediments associated with shells of gastropods in Wadi Al Luhay (Central Arabia), and charcoal remains in Al Hasa, Eastern Arabia (McClure, 1978; Hötzl, Lippolt, and others, 1978; Hötzl, Felber, Maurin, and Zötl, 1978; Felber et al., 1978).

Even though this research is believed to be an important step toward the understanding of the past morphoclimatology and geomorphology of Arabia, it is clear that there is an urgent need for further lithological dating of duricrusts, weathering horizons, and sinter deposits, among other possibilities.

Basaltic flows of the eastern Hijaz Plateau could prove to be of a great help in providing a marker horizon for insuing morpho-climatic changes during the late Tertiary early Quaternary.

Of particular importance, to this writer at least, is the further investigation of the Quaternary deposits of the Uruq Subay' basin and other similar interior playas. They might very well hold the answer to the humid phases of the climatic history of Arabia. In addition, the incorporation of bio-stratigraphic evidence from the Arabian coastal plains, the Red Sea and the Arabian Persian Gulf may yield some clues as to the climatic periodicity of the Near Eastern Quaternary; the interrelationships between terrestrial deposits, marine transgressions and regressions during the eustatic changes of sea level should shed new light on the Quaternary landform evolution in the Arabian Peninsula.

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