SOURCE OF SAND FOR AN NAFUD SAND SEA, KINGDOM OF SAUDI ARABIA

by

DeWayne J. Faulkender

B.S., Kansas State University, 1959

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1986

Approved by:

James R. Underwood

Major Professor

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Purpose of Study

The main objective of this study is to identify the source of the sand in An Nafud (The Great Desert) sand sea, a source that must fulfill three requirements:

1. An adequate volume of source rock must have been available.
2. The source rock must have been erodible and accessible to eolian activity.
3. The source rock must lie upwind of the sand sea.

Related objectives are:

1. Determination of the areal distribution and characteristics of An Nafud sand (grain size, sorting, skewness, and kurtosis).
2. Determination of the heavy-mineral content of the sand, compositional percent of individual minerals, and their areal distribution.
3. Determination of the heavy-mineral composition and percentages of the Paleozoic sandstone strata flanking the An Nafud sand sea.
4. Description of recent and paleoclimatic conditions.
5. Description of morphology of An Nafud sand sea including dune types, interdune areas, vegetation and its influence on sand stabilization, and evaluation of geologic processes acting in the sand sea at the present time.

Origin of Study

The idea for this study evolved in the spring of 1980 during a two-week field trip to Ar Rub al Khali (Empty Quarter) by Cole Smith, John Whitney, Mark Gettings, and the author, all from the U.S. Geological Survey, and H. A. McClure from the Arabian American Oil Company. John Whitney was engaged in the study of surficial deposits of the Arabian Peninsula (Saudi Arabia), and he recognized that no geological studies on the sand seas of Saudi Arabia had been published. This was discussed during the return trip from Ar Rub al Khali to Jeddah, Saudi Arabia, and the author's interest in such a study was heightened. Because the author was involved in geodetic surveying in northern Saudi Arabia, the logical choice for the study of a sand sea was An Nafud. The thesis proposal, The Source of Sand for An Nafud Sand Sea, was presented to, and accepted by, the Department of Geology, Kansas State University in December 1981.

Location and Accessibility

An Nafud sand sea covers about 70,000km^2 in north-central Saudi Arabia between 27°10' N. - 29°20' N. latitude and 38°10' E. - 42°50' E. longitude (Fig. 1). An Nafud sand sea, at its eastern extremity, merges with Ad Dahna, a sand sea that extends in a circular arc from the eastern edge of An Nafud to the northwestern corner of Ar Rub al Khali (Fig. 1).

No roads exist within An Nafud sand sea. Access to An

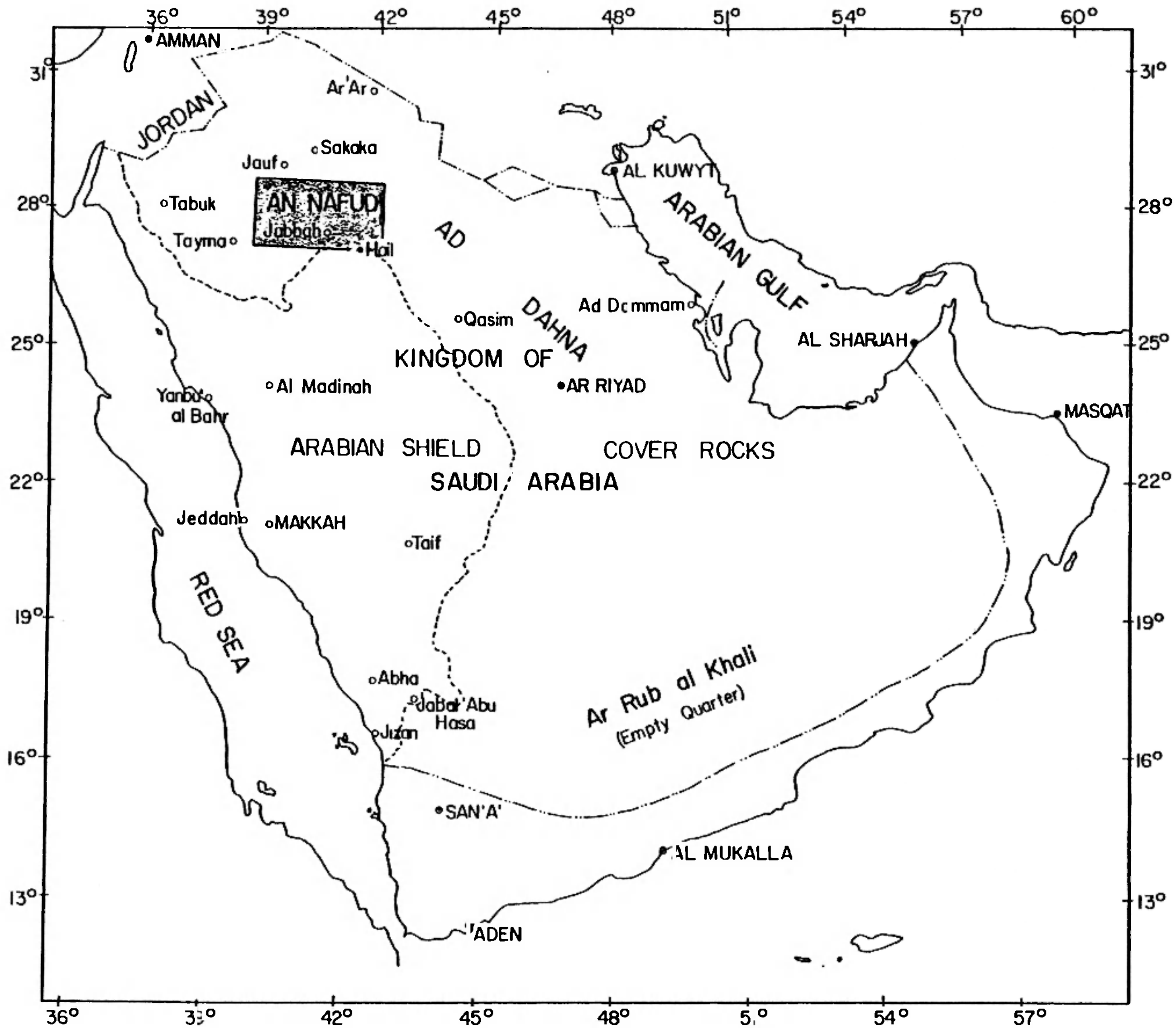


Figure 1. Location map of study area (shaded), Kingdom of Saudi Arabia (modified from U. S. Geological Survey, 1972). 1 inch = 120 miles

Nafud is either by helicopter or a well-equipped four-wheel drive vehicle. Asphalt highways, nearest to An Nafud, are at Hail, Jauf, and Tayma (Fig. 1). All other roads leading to An Nafud are track roads. Jubbah, the only village within An Nafud, is located about 100 kms west-northwest of Hail, near the southern margin of An Nafud (Fig. 1). No fuel or water is available within An Nafud sand sea. Collection of sand and rock samples was carried out by helicopter; two crossings were carried out by vehicle, one in November 1983 and another in October 1984.

Climate

Precipitation in An Nafud normally occurs between late fall and late spring and characteristically is in the form of brief, local, intense rainstorms. If rainfall is substancial, the stable sand will absorb and store moisture, thus reducing evaporation. The moisture is then available to support perennial vegetation and the germination of annuals.

Mean annual temperatures are 18°C to 20°C in northwestern Saudi Arabia, including An Nafud and the sandstone area to the west (Whitney and others, 1983). Areas southwest of An Nafud are somewhat warmer, averaging 20°C to 22°C. east and southeast of An Nafud, in the interior regions, mean annual temperatures are still warmer, averaging 22°C to 24°C (Bindagji, 1980).

Average summer temperature (June-August) for An Nafud area is 36°C. Winter average temperatures (December-February) for An Nafud range from 8°C to 12°C and are warmer toward the interior, ranging from 12°C to 16°C (Bindagji, 1980). Cooler winter temperatures in An Nafud help reduce evaporation and are partly responsible for the effectiveness of water in supporting vegetation.

Vegetation and Wildlife

Vegetation density is least along the margins of An Nafud and in general increases toward the interior. However, areas within the extreme interior display dead vegetation, indicating a recent period of aridity. Vegetation types include trees (4 to 5 m high), shrubs, and grasses. Few of the desert plants are edible by humans. Desert truffles, herbs, and seeds of the mesembryanthemum are among the ones used by the bedouin. Desert flowers appearing after sporadic rains are mostly dwarf varieties of the iris, chamomile, lily, and scarlet pimpernel.

Wildlife within An Nafud includes scorpions, snakes (sand viper and sand boa are most common), fox, rabbit, porcupine, hedge hog, jerboa, gerbil, and sand rat. Birds also abound in An Nafud and the surrounding area and include eagles, hawks, falcons, vultures, owls, and ravens. Species favored by the bedouin include sand grouse, quail, and coursers. The ostrich was last sighted in An Nafud area in the early 1950's, but ostrich egg fragments can still be found in some dry lake beds. Rare, but occasionally sighted in An Naful area, are ibex, gazelle, wolf, hyena, and jackal.

Culture

Bedouin of the Rashid tribe inhabit An Nafud sand sea and the surrounding area. Their primary diet is sheep, goat, or camel meat, together with rice. Each bedouin family owns a flock of sheep or a herd of goats or camels; some families own all three. The family lives in a goat-hair tent that is both warm during the winter months and cool during the summer months, depending upon how th sides are closed or opened. Cooking is done in large cookpots over open fires, normally inside the tent. All of the cooking and the herding of animals are done by the women or children. The social structure outside of the family is very restrictive for women and young ladies. After puberty, all women must wear a veil and abiya (long, black, wrap-around outer garment when outside of the tent or in the presence of other than family members. Social gatherings are segregated into groups of men and groups of women, and the family dwelling is divided accordingly. Children that have not reached puberty may be with either group. The primary social activity for men is gathering together to drink tea and coffee, at least two to three times a day. This is a time to discuss business and areas that have received rain, and to tell stories. Because the entire social structure is governed by Islamic principles and teachings, both men and women (if they so desire) meet at five predetermined times for prayer. prior to prayer time, the hands and feet mst be washed; prayer time is rigidly adhered to and takes precedence over all other activities.

Bedouin move according to the rains that determine the availability of grazing areas for their animals. Before the introduction of automobiles, the entire camp was moved using camels as the mode of transportation. Today, as they have been for at least the last ten years, trucks are used exclusively for moving both the camp and animals. As a direct result of this increased mobility, over-grazing has caused degradation of pasture land; the bedouin can move their animals from area to area so fast that the vegetation is unable to grow and mature.

An Nafud sand sea provides excellent grazing for sheep, goats, and camels, and therefore is inhabited by bedouin the year round. The most serious obstacle to life within An Nafud sand sea is water. There are no water wells except in the extreme eastern portion of An Nafud, therefore, all water must be hauled in to the animals by pickup or tanker. Small catchment basins have been constructed by hand in many of the Quaternary lake basins. Water in them supplements the water supply when rainfall is significant.

Previous Investigations

No field-based geologic studies of An Nafud sand sea, except by Whitney and others (1983), have been published. The work by Bramkamp and Ramirez (1963), Bramkamp and others (19630, Bender (1975), Brown and others (1963), Helal (1965), Powers and others (1966), the U. S. Geological Survey and Arabian American Oil Company (1963), and Saudi Arabia Ministry of Agriculture and Water (1968) all entailed general geologic studies of the Paleozoic sandstone of northern Saudi Arabia. Geologic studies of An Nafud sand sea by Breed and others (1979) and Fryberger (1979) were based on information derived from interpretation of Landsat images that cover the area and did not involve fieldwork. Geologic work by Whitney and others (1983) entailed studies to determine the Quaternary geologic history of An Nafud sand sea. As pointed out by Helal (1965), some confusion exists in the literature concerning names and ages of Paleozoic formations in northern Saudi Arabia. The geologic section recorded on the U. S. Geological Survey and Arabian American Oil Company map (1963) will be used exclusively throughout this paper; formation descriptions are modified by the author, based on his field investigations.

Field Procedures

Fieldwork was carried out completely by helicopter from three different field camps. By using a grid sampling technique, 35 dune samples were collected for textural and compositional studies. Samples were collected at approximate intervals of 30 minutes of latitude and 30 minutes of longitude. All dune samples were collected about one meter below the dune crest on the slipface side of each dune sampled. Twenty-four rock samples were collected from the area of outcrop of Paleozoic sandstone formations. Selective sampling was necessary because the Paleozoic sandstone is at least 2,000 m thick. Samples were collected from the Siq, Quweria, Ram and Umm Sahm, Tabuk, and Jauf formations of Paleozoic age, and the Sakaka Formation of Paleozoic? and Mesozoic? age. Paleozoic sandstone lies to the south, southwest, west, and northwest of An Nafud sand sea.

Acknowledgements

Thanks are extended to Maurice Brock, Robert Greene, John Whitney, and Lawrence Rooney, each of whom provided guidance, encouragement, and constructive advice. Without their help this paper would not have been completed.

Because of my absence from academic life for a number of years, the need for advice was considerable. Sincere gratitude is expressed to the committee members: James R. Underwood, Jr., thesis supervisor, the late Henry V. Beck, Joseph L. Graf, Jr., Page C. Twiss, and Wayne Williams, Kansas State University, for providing such advice.

Many thanks go to Bill Thompson for his superb help with the illustrations. Acknowledgement is also made of the Hydrology Division, Water Resources Department, Ministry of Agriculture and Water, Riyadh, Saudi Arabia for furnishing the wind and rainfall data for An Nafud area, which are quoted in this thesis.

A very special thanks to the authors family: wife Marlene, son Jeff, and daughter Twinkle, for their patience and encouragement throughout. They made many sacrifices in order that degree requirements could be completed.

GEOLOGY OF WESTERN SAUDI ARABIA

Stratigraphy

The rocks of the Arabian Peninsula are defined physiographically as the Arabian Shield (Precambrian) and Cover Rocks (younger than Precambrian). In western Saudi Arabia, Precambrian rocks are exposed to the greatest extent along the coastal ranges and the central interior.

Crystalline rocks of western Arabia occupy a 770,000 km^2 trapezoidal segment separated from the African Shield by the Red Sea rift. The granitic framework within the exposed area is similar to that of other shields in that it contains belts of Precambrian granitic or dioritic rocks, in places gneissic. Two major belts intersect at right angles beneath the Sahl Rakbah in the south-central part of the segment, one extending northeastward from the Red Sea coast, the other northwestward from the sedimentary cover of the western Ar Rub al Khali (Empty Quarter). The belt extending northeastward from the Red Sea rift has features of injection and magmatization and is flanked by a retrogressively metamorphosed group of basic igneous rocks, slate, and quartzite. The northwestward trending trending belt has characteristics of orthogneiss (Brown, 1960). Greenwood and others (1982) interpreted these belts as being the result of two compressional orogenies that occurred 800-760 and 690-640 My ago. A variety of igneous rocks, including granodiorite, adamellite, monzonite, and albite-pyroxene granite, is associated with the belts, and may be slightly younger than the gneisses. The gneisses may be roots of syntectonic batholiths (Brown, 1960). Somewhat younger batholiths and stocks of calc-alkalic granite are both concordant and discordant. In many places, widespread types of granite crop out as a mixture of two or three granites of uncertain age. Young intrusive rocks are soda-rich granite (with peralkaline facies), syenite, and rhyolite cropping out in plugs, stocks, and ring dikes of rather small extent individually; some batholiths near the eastern edge of the shield segment are of a younger magma series. In the northeastern part of the shield, volcanic necks associated with erruptions of rhyolite, dacite, tuffs, and related rocks occur (Brown, 1960).

Brown and Jackson (1960) have divided the Arabian Precambrian basement complex into three distinct sedimentary groups:

1. The Hali Schist-Basih Greenstone-Lith Complex.

   These rocks include chlorite-sericite schist, amphibolite schist, graphite schist, metadiorite, metagabbro, marble, quartzite, and volcanic rocks metamorphosed to greenschist. This group of rocks, about 21,000 m thick, is well exposed along Wadi Hali and Wadi Basih near the village of Al Lith.

2. Halaban Andesite-Murdama Formation.

   These units consist mainly of andesite, felsite, dacite, and trachyte together with agglomerate and conglomerate in the lower part, and low-grade metamorphic rocks (slate, phyllite, quartzite, and graywacke) in the upper part. This group of rocks is about 1,000 m thick.

3. Fatima Formation.

Karpoff (1957) applied the name "Fatima Series" to a section that includes the Abla Formation and Shammar Rhyolite. This group of sedimentary and volcanic rocks is partially metamorphosed and has been gently folded and cut by porphyritic sills and dikes of andesite and rhyolite. These strata are composed of arkose, shale or slate, siltstone, tuffaceous wacke, sandstone, and thin stromatolitic limestone members; total thickness is about 700 m.

Paleozoic sandstone, where exposed, lies unconformably on the Precambrian plutonic and sedimentary rocks. The An Nafud area is underlain by 1900 to 2600 m of Paleozoic sandstone, shale, and subordinate carbonate rocks without unconformity; lithologic components are dominantly sandstone (Table 1). About 75 percent of Paleozoic sediments are sandstone, the remainder being shale or siltstone, mostly marine as indicated by the abundant occurrence of acritarchs and chitinozoans (Saudi Arabia Ministry of Agriculture and Water, 1968). The relatively thin marine shale units and the much thicker sand bodies indicate that marine incursions

Age		Formation	Generalized lithologic description	Map designation	Thickness (m)	Major stratigraphic divisions
CENOZOIC	Quaternary and Tertiary	Surfical deposits	Gravel, sand, silt, alluvium, duricrust	Qe, Qu, Qd		
		Lava flows	Basalt	QTb		
MESOZOIC	Cretaceous	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone.	Ka	142	Carbonate rocks
		Sakaka	Sandstone; subordinate shale, rare dolomite lenses.	MPs	42	Terrigenous rocks
PALEOZOIC	Devonian	Jauf	Sandstone, limestone, and shale	Dj	299	Terrigenous rocks
		(Tawil Member)	Sandstone	Dt	1072	
	Silurian and Ordovician	Tabuk	Sandstone and shale	DSQt		
		Saq: Umm Sahm	Sandstone	OCs= Saq	600	
		Saq: Ram		OCur		
	Cambrian	Saq: Quweira		Cq		
		Saq: Siq (Wajid ?)		Cs		

Precambrian basement complex

Table 1. Outcrop sequence, northwestern Saudi Arabia (modified from Powers and others, 1966).

were relatively short, whereas much longer intervening continental episodes resulted in the deposition of thick, massive, crossbedded sandstone.

The Wajid Sandstone (Table 1) unconformably overlies the basement complex in some areas of the southern shield, and is unconformably overlain by the Upper Permian Kuff Formation. Powers and others (1966) considered the Wajid Sandstone to be Early Permian or older. However, recent palynological investigations of well cores (McClure, 1980) along the southeast shield strongly suggest a Cambrian-Ordovician age for the terrigenous units of the lower Wajid, which also suggests a possible correlation between the lower Wajid and the coarse terrigenous units of the basal Siq Formation in northwestern Saudi Arabia.

Rocks of Carboniferous age have not been reported in western Saudi Arabia, except at two sites: one near Ar'Ar (formerly Badinah) in the extreme north of the Kingdom and the other near Qasim in the north-central portion (Saudi Arabia Ministry of Agriculture and Water, 1968). In western Saudi Arabia the entire period from Late Devonian to Late Permian was undoubtedly a time of uplift and erosion (Powers and others, 1966).

Western Saudi Arabia is nearly devoid of Mesozoic strata, except for two known locations: in the southern part of western Saudi Arabia at Jabal Abu Hasa (lat 17°40' N., long 42°53' E.) where marine sandstone and shale of Jurassic age unconformably overlie the older Wajid Sandstone

(Whitney, 1983) and in northwestern Saudi Arabia where the Sakaka Sandstone of Mesozoic? or Paleozoic? age unconformably overlies the Lower Devonian Jauf Formation (Fig. 2). Strata of Mesozoic age crop out along a north-northwest trending line through central Saudi Arabia, forming the Tuwayq Escarpment (Table 2 and Fig. 2). Presumably western Saudi Arabia was subjected to erosion throughout most of the Mesozoic Era (Brown, 1970).

Early Tertiary deposits are few and of limited extent in western Saudi Arabia, except in the extreme northwest part. Brown (1980) studied a marine limestone of Paleocene age at Usfan, about 55 km northwest of Jeddah; Madden and others (1979) described a vertebrate fauna from Paleocene-age estuarine deposits east of Taif at Jabal Umm Himmar (lat 21°10' N., long 45°25' E.).

Late Cretaceous to late Eocene deposits of marine origin crop out north and northwest of An Nafud (Bayliss, 1981). Farther south, near Harrat Uwayrid, silicified boulders, ranging from 20 cm to 50 cm in diameter and containing Eocene marine fossils, have been recorded by Brown (1970). Brown (1970) beleived that the boulders may have been transported from Eocene deposits near Jordan. Whitney (1983), however, speculated that the deposit may represent a lag deposit rather than a transported deposit. Work by R. Gregory (oral communication, 1981) on the northern Harrats has shown this deposit to be more widespread than previously thought. The author visited the

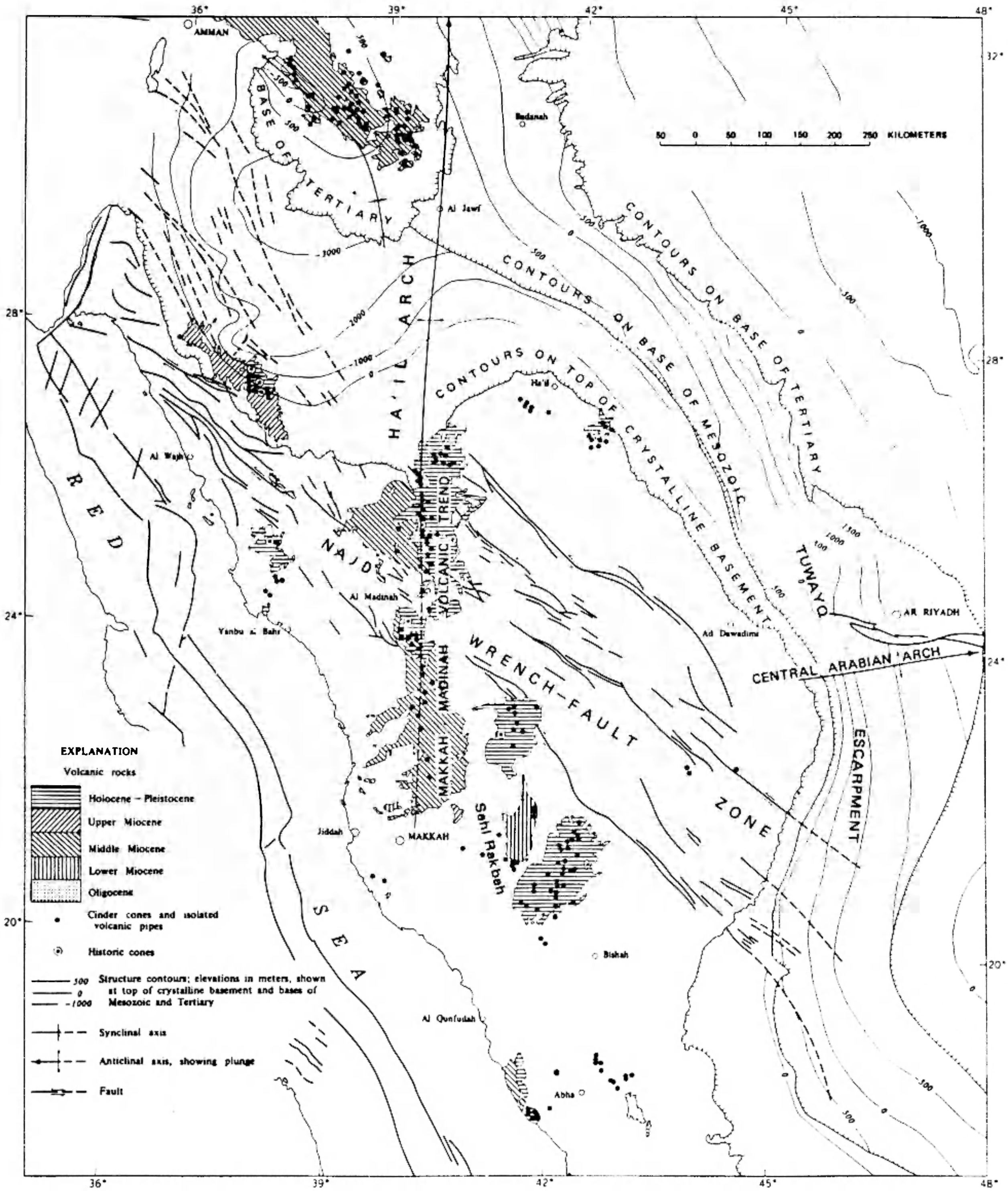


Figure 2. Generalized tectonic map of the northern part of the Arabian Shield (modified from Brown, 1972, and Greenwood, 1972).

deposit in 1981 and 1982; it lies unconformably on Precambrian rocks and is overlain by Tertiary-Quaternary basalt. The original Eocene deposit probably was subjected to erosional processes, and the more dense and resistent rock remained as lag from the original rock.

Marine and non-marine sedimentary rocks of middle and late Tertiary age are found along the Red Sea coast, and Oligocene basalt flows occur at high and low altitudes along the coastal ranges (Brown, 1970). Flat-lying plateau basalt of late Oligocene to early Miocene age covers lateritic profiles of Oligocene age in western Saudi Arabia (Madden and others, 1979; Brown, 1970). Along the Red Sea coastal plain Pliocene marine sedimentary rocks are exposed (Brown, 1970). At higher elevations, depoists of Pliocene age have been dated from their freshwater fauna and probably represent the development of individual depressions on the widespread terminal, middle Tertiary peneplain (Brown, 1970). Lava flows of Pliocene age are found at high and low altitudes and range in age from 12.3 My north of An Nafud to 9.1 My north of al Medina to 6.8 My south of Jeddah (Brown, 1970).

Ouaternary sediments in Saudi Arabia are composed mainly of residual alluvial, tuffaceous, lacustrine, and eolian deposits (Whitney, 1983). Eolian deposits, the most abundant, cover about one third of the penninsula mainly in the form of large and small sand seas. Quaternary pluvial deposits have been subjected to eolian processes during arid periods, resulting in a complex history of sedimentation and erosion.

Structure

The shield is bordered by Paleozoic, Mesozoic, and Cenozoic rocks that dip baisnward (shelf area). The dip is so slight as to be imperceptible to the eye. Data collected over the years from topographic, structure drill holes, and seismic surveys define a constant homocline with a width of about 400 kms and a constant dip (mainly northeast) of 1° to 2° in the Paleozoic strata to $0^{\circ}20'$ in the Mesozoic and Cenozoic strata (Powers and others, 1966). This homocline represents an area of unusal tectonic stability, with only slight changes in the strike and dip that are undoubtedly related to gentle flexures of the basement complex. This gentle flexing has been responsible for the primary structural features found in the Cover Rock strata, mainly, the east-northeast plunging Central Arabian Arch and the much more extensive north plunging Hail Arch (Fig. 2)., both named by Powers and others (1966). Major faults on the Arabian shield trend northwest and north-northwest (Fig. 2). The Najd wrench fault is the most prominent and extends across the central shield in a northwesterly direction. In the north-northwest, the Najd fault zone disappears under Paleozoic rocks. Field investigations by Brown (1960) have shown that the block north of the Najd fault zone has moved northwest with respect to the block south of the zone. Faults east of the Gulf of Aqaba and faults diverging from the Najd fault zone in the southwestern part of the shield also display the same left-lateral relative movement. North of the Najd fault, along the eastern edge of the shield, beds of Precambrian age are overthrust to the west. This overthrusting has caused the formation of conglomerate beds along the leading edge of the overthrust blocks as they moved westward. The entire fault system is indicative of a regional northwest-southeast force couple (Brown, 1960). High-angle normal faults have developed along the crest of the ramp on the Red Sea rift or diverge from it in a northerly direction. These faults follow older lineaments and, in places, have been superposed on Precambrian lineaments.

Geologic History

Results of many investigations show that the eastern margin of the Red Sea and the associated coastal structures in Saudi Arabia have a long geologic history, starting with the deposition of Precambrian eugeosynclinal sedimentary and volcanic rocks before 1,000 My and extending to deposition of Recent sediments. The northeastern flank of the Red Sea rift valley is in a shield area affected possibly by four plutonic events: 1,000, 735?, 660-670, and 570 My (Brown, 1970). The Arabian Shield is composed of two major gneissic belts that also contain belts of Precambrian granitic and dioritic rocks. One belt extends northeastward from the Red

Sea coast and the other norethwestward from the sedimentary cover of Ar Rub al Khali. Greenwood and others (1982) interpret these belts as recording two compressional orogenies that occurred 800-760 amd 690-640 My ago.

Near the end of the Proterozoic, peneplanation of the shield occurred and probably continued into Early Cambrian. The age for this erosional period is based on the relationship between the deformed sedimentary Jubaylah Formation and overlying, nearly horizontal, sequence of Cambrian-Ordovician sandstone. Binda (1981) suggested an age of 600-570 My for the Jubaylah Formation, based on microfossil and radiometric evidence, whereas Powers and others (1966) correlated the unfossiliferous Cambrian-Ordovician sandstone of northern Saudi Arabia with a trilobite-bearing unit in Jordan. Following the late Proterozoic to Early Cambrian erosional period, the Siq. Quweira, Ram, and Umm Sahm sandstone units were deposited. Outcrops of Nubian-type sandstone strata of Cambrian-Ordovician age lap upon the shield from Jordan southeastward to 45° E. longitude, where they are, in turn, overlapped by Permian limestone. Sandstone outliers of Paleozoic age occur in the central shield, proving that lower Paleozoic sandstone covered most, if not all, of the basement complex now exposed (Brown, 1970). Deposition continued throughout the Silurian and Early Devonian, during which time the Tabuk and Jauf formations were deposited (Figs. 3 and 4).

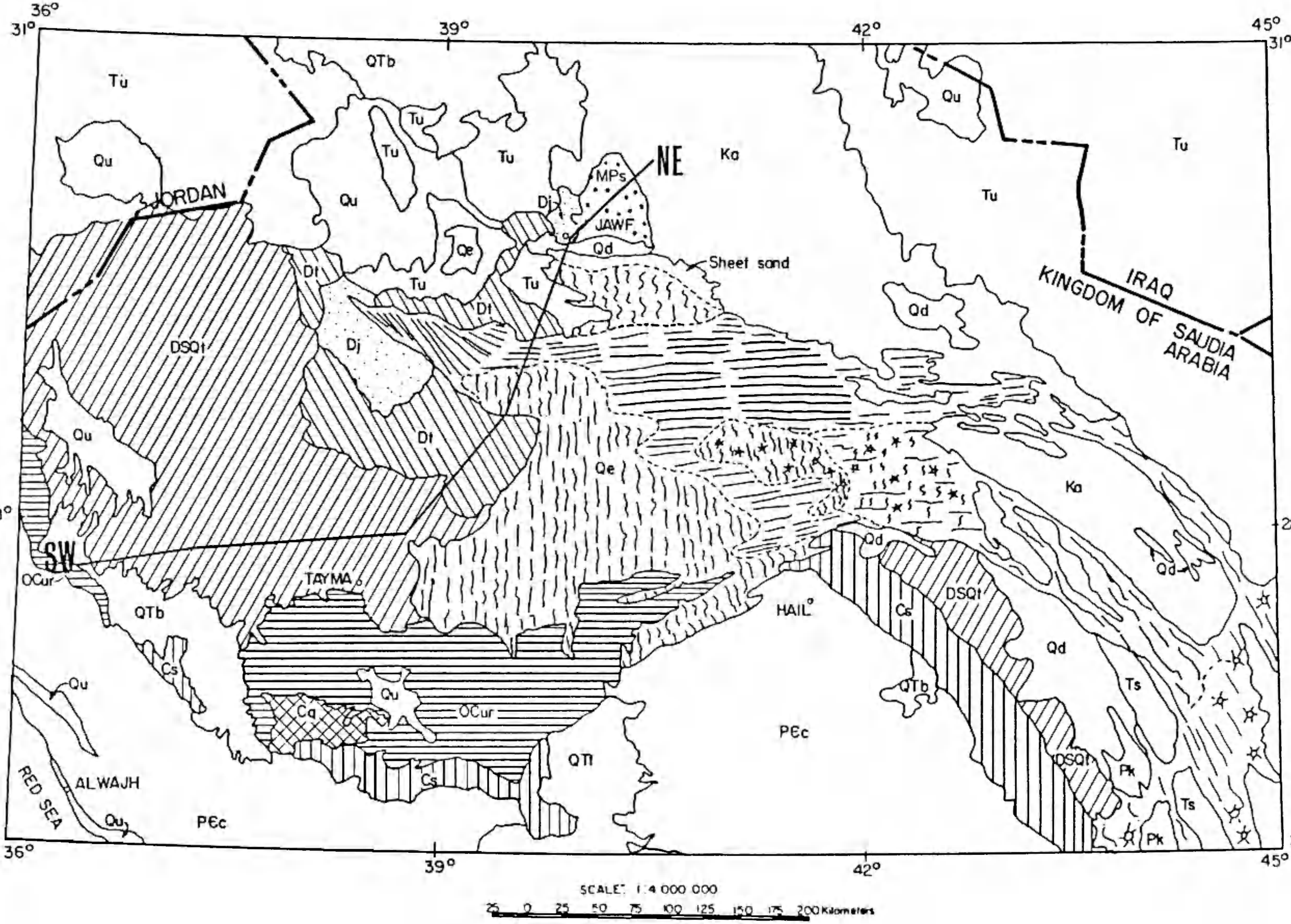


Figure 3. Generalized geology of An Nafud region, Kingdom of Saudi Arabia. Emphasis on Paleozoic sandstone and dune classification (modified from U.S. Geological Survey and Arabian American Oil Co., 1963).

EXPLANATION

CENOZOIC

- **Qe** — Eolian sand (also shown as individual dune type)
- **Qu** — Alluvium and related surficial deposits
- **Qd** — Duricrust
- **QTb** — Basalt
- **Tu** — Undifferentiated sandstone, marl, and limestone formations

MESOZOIC

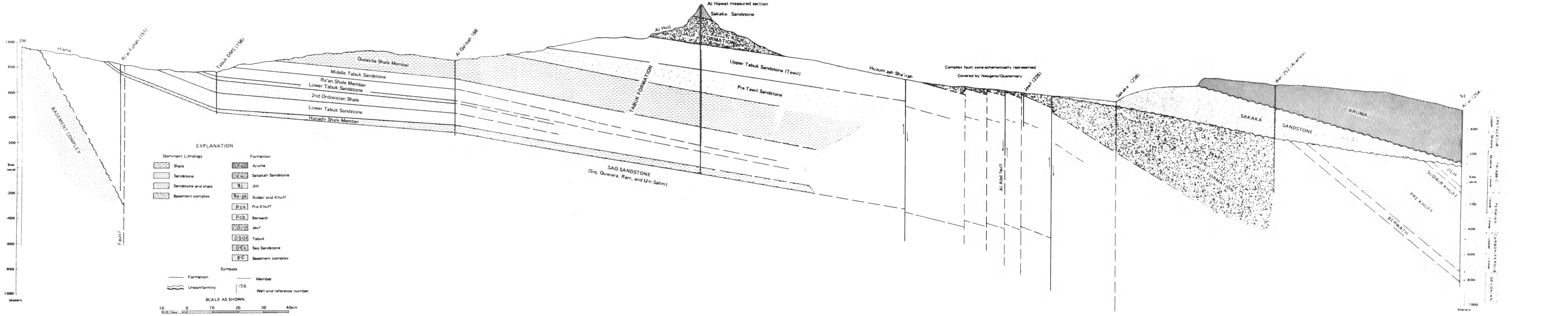
- **Ka** — Aruma Formation
- **Trj** — Jilh Formation
- **Pk** — Khuff Formation
- **MPs** — Sakaka Sandstone

PALEOZOIC

- **Dj** — Jauf Formation
- **Dt** — Tawil Member of the Tabuk Formation
- **DSQt** — Lower Tabuk Formation
- **OCur** — Umm Sahm and Ram sandstones
- **Cq** — Quweira Sandstone
- **Cs** — Siq Sandstone

- **PЄc** — Precambrian complex: igneous, metavolcanic, and metasedimentary rocks

- Sheet sand
- Transverse and barchanoid ridges
- Linear
- Linear and massif
- Complex: Includes linear, transverse and massif
- Contact
- Dune-form transition zone
- International border
- Cross section (see Fig. 4)



Vertical exaggeration 20X

Figure 4. Stratigraphic section, Tabuk and Jawf-Sakaka regions (from Saudi Arabia Ministry of Agriculture and Water, 1968).

The geologic history of the Arabian shield during the early Mesozoic Era is not well known. Presumably the craton was above sea level during this time and was subjected to erosion throughout the era (Brown, 1970). There is evidence, however of a brief transgression of a Jurassic sea. The evidence is preserved at only one known location in western Saudi Arabia; at Jabal Abu Hasa (lat 17°40' N., long 42°53' E.) marine sandstone and shale unconformably overlie the older Wajid Sandstone (Whitney, 1983). Cretaceous rocks, in northern Saudi Arabia, display the first definite sign of development of the Hail Arch. Sandstone of Middle Cretaceous age was deposited continuously across the crest of the Hail Arch (Fig. 2) essentially parallel to the strike of the Paleozoic strata (Powers and others, 1966). Upper Cretaceous rocks show sharp facies change from marine carbonate rocks on the east flank to continental sandstone across the crest, and were the last beds to be deposited over the arch before the strike of the interior homocline was shifted north by the rising basement (Powers and others, 1966). Upper Cretaceous and Eocene strata thicken in both directions from the crest of the Hail Arch (Powers and others, 1966).

Early Tertiary deposits west of the Hail Arch are few and of limited extent. For this reason it is very difficult to determine how far south the Hail Arch influenced depositional and erosional trends prior to Red Sea rifting (Whitney, 1983). Field investigations by Brown (1970) and

Madden and others (1979) of Paleocene deposits have shown that a Paleocene sea extended at least as far south as Jeddah and Taif. The eastern boundary of this Paleocene sea probably was the southern extension of the Hail Arch (Madden and others, 1979). Recent work by Bayliss (1981), north and northwest of An Nafud, has shown that marine deposition occurred from Late Cretaceous to late Eocene, the major marine transgression occurring during middle Eocene.

Marine and non-marine sedimentary deposits of middle and late Tertiary age are found along the Red Sea coast. Oligocene basalt flows are present at high and low altitudes along the western coastal ranges (Brown, 1970). Highly weathered Oligocene residual deposits appear to be the last record of the Arabian Shield as a low-lying, low relief, and quiescent craton (Whitney, 1983). The flat-lying plateau basalts of Oligocene age probably represents the first crustal or sub-crustal activity that eventually led to the formation of the Red Sea rift and uplift of the western edge of the shield (Whitney, 1983). The onset of rifting in the Red Sea is not well constrained. Brown (1970) believed that major rifting occurred just before or during early Miocene when flanks of the rift valley were ramped upward. Coleman and others (1979) believed that the intial crustal attenuation occurred 20 to 24 My ago, based on dates of tholeiitic basalts (of southwestern Saudi Arabia) which are interpreted to be the first magmatic products of the newly-formed Red Sea rift. Schmidt and others (1982) studied Tertiary rocks of the southern Tihama and concluded that the shield flood basalts and volcanic sedimentation represented by the Baid Formation (early to middle Miocene) represent deposits of continental rifting that preceded the actual formation of the Red Sea rift.

The Pliocene was a period of epeirogeny in Arabia and is reflected in Pliocene deposits (marine limestone and shale) along the Red Sea coastal plain, where sediments that were originally deposited below sea level now are exposed (Brown, 1970). The late Pliocene through late Pleistocene was most likely a humid period. Studies by Anton (1980) and Hötzl and others (1978) of the extensive gravel deposits of the Arabian Peninsula, red soils of the coastal mountains of western Saudi Arabia, weathering products of shield rocks and younger basalts, erosion of slopes along the Red Sea coastal ranges, and alluvial fans both upon the shield and below the western coastal ranges support the interpretation of a humid phase for this period. However, Whitney and others (1983) and Hötzl and others (1978), believed that arid episodes also occurred during this period, that the sand seas of Saudi Arabia began to form, possibly as early as late Miocene, but the growth was episodic rather than continual and extended into the late Pleistocene.

Quaternary Geomorphology and Climate

Studies of ancient climatic conditions during the Quaternary are few in Saudi Arabia. The first general observations pertaining to paleoclimatic conditions of Arabian sand seas were those reported by H. St. John Philby (1933). Philby, during his travels through Ar Rub al Khali (Empty Quarter), recognized and described lake beds lying between dunes and the vast gravel plains common in many areas of this sand sea. Philby equated his observations with a wetter climate sometime in the recent past.

The extensive gravel sheets of Ar Rub al Khali also were recognized by Holm (1960) as evidence of wetter climatic conditions during the Quaternary Period. In addition, Holm related former high stands of sea level in eastern Arabia to a wetter climate, and thus explained the existence of sabkha deposits as high as 150 m above present sea level. Faunal remains of antelope were found by Holm (1960) associated with lake beds in Ar Rub al Khali and convinced him of climatic fluctuations within the Pleistocene. Studies of the Quaternary geology of Saudi Arabia both by Holm (1960) and by Brown (1960), working independently, convinced them that the formation of Arabia's sand seas was a relatively recent event related to aridity in the Quaternary.

In eastern Arabia, a series of duricrust benches were studied by Chapman (1971, 1974). Chapman concluded from his studies that the duricrusts were formed during arid conditions rather than pluvial conditions. Radiocarbon dates determined by Chapman for the duricrust benches were inadequate, and he was unable to fit the terrace sequence into an established Pleistocene sequence. Whitney (1983) disagreed with Chapman's model of duricrust formation and believed that duricrusts in Saudi Arabia were formed during a pluvial rather than an arid period, based on radiocarbon dates determined by Whitney for duricrusts in Arabia's sand seas, cover rock, and shield areas.

Radiocarbon dates from Pleistocene and Holocene lacustrine deposits in Ar Rub al Khali by McClure (1976, 1978) indicate that the most recent arid periods were late Pleistocene (17,000 yrs to 9,000 yrs BP) and Holocene (6,000 yrs BP to present) and that the intervening pluvial periods were 36,000 yrs to 17,000 yrs BP and 9,000 yrs to 6,000 yrs BP.

The first detailed studies of Quaternary surficial deposits in Saudi Arabia were carried out by Al-Sayari and Zötl (1978). Surficial deposits in eastern Saudi Arabia were studied and in many cases isotopically dated. As a result, the dates for pluvial periods were refined to 30,000 yrs to 25,000 yrs BP and 9,500 yrs to 4,500 yrs BP and agree closely with the pluvial periods defined by McClure (1976, 1978).

Studies by Hötzl and others (1978) have shown that arid climatic conditions began in eastern Arabia during late Pliocene - early Pleistocene, the first dunes developing during this change to an arid climate. Their conclusion is based on the dunes in the western Ar Rub al Khali that rest on late Pliocene - early Pleistocene gravel plains and A Jurfurah dunes near the Arabian Gulf that rest on the regression plain and on the deltaic fan of Wadi as Shaba. Studies by Hötzl and others (1978) indicated that arid conditions prevailed, in eastern Arabia, throughout the remainder of the Pleistocene and through Holocene, with brief sporadic periods of humid climatic conditions.

Recent studies by Whitney (1982, 1983) of surficial deposits in western Saudi Arabia have provided additional information pertaining to Quaternary climatic conditions. Whitney (1982) and Whitney and others (1983) obtained radiocarbon dates for calcareous lacustrine and duricrust deposits from Arabia's sand seas and shield areas. Lake-forming activity took place 33,000 yrs to 21,000 yrs BP and 9,000 yrs to 5,000 yrs BP, with intense activity occurring 30,000 yrs to 24,000 yrs BP and 8,000 yrs to 6,000 yrs BP, and primary eolian activity occurring between 20,000 yrs and 10,000 yrs BP. Whitney (1983) concluded, from his studies, that the increase in eolian activity in the last 5,000 yrs has not been as intense as in the late Pleistocene episode.

AN NAFUD SAND SEA

Present Climate

In most parts of the world, present-day climatic conditions are usually relatively easy to describe. However, records on annual rainfall, wind direction, and wind speed in Saudi Arabia have been kept only for a few years and only for a few localities. The available data must be interpreted with caution.

Figure 5 shows the average annual rainfall for meteorological weather stations in An Nafud region. Larger rainfall amounts (74 mm to 111 mm) occur along the southeastern edge of An Nafud. In comparison, An Nafud region and the Paleozoic bedrock region to the west average about 50 mm a year precipitation. The only meteorological station lying within An Nafud sand sea is at Jubbah where an average of 41 mm a year, based on six years of record, has been recorded. Precipitation normally occurs between late fall and late spring in An Nafud. Rainstorms are usually localized, rather than regional.

Vegetation in An Nafud is relatively dense, including the slipfaces (Fig. 6), compared with vegetation density in the southern Ad Dahna and Ar Rub al Khali, and is the result of a number of factors that include: (1) a greater percentage of stable sand in An Nafud; (2) a slightly higher average annual rainfall then other sand sea areas; (3) lower average winter temperatures; and (4) possible lower average wind speeds that, in turn, reduce the quantity of new sediment being added to the sand sea. Vegetation density is least along the margins of An Nafud. This condition is directly related to various environmental conditions in each

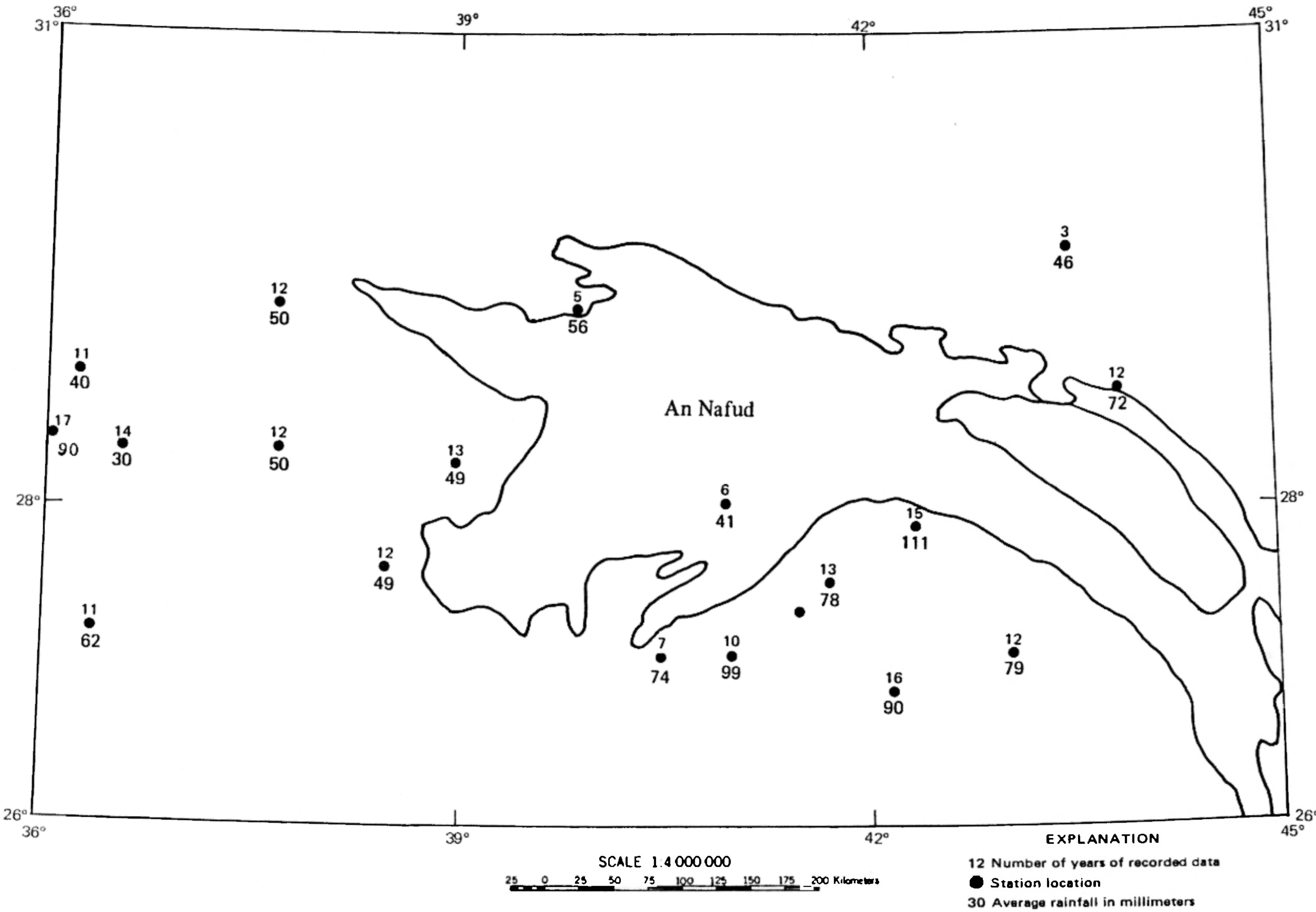
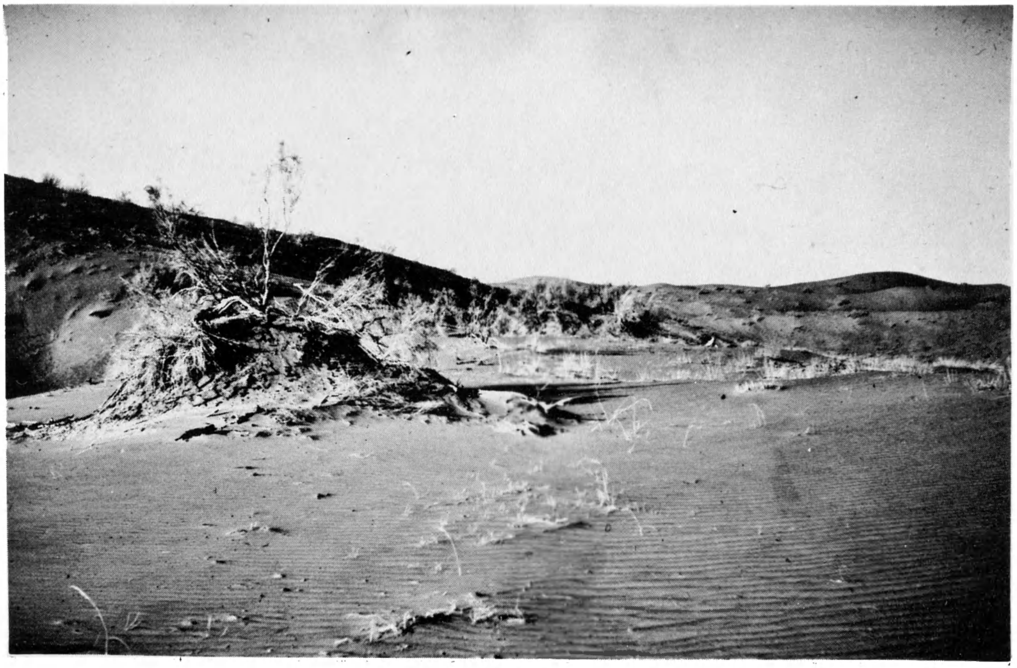


Figure 5. Average annual rainfall in mm, for meterorological stations in An Nafud region. Data, as of 1983, from Hydrology Division, Water Resources Department, Saudi Arabia Ministry of Agriculture and Water, Riyadh, Saudi Arabia (base map from U. S. Geological Survey, 1972).



(a) Active deflation in stable eolian sand. Note the exposed plant roots (center of photograph) and dry grass (lower center of photograph). Scale 1:10 (center of photograph)

(b) Typical vegetation cover, central part, An Nafud sand sea. Note vegetation on slipface and eroded lakebed below slipface (central part of photo). Scale 1:400

Figure 6. Photographs of vegetation cover and deflation, An Nafud sand sea.

fringe area. Along the west and southwest margins, a smaller percentage of dunes is stable, with a small amount of new sediment being added intermittently that, in turn, inhibits plant growth. In the northwestern extension and along the northern margin, sand thickness ranges from 2 m to 25 m, as compared to 100 m to 200 m in other areas of An Nafud. This reduced sand thickness limits the volume of moisture that can be stored in the sand, resulting in limited plant growth.

Based on a vegetation traverse by J. Whitney, U.S. Geological Survey, and Dr. E. Schulz, Geographisches Institut, University of Würzburg (FRG), from Hail to the central An Nafud, Whitney and others (1983) concluded that the plant assemblage becomes drier toward the interior of An Nafud, which suggests that the central portion is more arid than other areas. This shift in vegetation assemblage is accompanied by a slight increase in the number of active dune crests toward the interior.

Wind data for An Nafud area are provided in Figure 7; wind roses were calculated from individual monthly station reports. Each vector represents the percentage of observations for sixteen points of the compass, except for Al Ula, where only eight were recorded. Mean wind velocity for each station, calculated from the total observations of all wind directions, serves as a wind-intensity factor for comparing stations.

Mean wind-velocity values are greatest in the northwest

(8.5 knots) and southwest (7.6 knots) of An Nafud (Fig. 7) and are below the minimum required speed to transport sand (Fryberger, 1979). Wind-storm data are not available. Because of this, all wind data must be interpreted with caution, however, the low mean wind speeds are reflected in An Nafud sand sea by the low percentage (5 to 8 percent) of active dunes.

Standard deviations were calculated for the mean wind velocity at each station (Fig. 7), and the generally low values indicate that the range of wind speeds between maximum and minimum was small. Near the northwest edge of An Nafud, one station has a standard deviation of 0.476, greater than the range (0.043-0.183) of all stations, possibly indicating much higher wind velocities there. This station also recorded the highest mean wind velocity but has only three years of record.

The prevailing wind direction was calculated from the total observations at each station, and ranges from 12 - 31 percent between stations. Dune orientation strongly supports the view that the sand transporting wind is from the prevailing-wind direction at each station, however, without specific individual wind-storm data no absolute conclusion can be drawn. The prevailing wind west of An Nafud sand sea is from the northwest (Fig. 7), with strong secondary winds from the north and west. Dune trends in the west and southwest of An Nafud indicate that the primary sand-transporting winds came from the west-southwest and

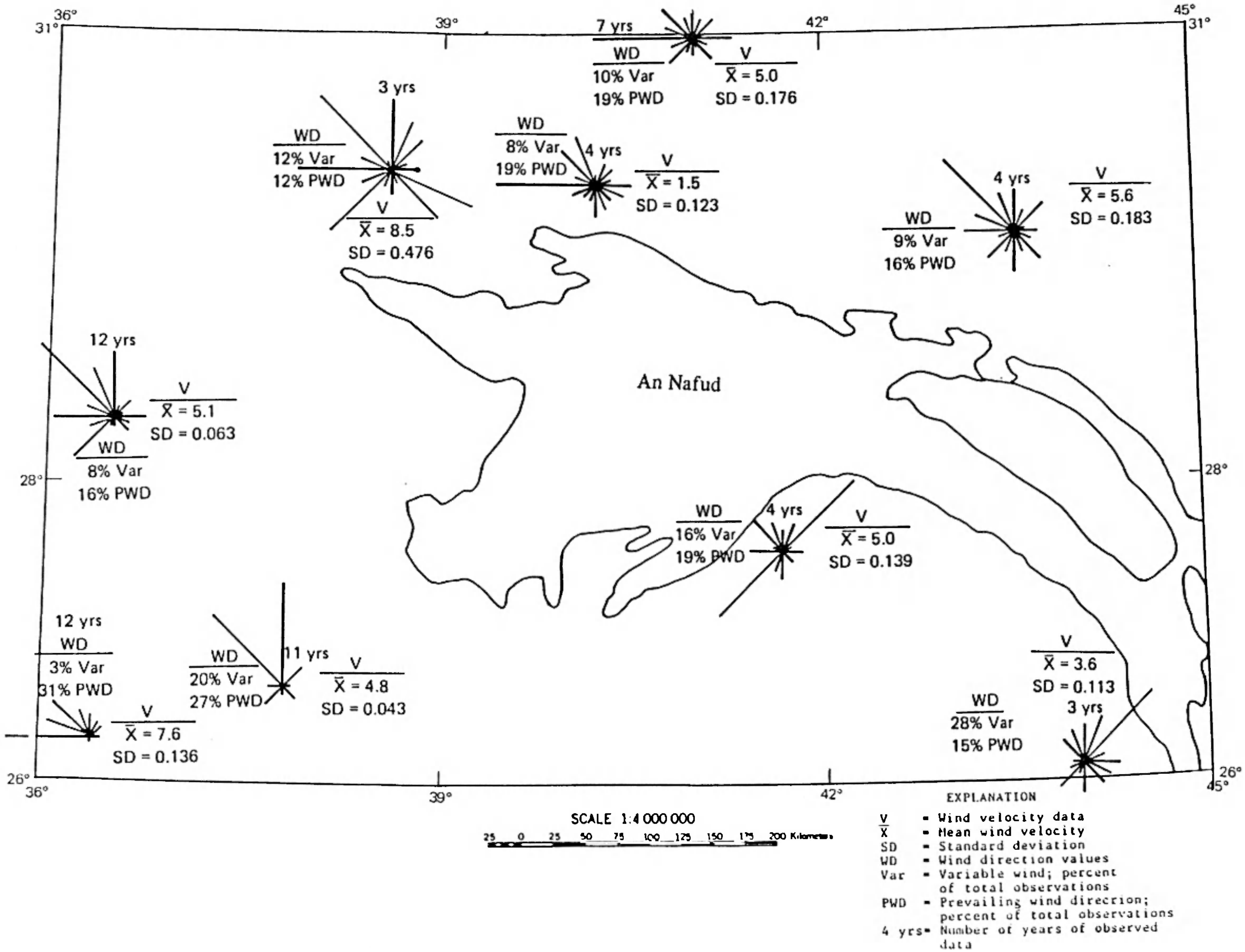


Figure 7. Wind rose diagram for meterorological stations in An Nafud region. Data, as of 1982, from Hydrology Division, Water Resources Department, Saudi Arabia Ministry of Agriculture and Water, Riyadh, Saudi Arabia (base map from U. S. Geological Survey, 1972).

southwest (Fig. 7). Longitudinal dunes of the central An Nafud have an east-west orientation, indicating that dune-forming winds were from the northwest and southwest, whereas northeast-facing cresentric slipfaces on these dunes suggest that southwesterly winds were the last to alter the primary dune shape. The small percentage (5 to 8 percent of total dune area) of active dunes and rather dense vegetation in An Nafud support the view that both storm- and prevailing-wind speeds have decreased during late Holocene, resulting in decreased eolian activity.

Sediment Studies

Sample Preparation. -- Each dune sample was split and approximately 200 gms selected from each split sample for sieve analysis and heavy-mineral separation. Rock samples were crushed to a U.S. Standard Mesh size of 30. Tribromomethane (Bromoform) of specific gravity 2.89 was used for separating the heavy-mineral fraction from 14 eolian sand samples and 24 crushed-rock samples. After separation, the heavy and light fractions from each sand and rock sample were washed, dried, and weighed.

Because the Paleozoic sandstone is extremely friable throughout most of the section, all rock samples except three were treated with resin prior to thin-section preparation. A thin section was prepared for each of 24 rock samples.

Analytical Methods. -- Thirty-five eolian sand samples were sieved into one phi class intervals. Testing was done with U. S. Standard Sieves: sizes 10, 18, 35, 60, 120, and 230 (minus one phi to four phi) plus pan, on a Soil Test (Model CL-323) motorized sieve shaker, for a period of 15 minutes for each sample. Results from the eolian-sand sieve analyses are listed in Appendix A. One-phi intervals were chosen because of the large area of study (70,760 km^2) and because this interval provides adequate textural data necessary for wind-direction analyses in An Nafud sand sea.

Mean grain size ($\frac{\sum fm}{100}$) and sorting ($\sqrt{\frac{\sum f(m-x_\phi)^2}{100}}$), using moment statistics as defined by McBride (1971), were calculated from sieve-analysis data for each sample. A histogram of grain size was constructed from sieve analysis data for each of 35 An Nafud sand samples, and plotted on a separate An Nafud base map. The histograms of grain size and the computed values for mean-grain size and sorting were interpreted for the purpose of determining the distribution of textural characteristics of An Nafud sand and, thus, the primary dune-forming wind direction.

The heavy-mineral fraction from each of 14 sand samples (Fig. 8), separated by bromoform, was examined with a binocular microscope, and individual grains were hand picked as instructed by W. C. Overstreet, U. S. Geological Survey (oral communication, 1980). Each individual grain was mounted on a glass slide for identification by X-ray diffraction (nickel-filtered copper $k\alpha$ radiation). A split

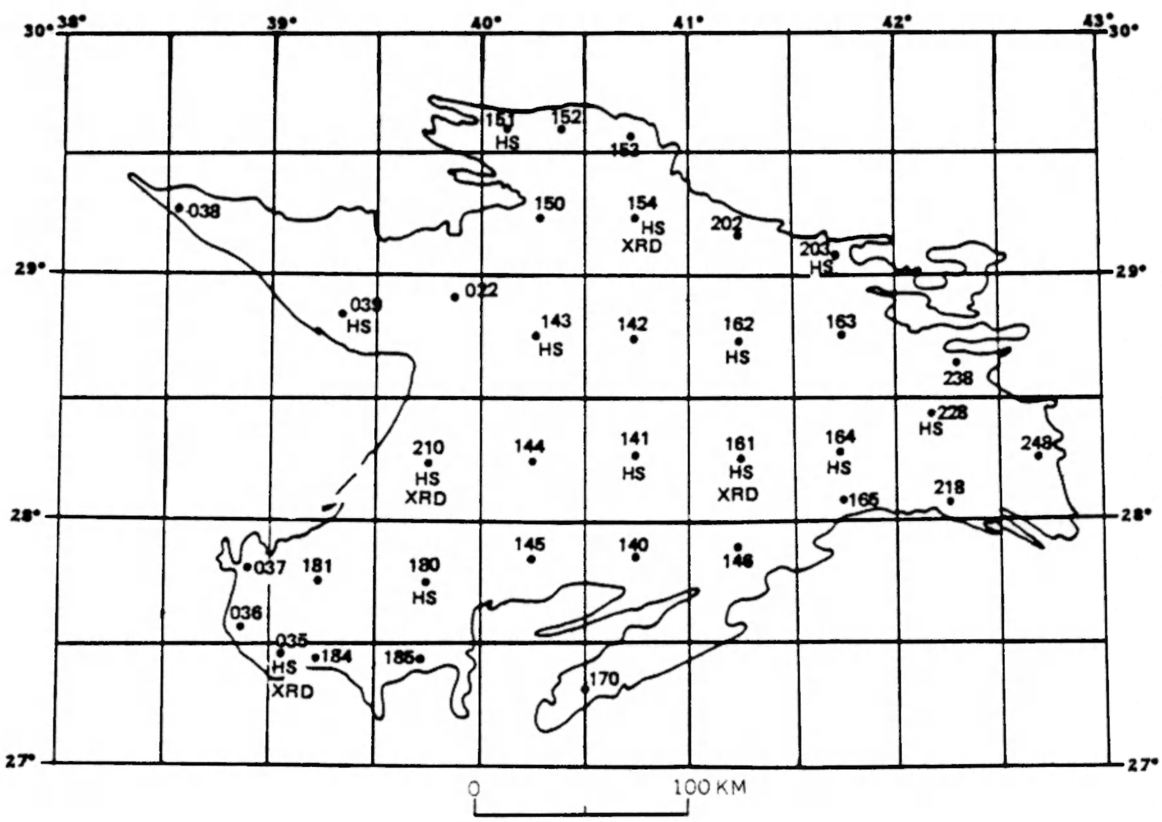


Figure 8. Location of dune samples in An Nafud sand sea, Kingdom of Saudi Arabia. (Base map from U. S. Geological Survey, 1972)

• 039 = Sample number and location
HS = Heavy mineral separation
XRD = Mineral identification by X-ray diffraction

portion of each of the 14 heavy-mineral fractions, from individual sand samples, was mounted on a glass slide (mounting medium = USP collodion). Each slide was examined with a petrographic microscope to determine the heavy-mineral assemblage for each sand sample. The heavy-minerals determined by X-ray diffraction served as a cross-check for the heavy-minerals determined with the petrographic microscope.

The frequency distribution of each major mineral within the heavy-mineral fraction, of the 14 sand samples studied, was determined by counting 200 individual grains from each sample by the ribbon method (Galehouse, 1971, p.391). Rare and opaque minerals were placed in separate groups, except for goethite. A histogram was then prepared for each of the 14 sand samples studied. The 14 individual histograms were then merged into one histogram to show the frequency distribution of each individual heavy mineral within An Nafud sand sea. Roundness and sphericity values for sand grains within each sand sample were determined visually from the chart by Krumbein and Sloss (1963, p. 111) for visual estimation of roundness and sphericity.

A thin section was prepared for each sample of Paleozoic sandstone (Fig. 9). Each thin section was examined with a petrographic microscope to identify the heavy-mineral assemblage in each rock sample and to determine the textural characteristics of each rock sample. A point count was to be done over each thin section to

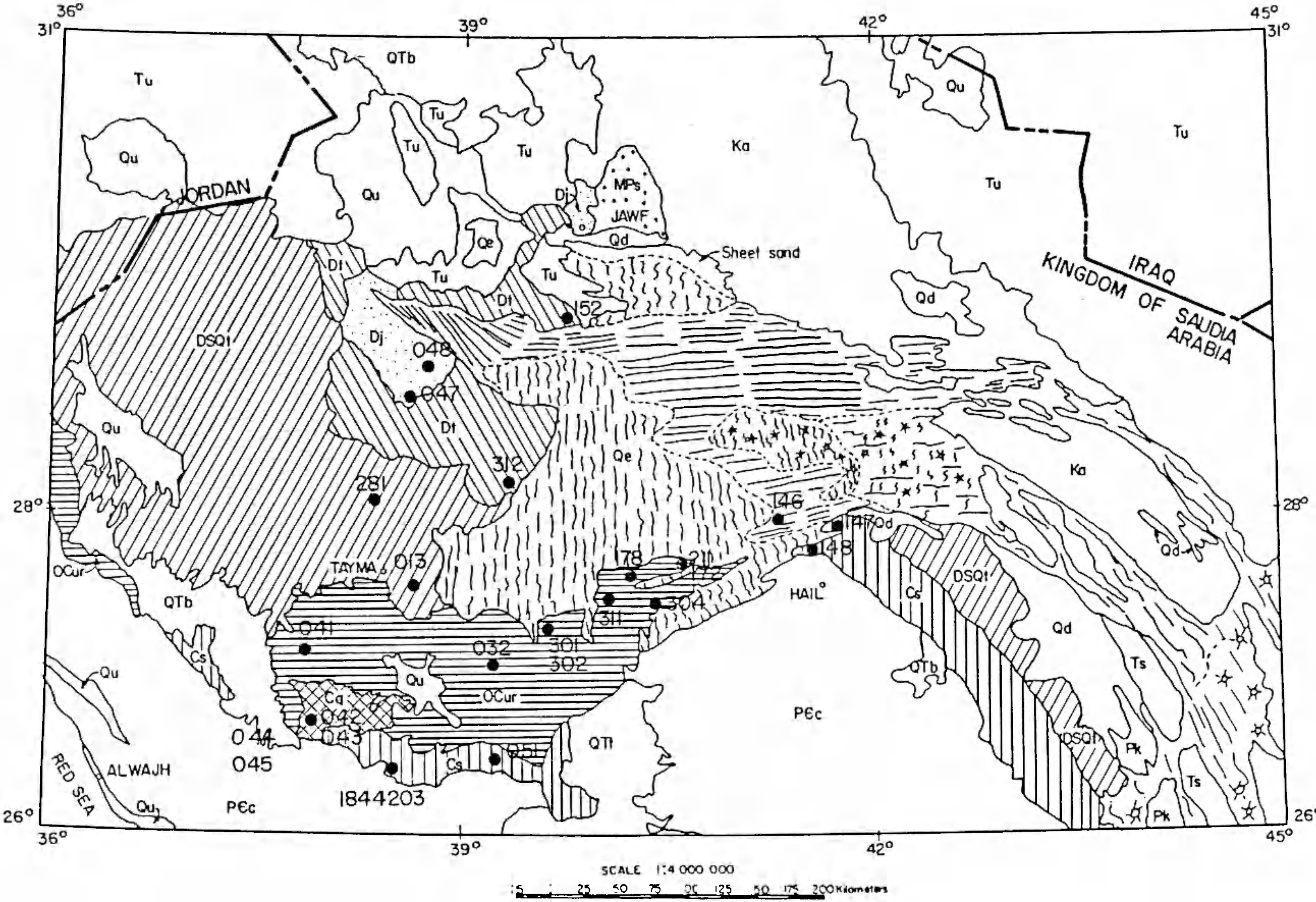


Figure 9. Paleozoic sandstone rock-sample locations.
● 281 = Sample number and location. (Base Map from U. S. Geological Survey and Arabian American Oil Co., 1963).

EXPLANATION

CENOZOIC

- Qe — Eolian sand (also shown as individual dune type)
- Qu — Alluvium and related surficial deposits
- Qd — Duricrust
- QTb — Basalt
- Tu — Undifferentiated sandstone, marl, and limestone formations

MESOZOIC

- Ka — Aruma Formation
- Trj — Jilh Formation
- Pk — Khuff Formation
- MPs — Sakaka Sandstone

PALEOZOIC

- Dj — Jauf Formation
- Dt — Tawil Member of the Tabuk Formation
- DSQt — Lower Tabuk Formation
- OCur — Umm Sahm and Ram sandstones
- Cq — Quweira Sandstone
- Cs — Siq Sandstone

- P€c — Precambrian complex: igneous, metavolcanic, and metasedimentary rocks

- Sheet sand
- Transverse and barchanoid ridges
- Linear
- Linear and massif
- Complex: includes linear, transverse and massif
- Contact
- Dune-form transition zone
- International border
- Cross section (see Fig. 4)

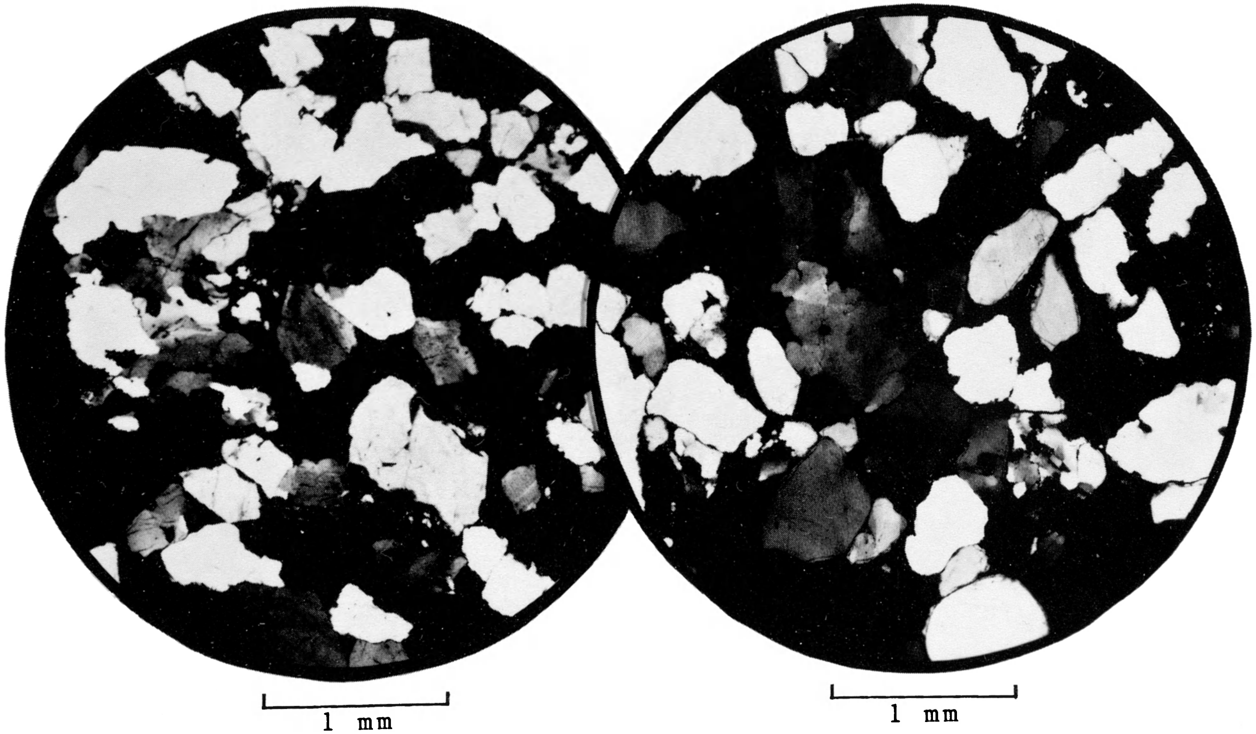
determine the concentration of each heavy mineral identified. However, the concentration of heavy minerals in each thin section was so low that a point count of each heavy mineral present would be invalid. Therefore, each crushed rock sample was separated using bromoform. The mineral concentrate was then separated on a Frantz separator, into magnetic and nonmagnetic mineral classes (Appendix D). After separation of each mineral concentrate, individual grains were selected from each magnetically separated group, in each rock sample, and identified by X-ray powder diffraction (Appendix E), using nickel-filtered copper $k\alpha$ radiation. The heavy-minerals determined by X-ray diffraction for each rock sample served as a cross-check for the heavy-minerals determined from each thin section for the same rock sample.

Paleozoic Sandstone

Potential Bedrock Source of An Nafud Sand. -- Paleozoic sandstone is exposed to the south, southwest, and west of An Nafud sand sea and is believed to be the primary source of An Nafud sand. Evidence that supports this belief is: (1) dune orientation within An Nafud sand sea strongly suggests that dune-forming winds were from the west and west-southwest during the late Pleistocene and early Holocene, (2) the potential source material lies upwind of the sand sea, (3) the exposed area of Paleozoic sandstone is the sandstone is erodible and was accessible to eolian activity during the late Pleistocene and early Holocene. This evidence strongly supports the view that the Paleozoic sandstone is the primary source for An Nafud sand, but more conclusive evidence is provided by a comparison of the heavy minerals from the potential sand source with the heavy minerals in An Nafud sand.

Stratigraphy and Petrography. -- All Paleozoic sandstone formations are quartz arenites, based on parameters by Folk (1980). Formations can only be identified, in the field, by color and erosional characteristics. The description and classification of each Paleozoic sandstone formation is based upon field observations, hand specimens, study of thin sections by petrographic microscope, and X-ray diffraction analyses (see Appendix B). Because Paleozoic sandstone formations are nearly homogeneous throughout the section, except for slight differences in heavy-mineral concentration and composition, only typical examples (photographed thin sections) of each formation are presented.

The Siq Sandstone lies unconfomably upon the basement complex and is characterized by a 70 m thick basal conglomerate composed entirely of quartz pebbles and gravel derived from the underlying Precambrian complex. The remainder of the formation is characterized by interstratified conglomerate beds, 0.1 to 0.3 m thick,



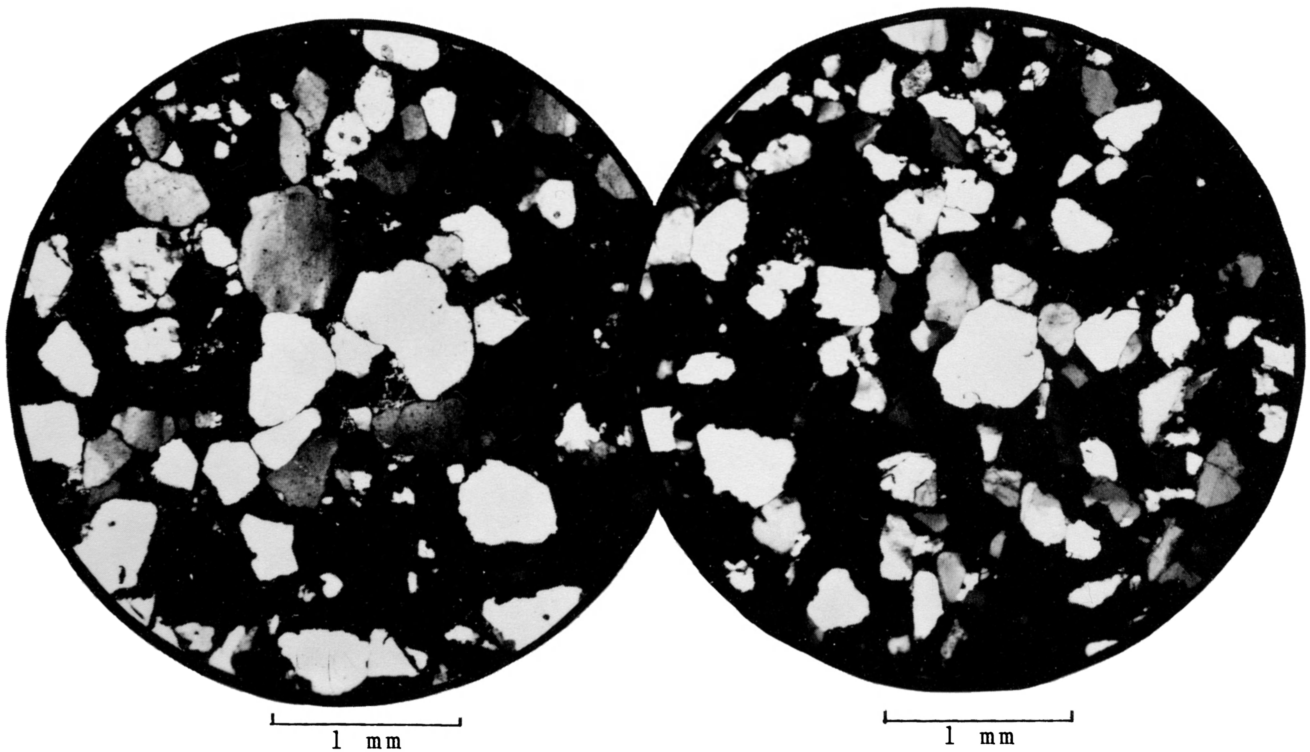
(a) Lower Siq sandstone. Quartz arenite, composed of angular to subrounded detrital quartz with microcrystalline aggregates of quartz and some secondary quartz overgrowths. Cementation slight.

(b) Middle Siq sandstone. Quartz arenite, composed of rounded to well-rounded detrital quartz. Note secondary growth and cementation of detretal quartz by quartz. Cementation slight.

Figure 10. Paleozoic sandstone, crossed nicols, x 25.

Table 2. Identified heavy minerals, weight percent of total sample(s), and ratio of light fraction to heavy fraction for each Paleozoic sandstone sampled in An Nafud sand sea area. Minerals identified by X-Ray powder diffraction and petrographic microscope.
*Not identified in An Nafud sand samples.

Age	Paleozoic Sandstone	Major Minerals	Minor Minerals	No. of Samples	Weight %	Ratio LF/HF
Mesozoic or Paleozoic	Sakaka	Dravite Rutile Anatase Fluor-apatite	Zircon	2	0.79	125:1
Devonian	Jawf	Dravite	Fluor-apatite	1	0.06	1800:1
Silurian	Tabuk	Goethite Rutile Dravite	Hematite Anatase Zircon Epidote	6	11.64	8:1
Ordovician	Umm Sahm and Ram	Goethite Hematite Dravite Chromite* Anatase	Rutile Sphene* Fluor-apatite*	6	1.36	72:1
Cambrian	Quweira	Goethite Anatase Chromite*	Rutile Zircon Hematite Dravite	4	2.06	48:1
	Siq	Dravite Chromite* Anatase Rutile	Zircon Diopside* Hematite	4	8.02	11:1



(a) Lower Quweira sandstone. Quartz arenite, composed of subrounded to rounded detrital quartz with microcrystalline aggregates of quartz. Cementation slight.

(b) Middle Quweira sandstone. Quartz arenite, composed of subrounded detrital quartz with some secondary growth and cementation of detrital quartz with secondary quartz. Cementation slight.

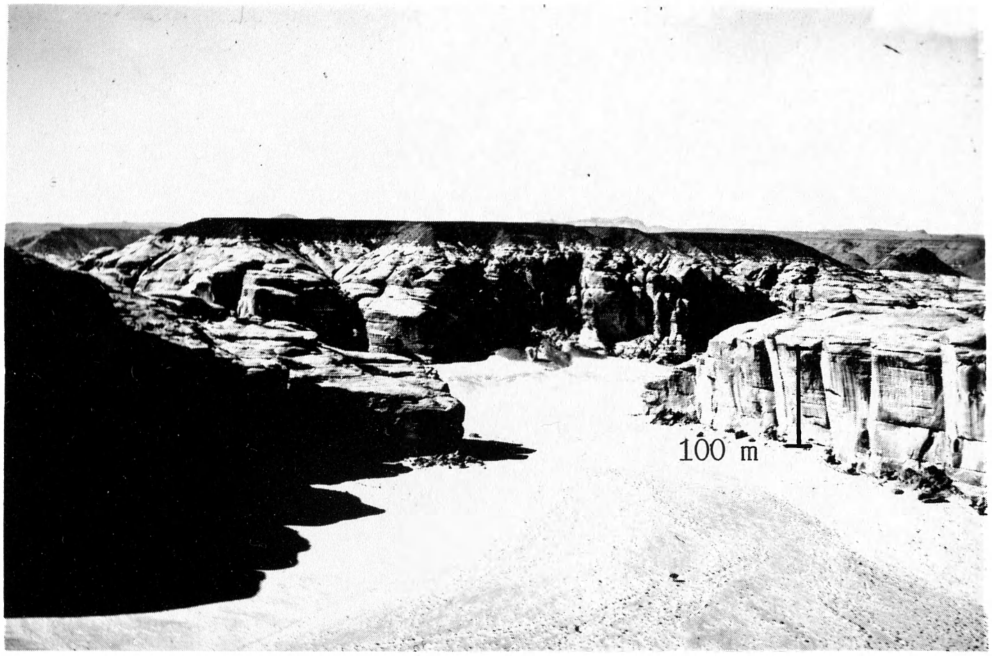
Figure 11. Paleozoic sandstone, crossed nicols, x 25.

composed of quartz pebbles, cobbles, and boulders. The Siq Sandstone is a poorly cemented, coarse- to medium-grained quartz arenite composed of angular to rounded quartz grains (Fig. 10 a and b). Major heavy minerals are dravite (Mg-tourmaline), rutile, anatase, and chromite, and minor heavy minerals are zircon, hematite, and diopside (Table 2). Dravite grains are light to dark green, highly rounded to subangular, anhedral, and subhedral, and exhibit extremely well-developed authigenic terminations. Anatase is yellow, reddish-brown, worn, corroded, euhedral fragments of octahedral crystals.

The Quweira Sandstone (Fig. 11 a and b) is conformable with the underlying Siq Sandstone and overlying Ram Sandstone. Two distinguishing characteristics of the Quweira Sandstone are color and erosion patterns. The sandstone is banded, the bands (about 0.1 m thick) ranging in color from brown to dark brown, to red to purple. Because some layers of sandstone possess a slightly higher degree of cementation, the sandstone tends to form overhangs or ledges in some localities. However, the cementation is slight throughout the major portion of the formation. The Quweira Sandstone is an quartz arenite composed of more than 92 percent coarse- to fine-grained quartz, but in general is medium-grained. Major heavy minerals are goethite, anatase, and chromite and minor heavy minerals are zircon, hematite, and diopside (Table 2). Anatase is yellow, light-brown, and sometimes colorless, occurring in microcrystalline quartz aggregates.

The Ram and Umm Sahm sandstones (Fig. 12) are considered as one unit in geologic literature because the Ram Sandstone is limited in exposure and both are petrographically similar. The Ram and Umm Sahm sandstones are conformable with the underlying Quweira Sandstone and the overlying Tabuk Sandstone. Both sandstones are quartz arenites composed of more than 95 percent coarse- to fine-grained quartz (Fig. 13 a and b). Conglomerates, 0.1 to 0.3 m thick, composed of well-rounded quartz pebbles and boulders are common throughout both formations. Interstratified ironstone beds about 0.2 m thick are common in the lower and middle portions of the Umm Sahm Sandstone. Some ironstone beds display casts of trilobite tracks. Cementation is slight throughout both formations, except in the upper Umm Sahm where cementation increases slightly. Major heavy minerals are dravite, hematite, goethite, and chromite; minor heavy minerals are rutile, sphene, and fluorapatite (Table 2). Dravite grains are light to dark green and usually wel rounded.

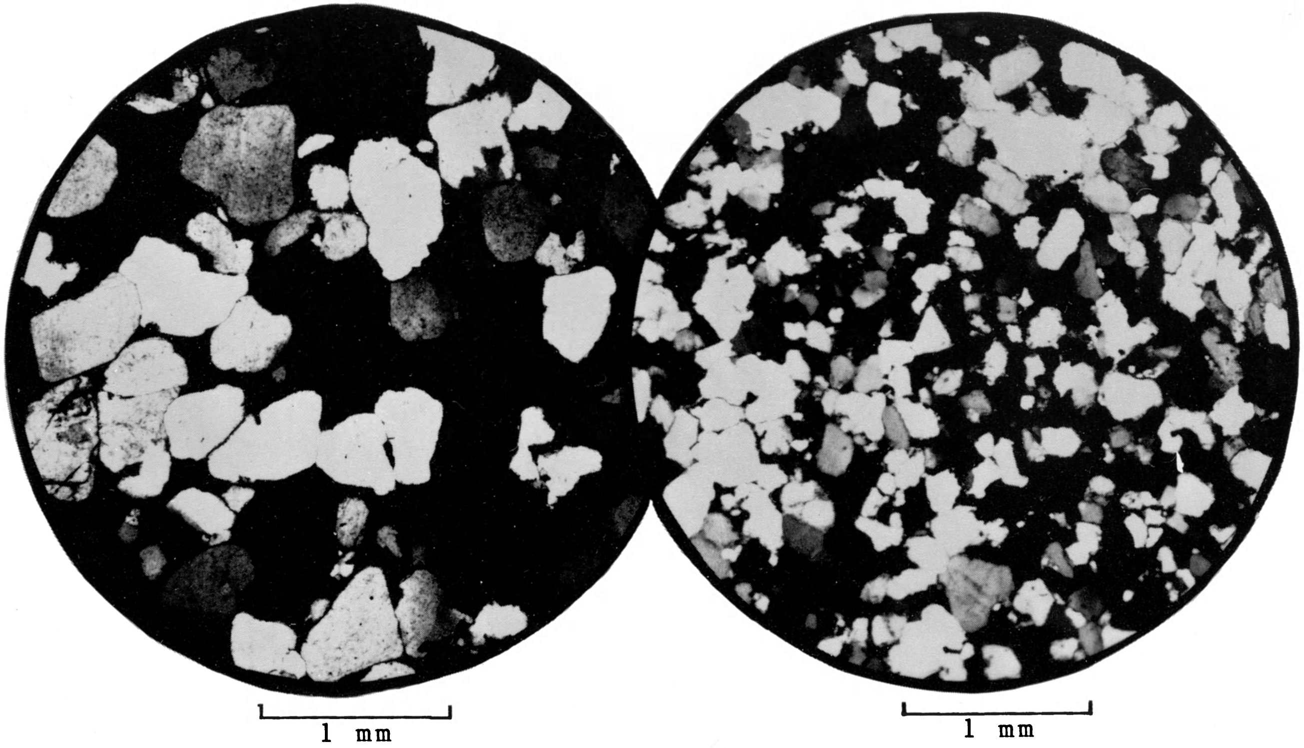
The Tabuk Formation is more than 1,000 m thick and is conformable with the underlying Ram and Umm Sahm sandstones and the overlying Jauf Formation. This formation is predominantly sandstone, but interstratified shale and siltstone beds of varied thickness occur throughout the section. Shale beds normally contain both invertebrate and plant fossils. The lower and middle sandstone units are



(a) Quweira sandstone overlain by a Tertiary-Quaternary basalt flow. 27°00′ N., 37°05′ E.

(b) Ram and Umm Sahm sandstones. Looking west, south edge of An Nafud sand sea, 27°35' N., 40°05' E.

Figure 12. Photographs of Paleozoic sandstone strata, An Nafud sand sea.



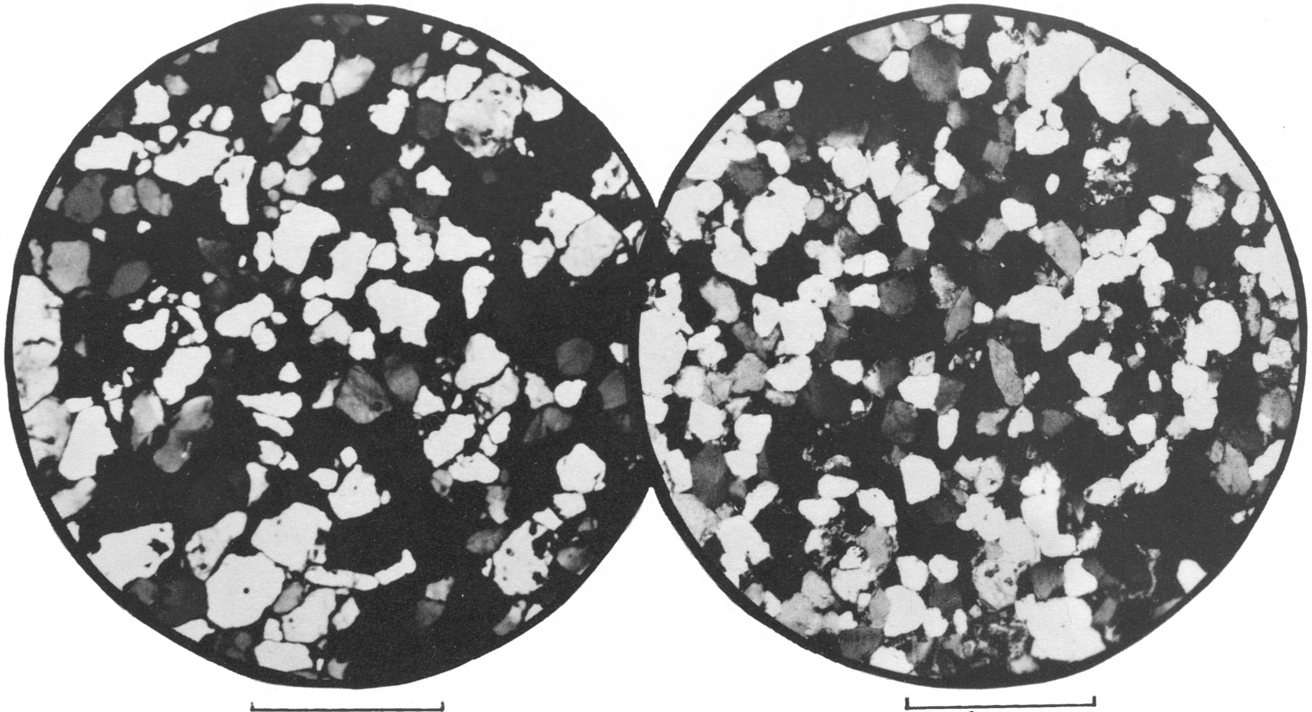
(a) Lower Ram and Umm Sahm sandstone. Quartz arenite, composed of subrounded to well-rounded detrital quartz, with some secondary growth and slight cementation of detrital quartz with quartz.

(b) Middle Ram and Umm Sahm sandstone. Quartz arenite, primarily produced by cementation of detrital quartz with quartz. Note subrounded to rounded outline of original detrital quartz.

Figure 13. Paleozoic sandstone, crossed nicols, x 25.

quartz arenites composed of more than 96 percent medium- to fine-grained quartz (Fig. 14 a and b). In contrast, the upper Tabuk Sandstone (Tawil Member) is a ferruginous quartz arenite containing 46 to 81 percent medium-grained quartz, slightly cemented by goethite and hematite. Goethite and hematite concentrations range from 19 to 54 percent in the upper Tabuk Sandstone. Major heavy minerals identified in the Tabuk terrigeneous sediments are dravite, rutile, and goethite. Associated minor heavy minerals are anatase, zircon, epidote, and hematite (Table 2). Dravite grains are light-to-dark green and usually well rounded. Anatase is colorless, light-green or light-brown, authigenically zoned, thin, tabular euhedral crystal fragments, and also occurs as crystal composites associated with authigenic aggregate material.

The Jauf Formation consists of interstratified beds of sandstone, fossiliferous shale, and limestone (biosparite), is conformable with the underlying Tabuk Sandstone, but is unconformable with the overlying Sakaka Formation. Only one sample, near the contact with the Tabuk Formation, was collected from this formation inasmuch as the strata crop out in only one locality in the study area and the entire upper portion is covered by scree. This sample could be from the upper Tabuk Sandstone (Tawil Member). The sandstone is an quartz arenite composed of more than 98 percent, medium to fine grained, rounded- to well-rounded quartz grains. The major heavy mineral is dravite and the



(a) Lower Tabuk sandstone.
Quartz arenite, composed of subrounded to rounded detrital quartz. Quartz cementation slight.

(b) Middle Tabuk sandstone.
Quartz arenite, composed of rounded to well-rounded detrital quartz and microcrystalline aggregates of quartz. Cementation slight.

Figure 14. Paleozoic sandstone, crossed nicols, x 25.

minor heavy mineral is fluorapatite (Table 2).

The Sakaka Formation consists of interstratified beds of sandstone, shale, and limestone. Terrigenous sediments of the Sakaka Formation are quartz arenites composed of more than 96 percent quartz grains. Quartz grains are rounded to well rounded and range from coarse to fine grained (Fig. 15 a and b). Cementation is normally slight, but in some places cementation by quartz does occur. Major heavy minerals are dravite, rutile, anatase, and fluorapatite. The minor heavy mineral is zircon (Table 2).

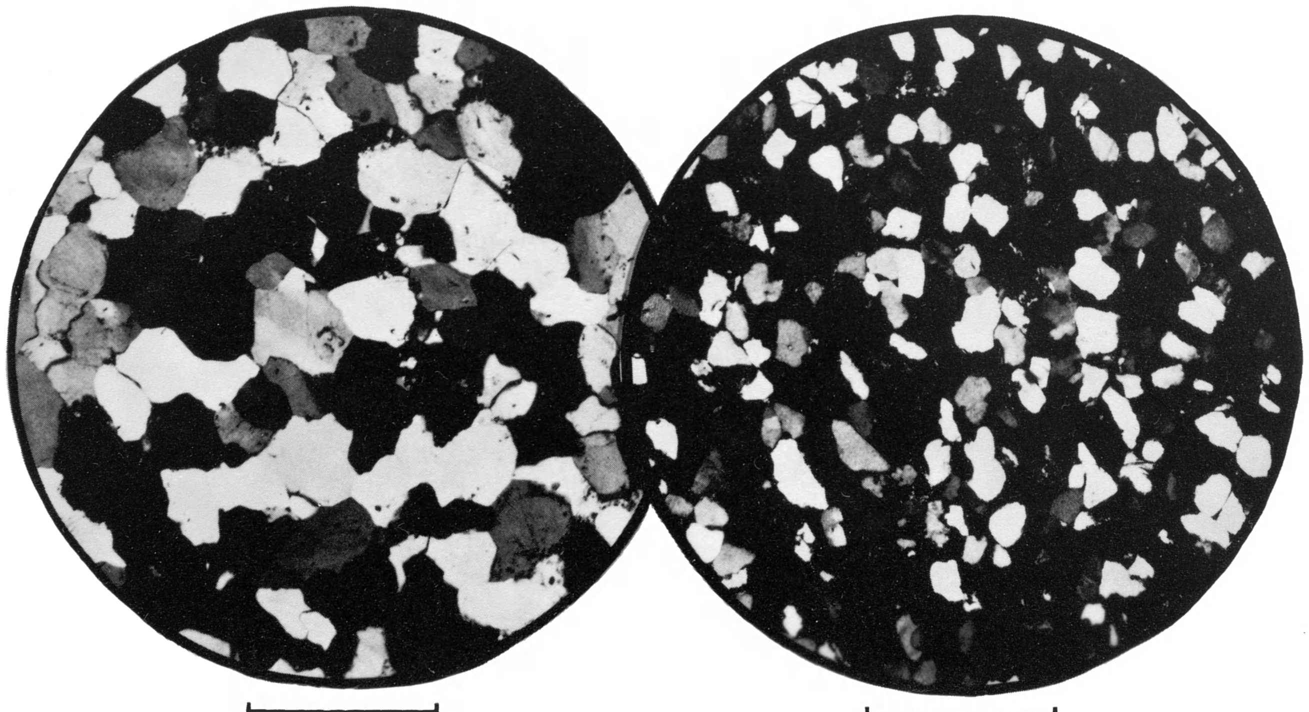
Eolian Sand Results and Discussion

Grain Size.-- Mean grain size for each sample was calculated using moment statistics (Table 3). A histogram (grain size) was prepared from the sieve analysis of each An Nafud sand sample and plotted according to sample location (Fig. 16). The grain size distribution was then interpreted in order to: (1) indicate the direction of prevailing dune-forming winds and sand source, (2) construct a model of dune-field development, and (3) study the distribution of grain size throughout the sand sea.

An Nafud sand is medium grained in the western portion of the dune field and grades into finer sizes from west to east across the dune field (Fig. 16). The overall grain-size distribution agrees with the dune orientation in An Nafud and strongly suggests that the prevailing dune-forming winds were from the west and west-southwest and

Table 3. Statistical values for An Nafud sand samples using moment statistical formulas at one-phi intervals

Sand Sample Number	Mean Grain Size in Ø units	Sorting in Ø unit
035	1.9	0.5
036	1.9	0.6
037	1.4	0.7
038	2.2	0.6
039	1.8	0.6
181	1.7	0.6
184	1.6	0.5
210	1.6	0.5
180	1.6	0.8
185	1.7	0.7
152	2.1	0.8
151	2.7	0.9
150	2.4	0.8
143	2.4	0.7
144	1.8	0.6
145	1.8	0.5
153	2.6	0.6
154	2.2	0.7
142	2.1	0.7
141	2.0	0.6
140	1.7	0.5
170	1.9	0.6
202	2.4	0.7
162	2.1	0.7
161	1.9	0.5
146	2.0	0.6
165	2.2	0.6
164	2.5	0.7
163	2.2	0.7
203	2.5	0.6
022	1.8	0.9
218	2.4	0.5
228	2.5	0.3
238	2.3	0.5
248	2.6	0.4



(a) Lower Sakaka Sandstone. Quartz arenite. Primarily a mosaic of quartz produced by cementation of detrital quartz with quartz. Note well-rounded outline of original detrital quartz.

(b) Middle Sakaka sandstone. Quartz arenite. A mature sand slightly cemented by quartz. Some Microcrystalline aggregates of quartz. Cementation slight and porosity high.

Figure 15. Paleozoic-Mesozoic sandstone, crossed nicols, x 25.

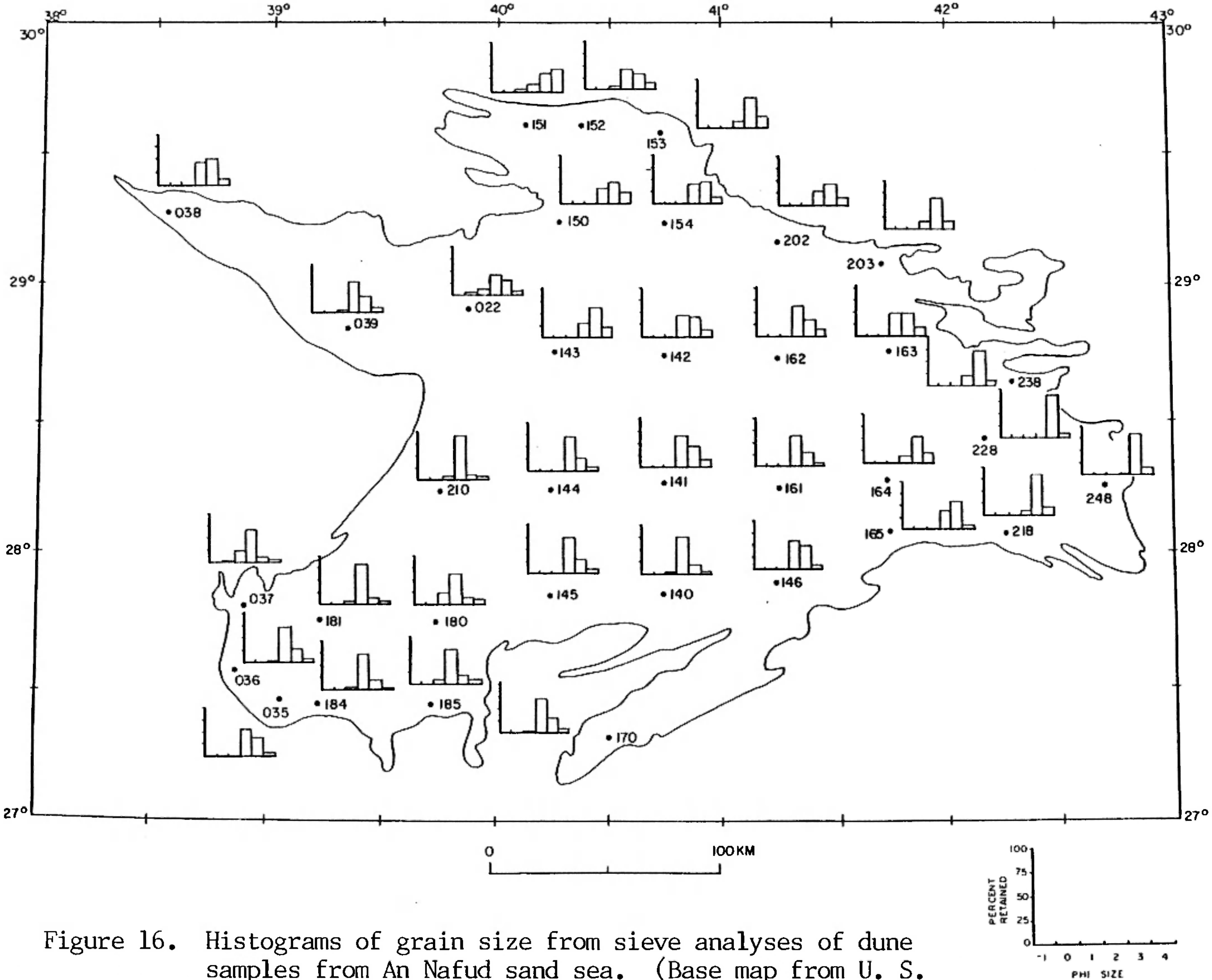


Figure 16. Histograms of grain size from sieve analyses of dune samples from An Nafud sand sea. (Base map from U. S. Geological Survey, 1972)

that the sand source lies west and southwest of An Nafud.

The grain-size distribution in the extreme northwestern extension and along the northern margin of An Nafud does not reflect a gradational trend, as does the major dune system of An Nafud. Fine-grained sand occurs in both areas and is probably the result of: (1) a finer sand source to the west and northwest and (2) more variable wind conditions in the area that tend to rework the sand resulting in finer grain size.

Sorting.-- A sorting value for each sample was calculated using moment statistics (Table 3). Sorting values are: 0.00 to 0.35 phi, very well sorted; 0.35 to 0.50 phi, well sorted; 0.50 to 0.70 phi, moderately well sorted; and 0.70 to 1.00 phi, moderately sorted (Folk, 1980). Sorting improves from west to east across the southern half of An Nafud, and the sand is moderately well sorted in the northern half, except in the north-northwest corner where moderately active sand prevails. In general, the moderately well-sorted sand lies in the linear dunes, the well-sorted sand in the transverse and barchanoid ridge dunes, and the very well-sorted sand in the star dunes of An Nafud sand sea. As expected, sorting generally improves in the downwind direction.

Roundness and Sphericity.-- The determination of roundness and sphericity for each sand sample was made by using the chart by Krumbein and Sloss (1963, p 111) for visual estimation of roundness and sphericity; the x-axis, roundness, is numbered 0.1, 0.3, 0.5, 0.7, and 0.9, and the y-axis, sphericity, is numbered 0.3, 0.5, 0.7, and 0.9. Higher numbers indicate an increase in roundness and sphericity. All sand samples have roundness values of 0.5 or greater; the less well-rounded sand is located along the western and northwestern edges of the sand sea. Sphericity values are 0.7 or 0.9 for all samples; those with a sphericity of 0.7 lie in the western and northwestern areas. Most of the grains are rounded to well-rounded and have a high degree of sphericity, indicative of an eolian, very mature sand.

Mineral Composition.-- Heavy minerals from the sand samples were examined to identify: (1) the source for the dune sand, (2) possible correlation of the distribution of heavy-minerals with the paleowind regime, and (3) potentially significant economic mineral deposits. The major heavy-mineral assemblage from the dune sands includes: dravite, zircon, epidote, rutile, goethite, magnetite, hematite, and limonite (Appendices B and C). Dravite and zircon are the most abundant heavy-minerals; minerals that appear in minor amounts are: wilkeite (Apatite Group, Dana, 1949, p. 706), gorceixite (Hamlinite Group, Dana, 1949, p. 711), goyazite (Hamlinite Group, Dana, 1949, p. 711), gahnite (Dana, 1949, p.489), hinsdalite (shows certain relations to Hamlinite Group, Dana, 1949, p. 738). The preceding phosphate minerals are not rare in An Nafud sand sea area, because phosphate deposits (Bayliss, 1981) are common in northern Saudi Arabia.. Figure 17 depicts graphically the frequency distribution of the heavy-minerals identified in the dune samples; the rarer minerals are grouped together. The opaque and iron-rich minerals, except goethite, also are placed in one group.

The areal distribution of dravite (Fig. 18) changes abruptly along an east-west line in the middle of the sand sea. This change probably is the result of the wind regime inasmuch as the northern portion of An Nafud is dominated by linear dunes; or possibly the sand deposited in this area is from a dravite-poor source. The concentration of dravite is greatest in the southern part of the sand sea. Zircon, Figure 19, shows a distinct pattern of higher concentrations in the northwestern area and decreasing concentration to the north, northeast, and east. The distribution of zircon coupled with that of dravite provides a definite indication that An Nafud has more than one sand source. Epidote, Figure 20, shows higher concentrations on the northern side and in the southwestern corner but is evenly distributed over most of the sand sea. The distributions of rutile and goethite (Fig. 17) both show a slightly higher concentration in the central and northwestern parts, gradually decreasing to one percent in the eastern An Nafud. These were not mapped inasmuch as they reflect the same direction of

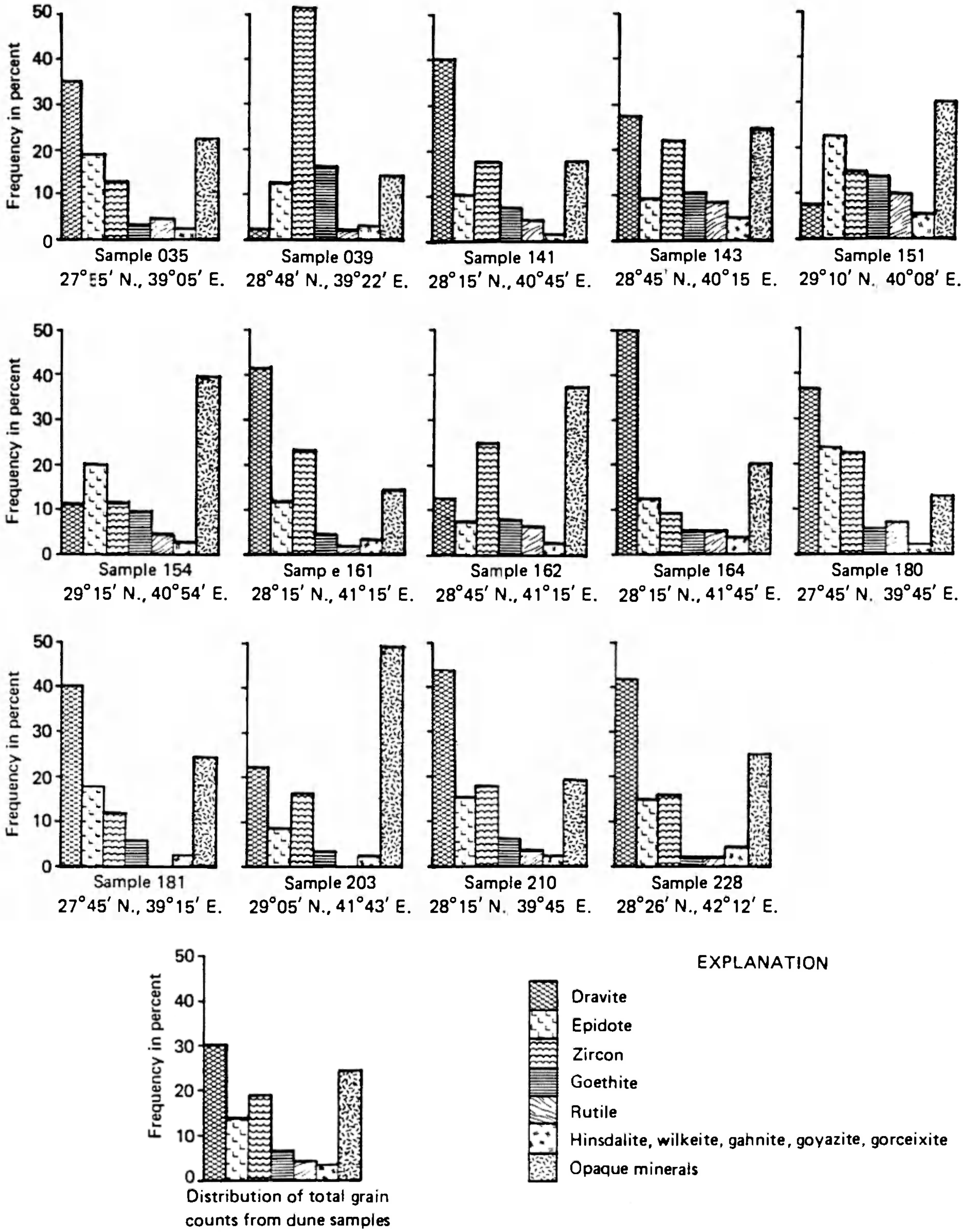


Figure 17. Heavy-mineral histograms and distribution of total grain counts of dune samples from An Nafud sand sea.

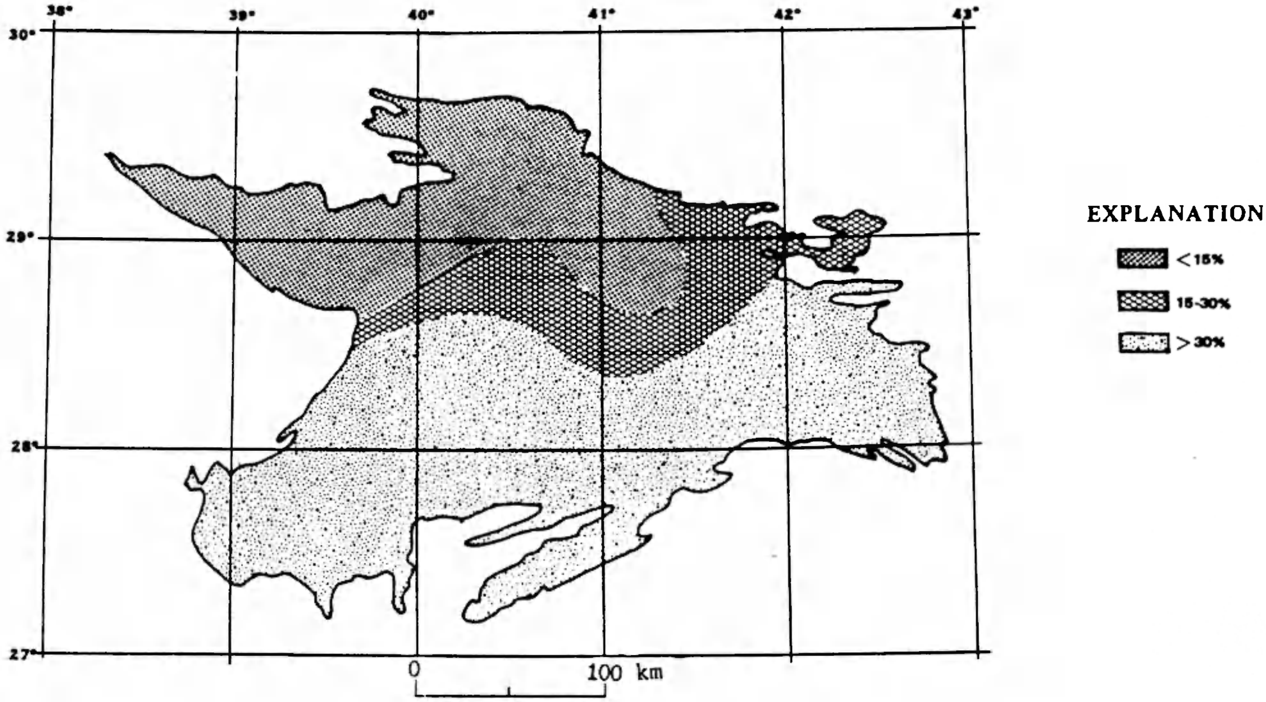


Figure 18. Areal distribution of dravite (tourmaline) in An Nafud sand sea. Based on frequency, in percent, of heavy-mineral grain counts of dune samples. (Base map from U.S. Geological Survey, 1972)

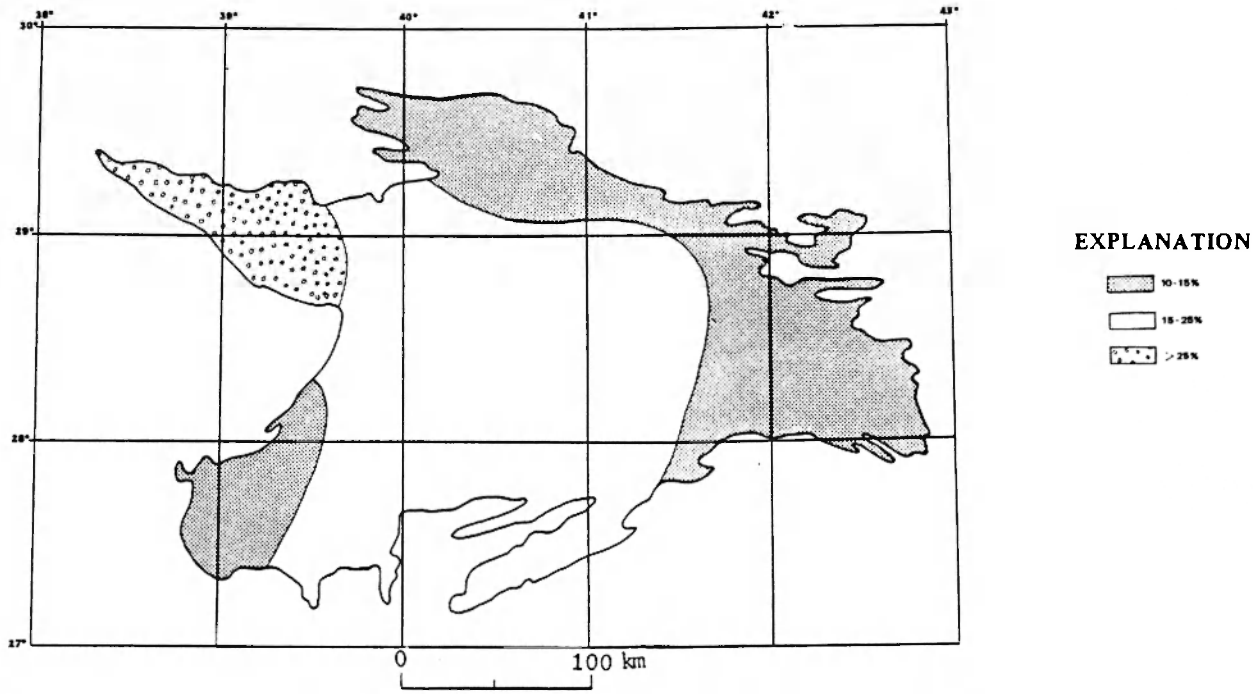


Figure 19. Areal distribution of zircon in An Nafud sand sea. Based on frequency, in percent, of heavy-mineral grain counts of dune samples. (Base map from U. S. Geological Survey, 1972)

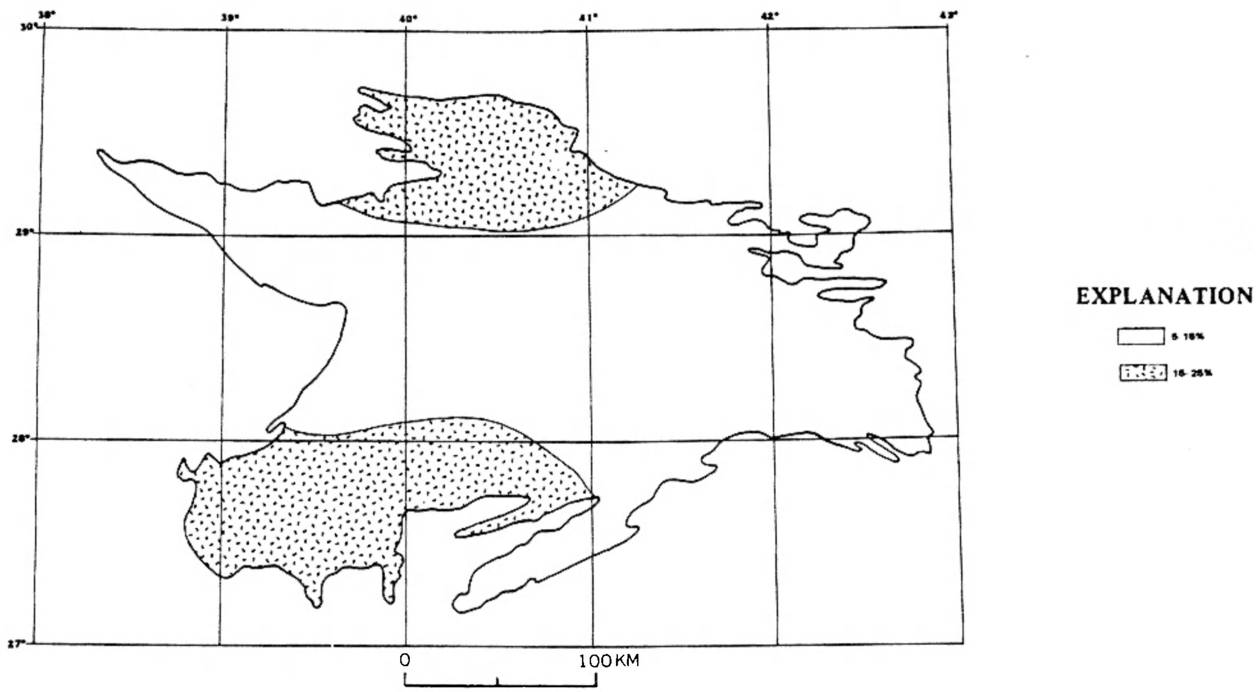


Figure 20. Areal distribution of epidote in An Nafud sand sea. Based on frequency, in percent, of heavy-mineral grain counts of dune samples. (Base map from U. S. Geological Survey, 1972)

dune-forming wind, overall west to east, as dravite, epidote, and zircon.

In summary, the heavy-mineral concentration decreases west-to-east across An Nafud sand sea. Mean-grain size decreases west-to-east across An Nafud, sorting improves west-to-east across An Nafud, and sand grains increase in roundness and sphericity west- to -east across An Nafud. Therefore, both the textural characteristics of An Nafud sand and the heavy-mineral distribution across An Nafud strongly suggest that the prevailing dune-forming winds were from the west and west-southwest, except in the northwest extension, where a northwesterly wind may have been dominant. The heavy-mineral distribution over An Nafud sand sea also indicates that An Nafud sand may have originated from more than one source, however, the distribution is dependent upon the heavy-mineral assemblage of each Paleozoic sandstone and the direction each exposure of Paleozoic sandstone lies from An Nafud sand sea.

Quaternary History

Dune Systems.-- Major dune forms (Bagnold, 1941; 1951) of An Nafud include linear, transverse, barchanoid ridge, and massif (superimposed star dunes). Aerial photographs (stereoscopic-pairs, Figs. 21, 22, 23, and 24) show the major dune forms and their orientation. Based on the orientation of the barchanoid ridge and transverse dunes in the western and southwestern areas of An Nafud, these dunes

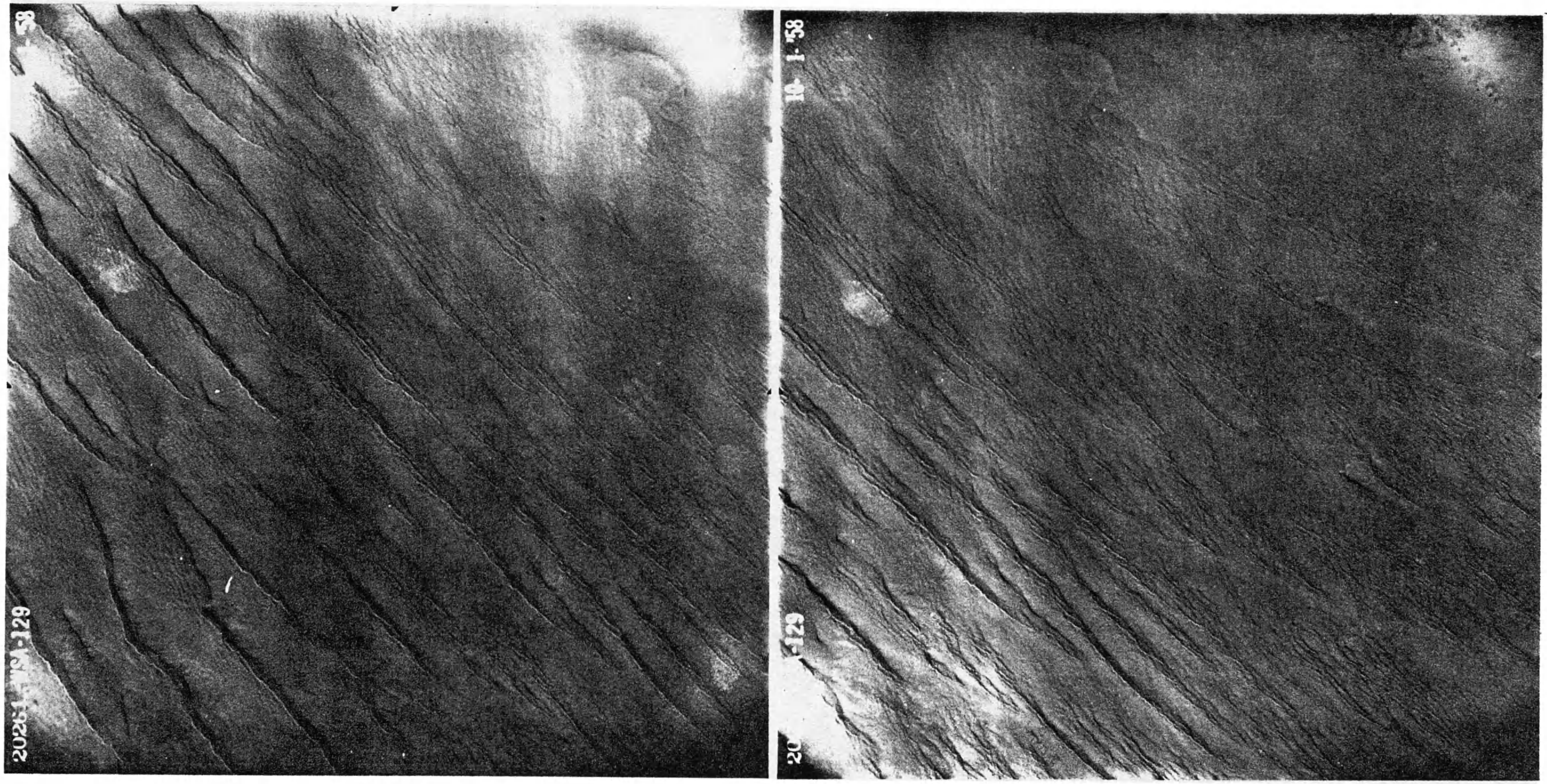


Figure 21. Vertical aerial photographs (stereoscopic pair) of linear dunes from the northwestern part of An Nafud sand sea. Average dune height: 100 ft. Average spacing between dunes: 3,000 ft. Scale 1:120,000 (Courtesy of the U. S. Geological Survey Saudi Arabian Mission, Jeddah, Saudi Arabia).

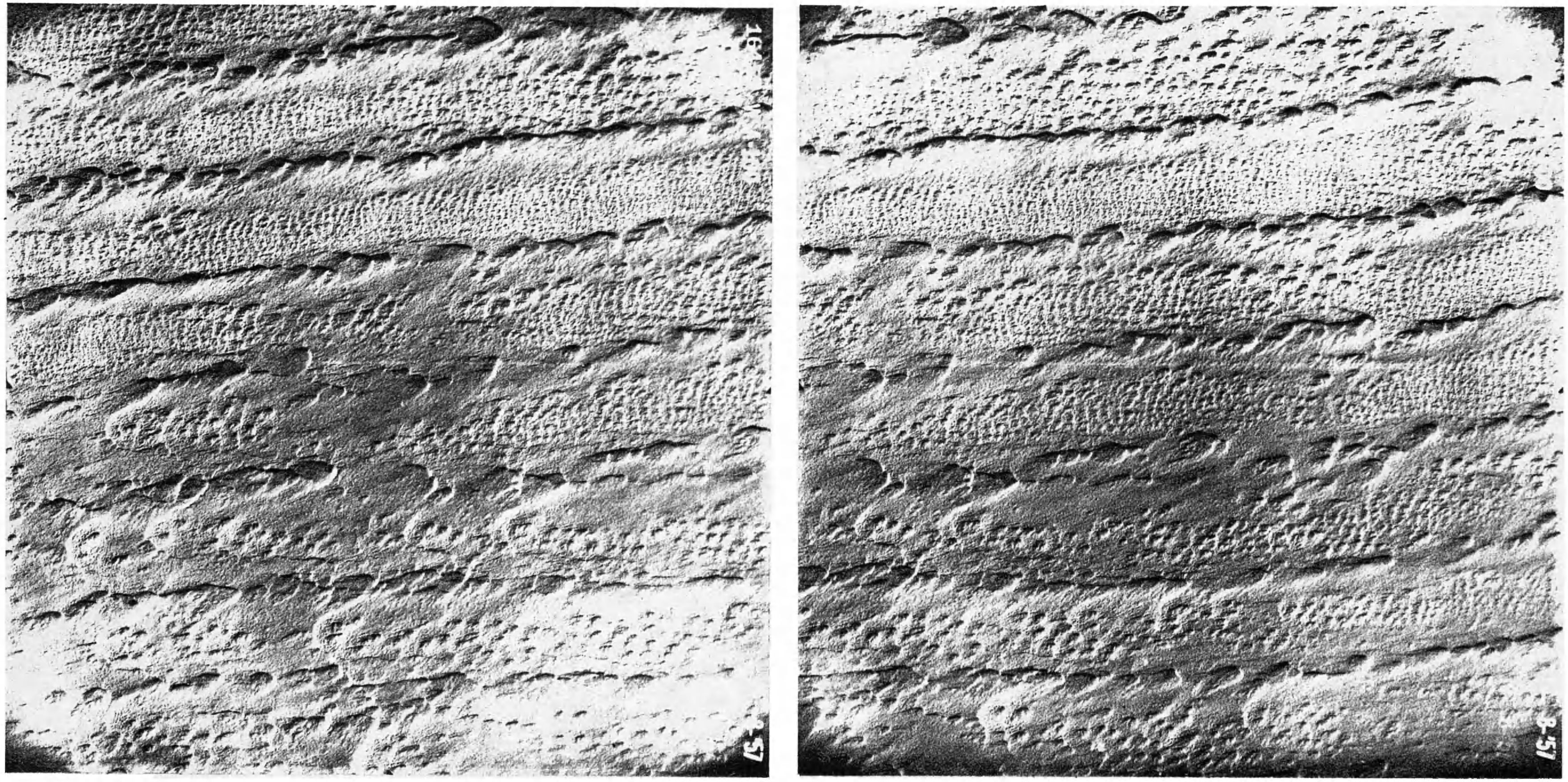


Figure 22. Vertical aerial photographs (stereoscopic pair) of linear dunes from the east-central part of An Nafud sand sea. Note blowouts in dune troughs and complex dunes on the broad crests. Average dune height: 250 ft. Average spacing between dunes: 6,000 ft. Scale 1:120,000 (Courtesy of the U. S. Geological Survey Saudi Arabian Mission, Jeddah, Saudi Arabia).

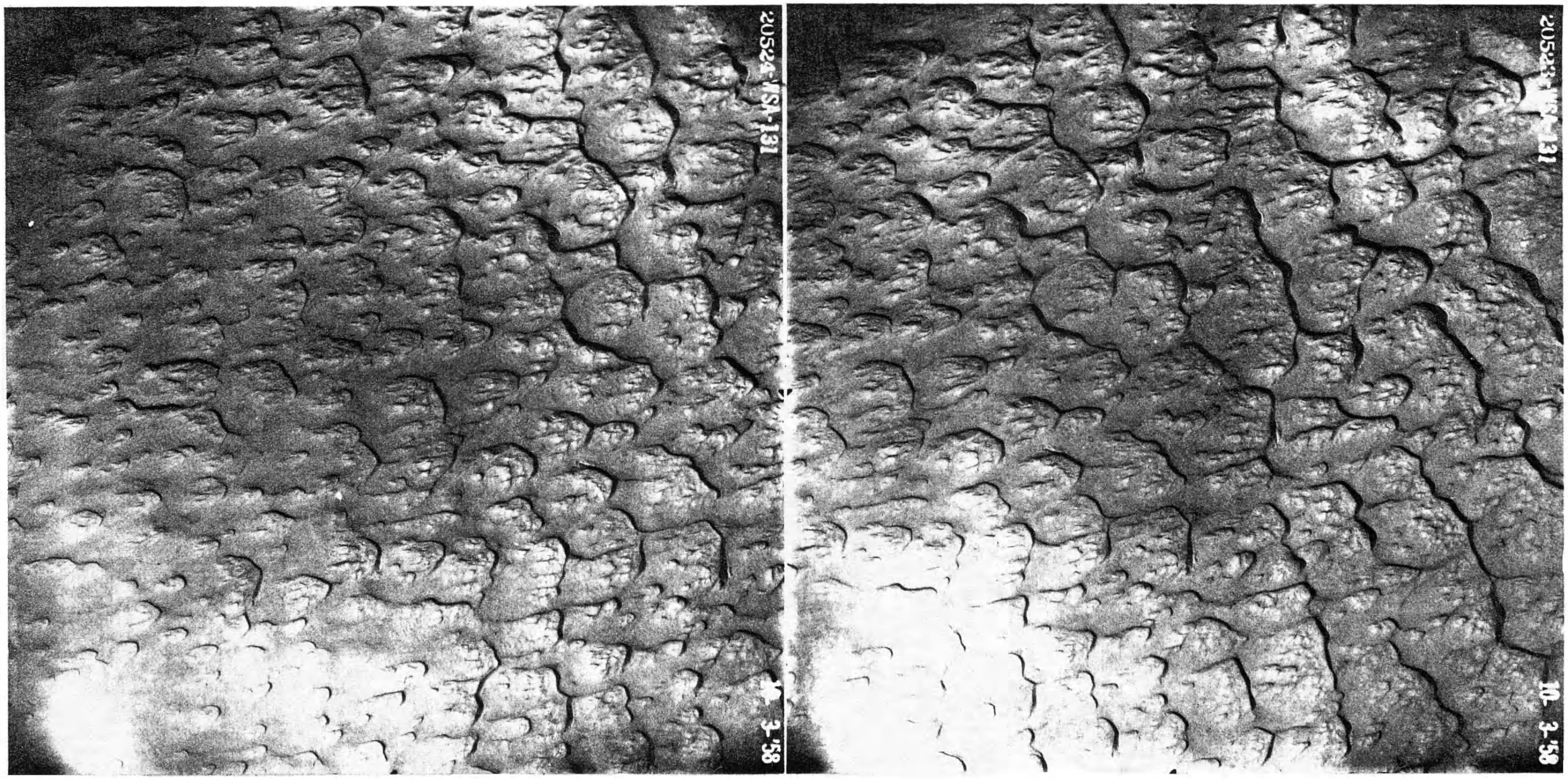


Figure 23. Vertical aerial photographs (stereoscopic pair) of transverse and barchanoid-ridge dunes from the central part of An Nafud sand sea. Average dune height: 100 ft. Average dune spacing: 5,000 ft. Scale 1:120,000 (Courtesy of the U. S. Geological Survey Saudi Arabian Mission, Jeddah, Saudi Arabia).

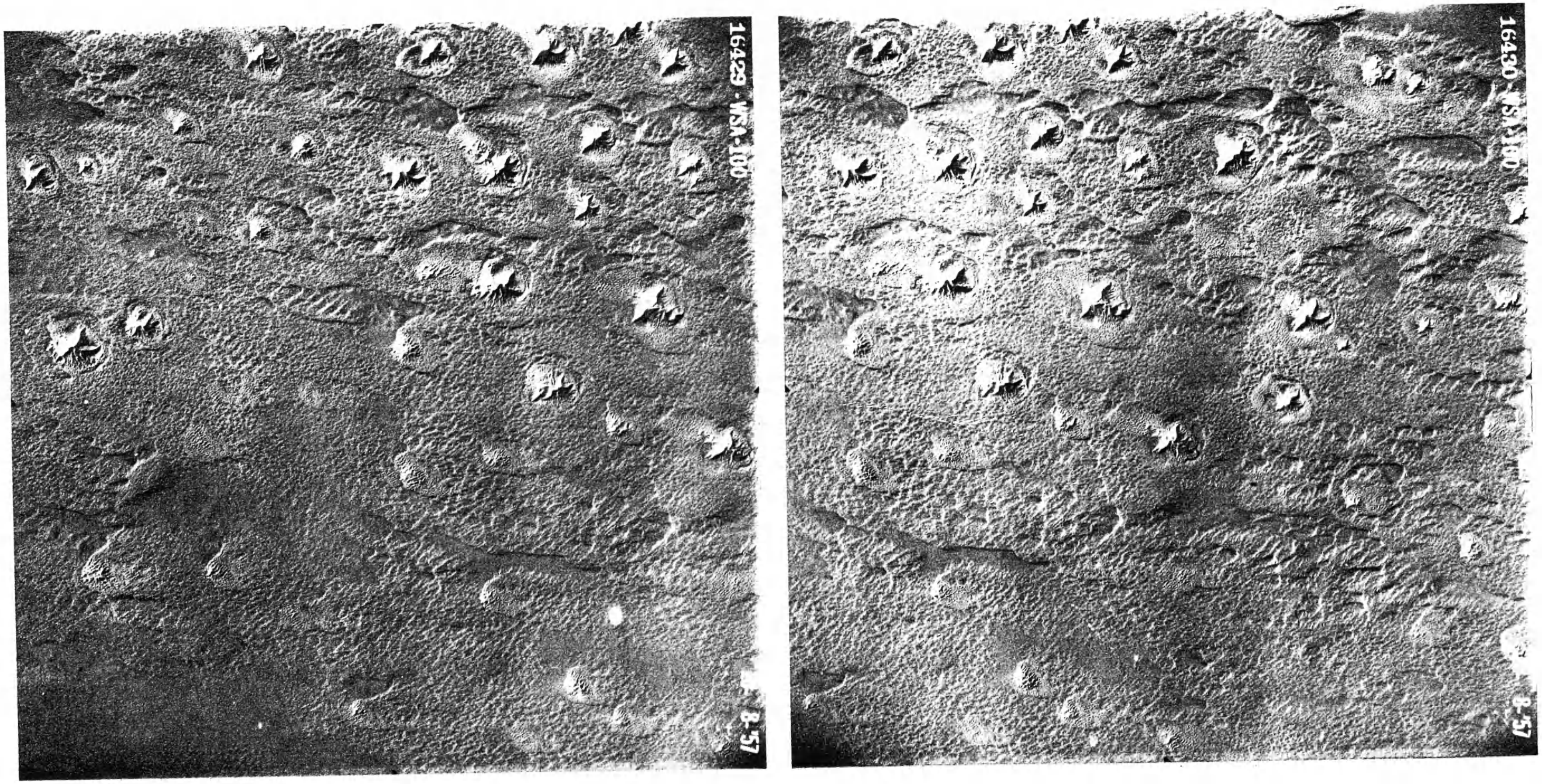


Figure 24. Vertical aerial photographs (stereoscopic pair) of massif dunes (star dunes) from the eastern part of An Nafud sand sea. Average dune height: 250 ft. Average dune spacing: 4,500 ft. Scale 1:120,000 (Courtesy of the U. S. Geological Survey Saudi Arabian Mission, Jeddah, Saudi Arabia).

are interpreted to have been formed by west, west-southwest, and southwest winds. Linear dunes in the central An Nafud (east-west orientation) were formed by northwest and southwest winds. In the eastern portion of An Nafud, near the transition point between An Nafud and Ad Dahna, massif dunes have been formed by multidirectional winds. In the northwest extension of An Nafud, linear (seif) dunes trending northwest-southeast are dominant. In the extreme northern portion of An Nafud, dune forms are minimal and sheet sand dominates the landscape.

The primary dune system of An Nafud basically is stabilized; the dune system is not moving nor is any appreciable amount of new sand being added. Mobile, unstable sand is superimposed on the crests of older dunes, except for a small area of mobile dunes in the northwestern extension of An Nafud. Field observations suggest that the active sand on the crests is not new sand but reworked older sand that has become available as a result of deflation of exposed older dunes. The active dunes along the crests of older dunes are 5 to 10 m high and are generally linear and star dunes, indicating variable wind conditions during the recent past and at the present time. The active and mobile sand constitutes only 5 to 8 percent of the total sand area of An Nafud. Studies by Breed and others (1979) and Fryberger and Ahlbrandt (1979) based on interpretation of Landsat images of An Nafud, have correctly assessed the wind directions responsible for formation of the major dune system. These studies did not, however, identify three important conditions that characterize An Nafud today: (1) relatively dense vegetation on the older dune system, (2) stability of the primary older dune system, and (3) active dunes superimposed on the older stable dunes. These observations are especially important because An Nafud, based on unpublished meteorological data, has been described as possessing a high-energy wind environment with the highest potential for sand movement of any of the world's sand seas (Fryberger and Ahlbrandt, 1979). The field observations of vegetation cover, dune stability, and the relatively small volume of mobile sand in An Nafud, suggest that Landsat images must be used with caution.

Dunes in the northwest extension of An Nafud are active and the least stable when compared with dunes in other areas of An Nafud. This condition most likely results from slightly higher wind speeds in the area, less rainfall, sparse vegetation, and the possibility of new sand being added to the area. The prevailing nothwest wind in the northwest extension is reflected by an increase in dune size and thickness south and southeast across the area. Therefore, if new sediment is being added to the northwest extension, the Tertiary-Quaternary gravel plains northwest of the extension are the probable source.

Dune orientation strongly suggests that An Nafud is a unidirectional sand sea, that is, the primary dune system was formed by west-southwest prevailing winds. Radiocarbon dates determined for An Nafud lacustrine deposits strongly suggest that An Nafud sand sea was formed between about 20,000 yrs to 9,000 yrs BP. Field observations support the fact that the primary dunes composing about 95 percent of the sand sea are not active in the present arid climate. Available wind data suggest that winds in An Nafud region have become more variable in the recent past, compared to the wind regime during formation of An Nafud sand sea. Field observations, vegetation density, rainfall data, wind data, and isotopic dates of lacustrine deposits indicate that stabilization of the primary older dunes of An Nafud began after 5,000 yrs BP and that stabilizing conditions prevail at the present time in An Nafud.

Source of Sand.-- Results from the study of dune orientation, sand thickness, An Nafud sand samples in relation to sand-grain size and sorting values, and heavy-mineral distribution within An Nafud support the concept that the dune-forming wind was from the west-southwest. Dune orientation is primarily north-south with east facing slipfaces. Sand thickness decreases southwest to northeast across An Nafud. Sand thickness is greatest along the southwest and south-central margin of An Nafud sand sea. Sand-grain size decreases from west to east across An Nafud and sorting impoves from moderately well-sorted in the west to very-well sorted in the eastern extremity of An Nafud sand sea. Therefore, if the dune-forming wind was from the west-southwest, the heavy minerals identified in An Nafud sand samples should decrease, west to east across An Nafud, according to their specific gravity. The isopleth maps (Figs. 18, 19, and 20) show that the heavy minerals identified in An Nafud sand do, in general, decrease from west to east across An Nafud, providing further evidence that the dune-forming wind was from the west-southwest. Therefore, if the dune-forming wind was from the west-southwest and if the Paleozoic sandstone was the source of sand for An Nafud sand sea, then the heavy minerals identified in An Nafud sand should correlate with the heavy minerals identified in the Paleozoic sandstone.

The major heavy minerals identified in An Nafud sand samples are dravite, zircon, epidote, goethite, rutile, and opaque minerals (see Appendices B and C, for complete analyses). Major heavy minerals identified in the Paleozoic sandstone samples are dravite, rutile, anatase, fluorapatite, goethite, hematite, and chromite. Minor heavy minerals are zircon, epidote, sphene, and diopside (see Appendices D and E for complete analyses).

Heavy minerals identified in the Paleozoic sandstone samples, but not identified in An Nafud sand samples include anatase, sphene, diopside, fluorapatite, and chromite. With respect to anatase and sphene, anatase is trimorphous with rutile and brookite; and both anatase and rutile occur as alteration products of sphene. Sphene is a minor constituent in one sample from the Umm Sahm and Ram sandstones. Diopside, pyroxene group, was identified as a minor heavy mineral in one sample from the Siq Sandstone. Fluorapatito was identified in one rock sample from the Sakaka Sandstone and from one rock sample from the lower Umm Sahm and Ram sandstones. The Sakaka Sandstone crops out in only one location near the northwest edge of An Nafud, and the lower Umm Sahm and Ram sandstones crop out in one location south of the south central margin of An Nafud. Thus, if fluorapatite is a detrital heavy mineral in An Nafud sand it would be rare. Chromite appears as a major heavy mineral in the Siq, Quweira, Umm Sahm, and Ram sandstones, but was not identified in An Nafud sand samples. However, gahnite (Zn-spinel) and magnetite were identified in An Nafud sand samples. Therefore, the heavy minerals identified in An Nafud sand samples correlate very well with the heavy minerals identified in the Paleozoic sandstone samples, except for chromite.

In comparing An Nafud heavy-mineral suite with that of each Paleozoic sandstone formation, the best correlation is with the heavy-mineral suite identifed in the Tabuk formation. In addition, the exposure of the Tabuk Sandstone is larger in areal extent than the other Paleozoic sandstone formations, and this large area of exposure lies to the west and west-southwest of An Nafud sand sea. Therefore, the evidence strongly suggests that the dune-forming wind was from the west-southwest and that the Tabuk Sandstone was the primary source of An Nafud sand; the Siq, Quweira, Umm Sahm, and Ram sandstones contributed, but to a lesser degree.

<u>Lake Deposits</u>.-- Quaternary climatic conditions of An Nafud can best be projected from data derived from climatic and geologic studies of the late Tertary and Quaternary systems in eastern and southern Saudi Arabia, and then substantiated from field observations and isotopic dating of Quaternary lacustrine deposits in An Nafud sand sea. As is true for the other sand seas of Saudi Arabia, major problems do exist in attempting to project An Nafud climatic conditions during the Quaternary: (1) the sands that underlie An Nafud sand and associated lacustrine deposits (Fig. 25), (2) the limited exposure of lacustrine deposits and bedrock surfaces, and (3) the sparsity of reliable elevations on exposed surfaces.

Two different sands, a white sand and a beige to light brown sand, underlie An Nafud sand and lacustrine deposits (Fig. 25). The white sand is composed entirely of coarse-to-medium quartz grains, cross-bedded with little or no cementation; some exposures display root casts. All grains are well rounded and frosted. The beige to light brown sand is composed of medium quartz and zircon grains, with zircon constituting less than one percent of the total sand grains; all grains are well rounded, frosted, and iron stained. Where exposed, the beige to light brown sand is unconsolidated, and no bedforms are evident. The textural

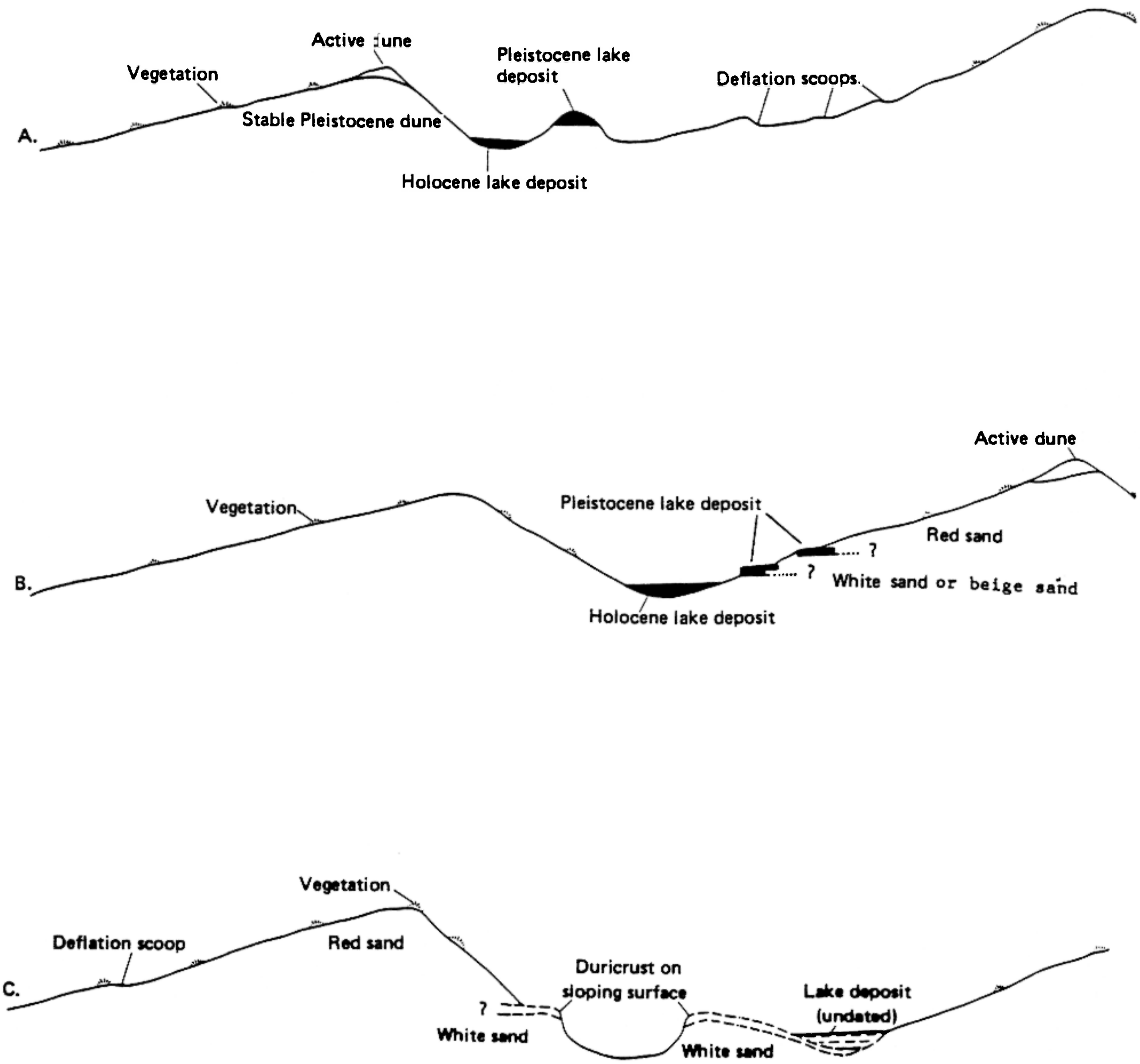


Figure 25. Schematic cross sections illustrating typical stratigraphic settings of Pleistocene and Holocene lake beds, An Nafud sand sea (from Whitney and others, 1983).

characteristics of both sands strongly suggest that they are eolian deposits. However, there is a possibility that the white sand was, originally, a sandstone (Tertiary or older) that was leached with a subsequent loss of cementing material and secondary minerals during a pluvial episode and a resulting higher water table. Detailed geologic studies are required to resolve this question.

In general, the white sand is normally exposed in the west, southwest, and southern areas of An Nafud, and the beige to light brown sand in the central and eastern portions of An Nafud. In some places in An Nafud, both sands were found exposed in a specific sequence, but only if two different levels of lacustrine deposits were present (Fig. 25). The older white and beige eolian sand and lacustrine deposits that underlie the younger An Nafud sands and that are exposed in interdune areas, provide the first evidence of alternating dry and wet phases in the region.

Samples of calcareous lake-bed deposits from separate An Nafud interdune areas were collected by the author and John Whitney (U.S. Geological Survey) and isotopically dated by Meyer Rubin (U.S. Geological Survey), Table 4. Included in Table 4 are isotopically dated samples, collected by John Whitney, of organic material from An Nafud and of lake-bed deposits from areas south and southwest of An Nafud. In conjuction with Table 4, and of great importance in projecting Quaternary climatic conditions of An Nafud, is Figure 25 that illustrates typical stratigraphic settings of

Table 4. Radiocarbon-dated lacustrine and interdune deposits in Saudi Arabia's northern sand seas. ** Deposits dated by Ganard and others, Pers. Comm., 1982. (From Whitney and others, 1983).

Sand Sea	Location	Laboratory Number	Material	Radiocarbon Age Years B.P.
An Nafud	27°36'N/38°50'E	B-3461	Organic	5,280 ± 100
Nafud As Sirr	26°10'N/44°19'E	B-2988	$CaCO_3$	5,480 ± 70
Nafud Urayk	25°35'N/42°40'E	B-3466	$CaCO_3$	5,640 ± 90
An Nafud	28°10'N/40°50'E	Q-3118**	Organic	6,685 ± 50
Nafud Urayk	25°37'N/42°39'E	B-3523	$CaCO_3$	8,440 ± 90
An Nafud	28°50'N/40°15'E	W-4835	$CaCO_3$	24,340 ± 300
An Nafud	28°10'N/40°50'E	Q-3117**	$CaCO_3$	25,630 ± 430
An Nafud	28°15'N/41°15'E	W-4847	$CaCO_3$	25,750 ± 310
Nafud Urayk	25°20'N/40°15'E	W-4987	$CaCO_3$	26,400 ± 400
An Nafud	28°15'N/39°45'E	W-4864	$CaCO_3$	27,120 ± 420
An Nafud	28°15'N/41°15'E	W-4855	$CaCO_3$	27,570 ± 500
An Nafud	27°50'N/41°04'E	W-4838	$CaCO_3$	29,000 ± 600
Nafud Urayk	25°32'N/42°36'E	W-4972	$CaCO_3$	>31,000
An Nafud	28°45'N/40°45'E	W-4959	$CaCO_3$	>32,000
An Nafud	29°35'N/40°13'E	W-4978	$CaCO_3$	>38,000

lacustrine deposits and associated older and younger eolian sands in An Nafud dune areas.

Radiocarbon dates determined for samples W-4959 (greater than 32,000 yrs BP) and W-4978 (greater than 38,000 yrs BP), Table 4, must be interpreted with caution, because isotopic dates greater than 30,000 yrs, determined from calcareous deposits, have a low reliability factor. However, those two dates when considered with the fact that the lake-bed deposits found in An Nafud lie on unconsolidated eolian sand, certainly suggest that a period of aridity and at least one pluvial episode occurred prior to 30,000 yrs BP. According to McClure (1976), a pluvial phase began at about 36,000 yrs BP in southeastern Saudi Arabia. Studies by Whitney (1983) indicate that a pluvial episode began at about 33,000 yrs BP in western Saudi Arabia.

The major grouping of radiocarbon dates for An Nafud lacustrine deposits is between 29,000 yrs and 24,000 yrs BP; these dates undoubtedly define a pluvial episode with intervening periods of aridity. One significant aspect of the data in Table 4, is that they indicate an absence of An Nafud calcareous lacustrine deposits prior to 24,000 yrs BP, although it is certainly possible that some exist. However, based on the radiocarbon dates from Table 4, an intense period of aridity and eolian activity probably occurred between approximately 22,000 yrs and 9,000 yrs BP, and An Nafud sand sea was most likely created during this period.

During the course of field work in An Nafud no calcareous deposits of Holocene age were found. Numerous small pan deposits occur in the lee of the large barchanoid ridge dunes. The pan deposits, composed mainly of gypsiferous sand, were laid down in small natural basins, similar to miniature playas, by ephemeral stands of water. Pan deposits cannot be dated by present methods but probably are early Holocene in age, inasmuch as they were formed after emplacement of the present dunes (22,000 yrs to 9,000 yrs BP), thus suggesting that a pluvial episode did occur between 9,000 yrs BP and the present. This episode was of less intensity than the late Pleistocene pluvial episode (29,000 yrs to 24,000 yrs BP). Radiocarbon dates for two samples of organic material from An Nafud (Table 4) of 6,685 yrs BP and 5,280 yrs BP support the view that a pluvial period did occur between about 9,000 yrs to 4,500 yrs BP, and studies by McClure (1976), Al-Sayari and Zötl (1978), and Whitney (1983) have shown that a pluvial episode did occur from early to middle Holocene in other areas of Saudi Arabia. A plausible explanation for the absence of early to middle Holocene calcareous lake beds in An Nafud is that the pluvial episode (9,000 yrs to 5,000 yrs BP) was not as intense in northern Saudi Arabia as it was in the southern and eastern regions of Saudi Arabia, and therefore, An Nafud lacustrine deposits were limited in extent and thickness. Field observations that support this view are: (1) faunal remains of antelope were not found by the author in An Nafud but were found in lake-bed deposits of Holocene age in Ar Rub al Khali, (2) tools of Mesolithic and Neolithic age were not observed, except on the extreme fringes of An Nafud sand sea, and (3) interdune areas have been subjected to deflation for an extended period of time, based on the depth of deflation around older vegetation and the depth of lag (2 cm to 4 cm) on the windward side of An Nafud dunes. Therefore, if thin calcareous lake beds of early to middle Holocene age did exist, they were most likely destroyed by eolian processes during the last 4,000 to 5,000 yrs.

Topographic and Gravity Surveys. -- Topographic and gravity surveys were carried out simultaneously along lines A-A' and B-B' (Fig. 26), by the author and M. Gettings, U.S. Geological Survey. Elevations were established by doppler satellite receivers and altimeter. A base station was established at camp and the elevation was determined by the doppler method and referenced to mean sea level. Elevations were established (doppler method) at intervals of about 40 kms and gravity stations (elevations by altimeter) at intervals of about 10 kms along both profiles. Altimeter elevations were referenced to the base station and doppler stations along each profile and corrected for temperature and humidity. Doppler elevations were established alternately, where possible, on the sand surface and then on bedrock of Quaternary, Tertiary, or Paleozoic age.

Based on established elevations and additional

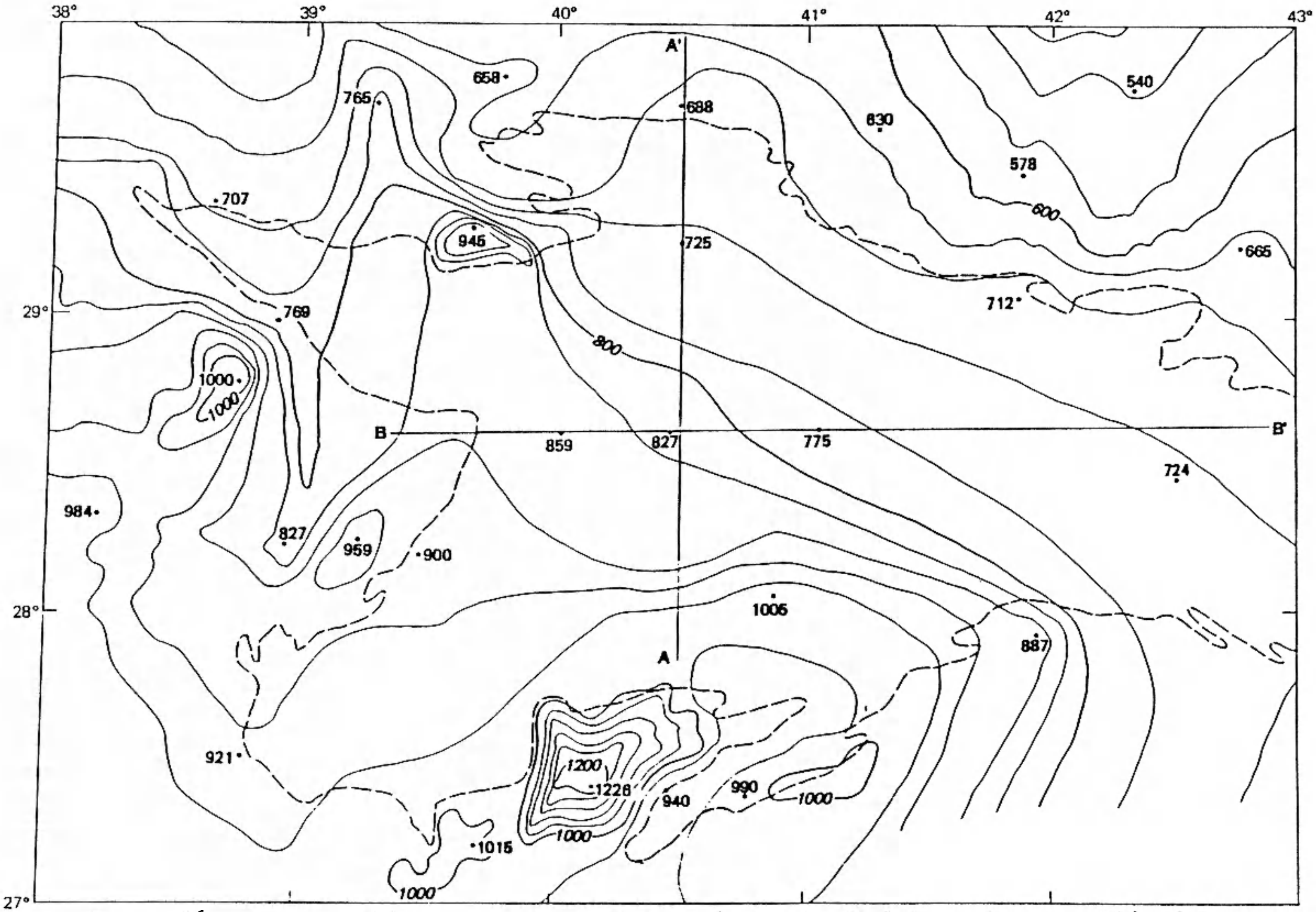


Figure 26. Topographic map of An Nafud region. An Nafud sand sea outlined by dashed line. Elevations, in meters, referenced to mean sea level. A-A' and B-B' are topographic and gravity profile lines (map by Faulkender and Gettings, 1981). Contour interval = 40 m, scale 1:2,000,000.

elevations from maps by Bramkamp and others (1963) and Brown and others (1963), a topographic map was compiled for An Nafud sand sea (Fig. 26). Figure 26 shows a decrease in elevation from south to north of about 300 m and from west to east of about 180 m. The entire An Nafud surface slopes gently to the northeast, except in the southwest and northwest corners, where north-flowing drainage is apparent. The contours do not indicate a topographic basin, but rather a planar surface inclined uniformly to the northeast. From southwest to northeast the elevation decreases about 210 m. Figure 27 illustrates the topographic profiles three dimensionally. Sand thickness is greatest in the south (about 150 m), but is thinner west to east, averaging between 60 m to 100 m. Thus, An Nafud sand sheet forms a wedge of sand that lies on the gently northeast-dipping Phanerozoic surface.

Gravity data for both profiles (Fig. 27) were interpreted by M. Getting, U.S. Geological Survey, using a density value of 2.67 gm/cm^3 for An Nafud sand (oral comm., 1983). Large, simple Bouguer anomalies that occur along both profiles indicate a number of faults that appear to be horst-graben structures. These deep-seated structures most likely reflect faults in the Precambrian basement complex. South and north of the northwest extension, faults (striking northwest and southeast) cut the Phanerozoic rocks. Tertiary and Quaternary sandstone and marl are present in a graben-like structure in the northwest area

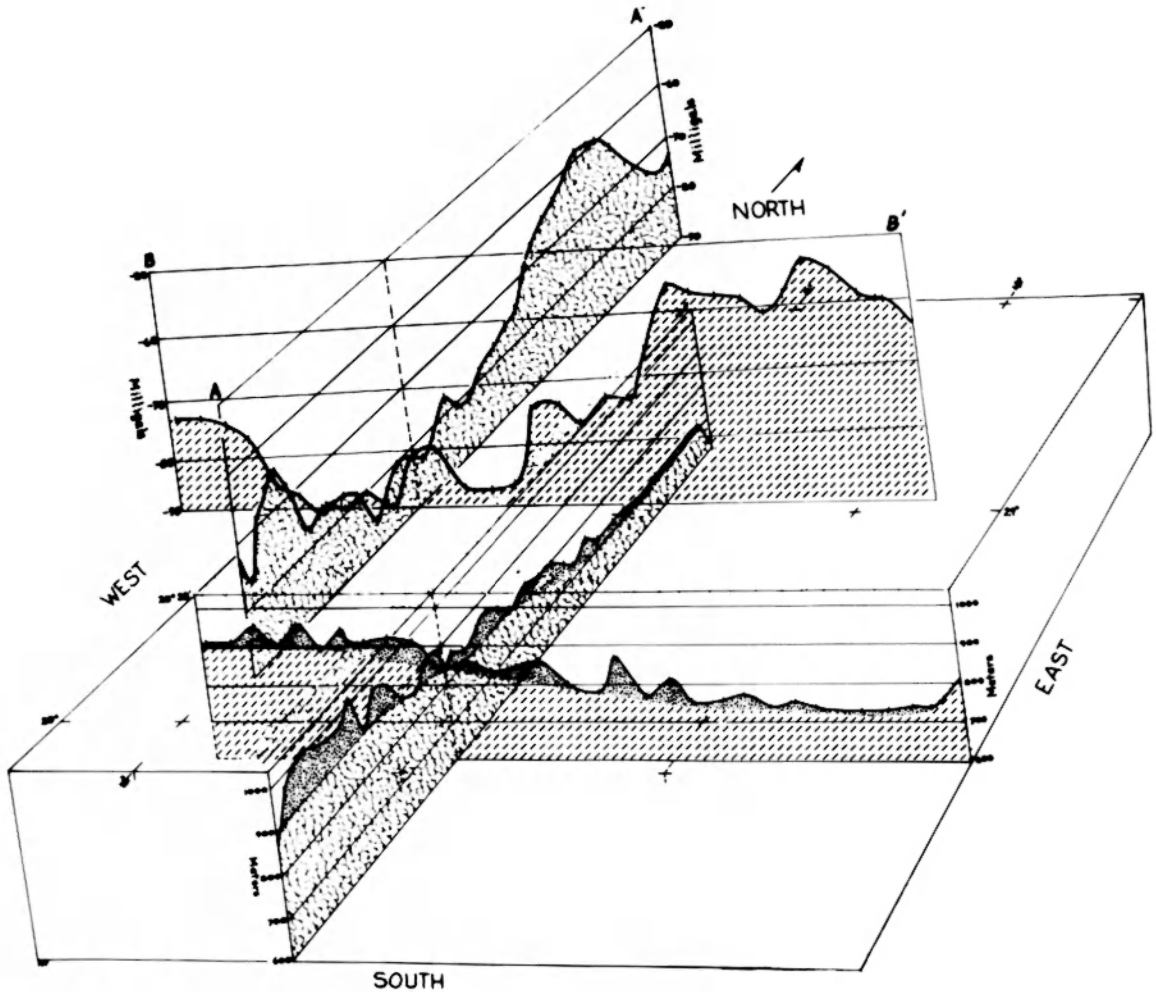


Figure 27. Topographic and simple Bouguer gravity-anomaly profiles across An Nafud sand sea, north-central Saudi Arabia. Horizontal scale: 1:2,000,000 (M. Gettings, U. S. Geological Survey, Pers. Comm. 1983).

(29°30' N. lat - 40°00' E. long) of An Nafud where sand cover is thin and discontinuous. The gravity profiles, therefore, most likely define the southeasterly extension of the fault system in the northwest extension of An Nafud sand sea.

Mean sea-level elevations and interpreted gravity data along both profiles strongly suggest that the surface underlying An Nafud sand is a peneplane, sloping gently to the northeast and that the faults underlying An Nafud are deep-seated, that is, within the Precambrian basement complex. An Nafud sand sea, therefore, was not formed in a topographic low, but was most likely the end product of wind regime and sand source. These conclusions are based on three factors: (1) the dune-forming winds are believed to have been from the west and west-southwest during late Pleistocene and early Holocene, (2) the most extensive exposure of Paleozoic sandstone is west and southwest of An Nafud, and (3) the wind regime was most likely from the west and northwest during late Holocene to the present. All of these factors would contribute to thicker sands in the southern and southwestern areas of An Nafud.

Discussion

The late Pleistocene-Holocene environmental history of An Nafud sand sea is chiefly a history of alternating climate changes that resulted in alternating episodes of vigorous eolian activity and dune system stability. Dated lacustrine deposits from An Nafud fall primarily into two periods of pluvial activity. Maximum lacustrine activity took place in late Pleistocenc (32,000 yrs to 24,000 yrs BP); the largest number of dated lake sediments were deposited between 27,800 yr sand 25,500 yrs BP in An Nafud sand sea. A second lake-forming episode occurred in early to middle Holocene time between 8,500 yrs and 5,000 yrs BP, and appears to have had a period of maximum activity between about 6,500 yrs and 5,200 yrs BP. Both pluvial periods correlate well with pluvial activity in other parts of Saudi Arabia. However, the early to middle Holocene pluvial period in An Nafud appears to have been of lessor intensity in An Nafud sand sea then in other parts of Saudi Arabia. For example, the early to middle Holocene lake-bed deposits in An Nafud are limited in number and are relatively thin compared with lake-bed deposits of the same age in Ar Rub al Khali sand sea in southeastern Saudi Arabia.

Because eolian sand lies stratigraphiclly above and below lacustrine deposits in An Nafud, maximum eolian activity must have occurred there between pluvial periods when the dune-forming wind achieved its highest velocity. Wind data for An Nafud sand sea indicate that wind velocity has decreased in the recent past, resulting in a decrease in eolian activity and dune mobility. The sand over more than ninety percent of An Nafud has become stable in the recent past as the wind velocity decreased and vegetation cover increased. Active deflation in An Nafud sand sea appears to have decreased recently because most of the deflation depressions observed in the field or on aerial photographs contain vegetation.

Heavy-mineral data from the Paleozoic sandstone and An Nafud sand samples, show that the two mineral suites have a high degree of correlation, and that the best correlation occurs between the Tabuk Sandstone (Silurian-Ordovician age) heavy-mineral suite and An Nafud sand heavy-mineral suite, except for chromite. Therefore, heavy-mineral data strongly suggest that the Tabuk Sandstone was the primary sand source and that the remaining Paleozoic sandstone formations were, most likely, a secondary source. The histograms showing the distribution of grain size in An Nafud sand sea, support the concept that the dune-forming wind was from the west-southwest and that the sand source lies to the west-southwest of An Nafud. The supporting facts are: (1) grain size decreases from west to east across An Nafud, (2) sorting improves west to east across An Nafud, and (3) the concentration of dravite, zircon, and epidote decrease from west to east across An Nafud sand sea.

Summary

The conclusions from this study are: (1) the evidence strongly suggests that the primary source of sand for An Nafud sand sea was the Tabuk Sandstone; secondary sources from the other Paleozoic sandstone formations, (2) the dune-forming wind was from the west-southwest, (3) An Nafud

sand sea began to develop during the late Pleistocene, (4) the average wind velocity for An Nafud region has decresed in the recent past, and (5) An Nafud sand sea is, at the present time, a stable sand sea. These conclusions are based on available climatic data, radiocarbon-dated lacustrine deposits, field observations, dune forms, textural and mineralogical studies of An Nafud sand samples, and mineralogical studies of Paleozoic sandstone samples.

Suggested areas of study for future work in An Nafud are: (1) a comparison of quartz types in An Nafud sand and Paleozoic sandstone, (2) a detailed study of lacustrine deposits in relation to paleoclimate and possible economic mineral deposits, and (3) a detailed study of the textural parameters of An Nafud sand as related to dune forms.

REFERENCES

Ahlbrandt, T. S., 1974, The source of sand for the Killpecker sand-dune field, southwestern Wyoming: Sedimentary Geology, v. 11, p. 39-57.

Al-Sayari, S. S. and Zotl, J. G., eds., 1978, Quaternary Period in Saudi Arabia: New York, Springer-Verlag, 334 p.

Anton, D., 1980, Climatic influence in the Cenozoic evolution of the Arabian Shield south, Abs.: 26th International Geology Congress, Paris, 1980.

Bagnold, R. A., 1941, The physics of blown sand and desert dunes: London, Methuen, 256 p.

Bagnold, R. A., 1951, Sand formations in Saudi Arabia: Geological Journal, v. 117, p. 78-86.

Bayliss, D. D., 1981, Lithostratigraphy and biostratigraphy of the Sirhan-Turayf phosphate area: Saudi Arabian Ministry of Petroleum for Mineral Resources, Open-file report, RF-OF-01-25, 131 p.

Bender, F., 1975, Geology of the Arabian Peninsula, Jordan: U.S. Geological Survey Professional Paper 560-I, 36 p.

Binda, P. L., 1981, The Precambrian-Cambrian boundary in the Arabian Shield, A review: Bulletin of the Faculty of Earth Sciences, King Abdulaziz University, v. 4, p. 107-120.

Bindagji, H. H., 1980, Atlas of Saudi Arabia: Oxford, Oxford University Press, 60 p.

Bramkamp, P. A., Brown, G. F., Holm, D. A., and Layne, N. M., 1963, Geology of Wadi as Sirhan quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-200 A, scale 1:500,000.

Bramkamp, P. A. and Ramirez, L. F., 1963, Geology of the Darb Zubaydah quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-202 A, scale 1:500,000.

Bramkamp, P. A., Ramirez, L. F., Brown, G. F., and Pocock, A. E., 1963, Geology of the Wadi ar Rimah quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-206 A, scale 1:500,000.

Bramkamp, P. A. Ramirez, L. F., Stieneke, M., and Reiss, W. H., 1963, Geology of the Jauf-Sakaka quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-201 A, scale 1:500,000.

Breed, C. S., Fryberger, S. G., Andrews, W., McCauley, C., Lennartz, F., Gebel,D., and Horstman, K., 1979, Regional studies of sand seas using Landsat (ERTS) Imagery, in A study of global sand seas, Mckee, E. D., ed.: U.S. Geological Survey Professional Paper 1502, p. 309-381.

Brown, G. F., 1960, Geomorphology of western and central Saudi Arabia: 21st International Geological Congress, Copenhagen, 1960, Proceedings, p. 150-159.

Brown, G. F., 1970, Eastern margin of the Red Sea and coastal structures in Saudi Arabia: Philosophical Transactions of the Royal Society of London, ser. A, v. 267, p. 75-87.

Brown, G. F., 1972, Tectonic map of the Arabian Peninsula, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Recsources Arabian Peninsula Map AP-2, scale 1:4,000,000.

Brown, G. F. and Jackson, R. O., 1960, The Arabian Shield: 21st International Geological Congress, Copenhagen, 1960, Rept., pt. 9, p. 69-77.

Brown, G. F., Layne, N., Goudarzi, G. H., and Maclean, W. H., 1963, Geology of the northeastern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-205 A, scale 1:500,000

Brown, G. F., Jackson, R. O., Bogue, R. G., and Elberg, E. L., 1963, Geology of the northwestern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Geologic Investigations Map I-204 A, scale 1:500,000.

Chapman, R. W., 1971, Climatic changes and the evolution of landforms in the eastern province of Saudi Arabia: Geological Society of America Bulletin, v. 82, p. 2713-2728

Chapman, R. W., 1974, Calcareous duricrust in Al-Hasa, Saudi Arabia: Geological Society of America Bulletin, v. 85, p. 119-130.

Coleman, R. G, Hadley, D. G., Fleck, R. J., Hedge, C. E., and Donato, M. M., 1979, The Miocene Tihama Asir ophiolite and its bearing on the opening of the Red Sea: U.S. Geological Survey Saudi Arabian Project Report 255, 34 p.

Dana, E.S., 1949, Textbook of mineralology, revised and enlarged by Ford, W. E., 4th ed.: New York, John Wiley, 851 p.

Folk, R. L., 1980, Petrology of sedimentary rocks: Austin, Texas; Hemphill's Book Store, 170 p.

Fryberger, S. G., 1979, Dune forms and wind regime, in Mckee, E. D., ed., A study of global sand seas: U.S. Geological Survey Professional Paper 1052, Washington, D. C., p. 137-169.

Fryberger, S. G., and Albrandt, T. S., 1979, Mechanisms for the formation of eolian sand seas: Zeitschrift für Geomorphologie, v. 23, p. 440-460.

Galehouse, J. S., 1971, Point counting, in Procedures in sedimentary petrology, R. E. Carver, ed.: New York, Wiley-Interscience, p. 385-407.

Garrard, A. N., Harvey, C. P. D., and Switzer, V. R., in press, Environment and settlement in the upper Pleistocene and Holocene at Jubbah in the Great Nafud, northern Arabia: Riyadh, Atlal, v. 5.

Greenwood, W. R., 1972, The Hail arch--a key to the Arabian Shield during evolution of the Red Sea rift: Saudi Arabian Directorate General of Mineral Resources Bulletin 7, 5 p.

Greenwood, W. R., Stoeser, D. B., Fleck, R. J., and Stacey, J. S., 1982, Late Proterozoic island-arc complexes and tectonic belts in the southern part of the Arabian Shield, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-8, 46 p.

Hadley, D. G., and Fleck, R. J., 1980, Reconnaissance geology of the Al Lith quadrangle, sheet 20/40 C, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Report 270, 19 p.

Helal, A. H., 1965, Stratigraphy of outcropping Paleozoic rocks around the northern edge of the Arabian Shield (within Saudi Arabia): Deutschen Geologischen Gesellschaft, Zeitschrift, v. 117, p. 506-543.

Holm, D. A,., 1960, Desert geomorphology in the Arabian Peninsula: Science, v. 132, no. 2437, p. 1369-1379.

Hötzl, H., Felber, J., and Zötl, J. G., 1978, The Quaternary development of the upper part of Wadi Rimah, in Al-Sayari and Zotl, eds., Quaternary Period in Saudi Arabia: New York, Springer-Verlag, p. 173-182.

Karpoff, R., 1957, Esquisse geologique de l' Arabie Seoudite: Soc. Geol. France Bull., ser. 6, v. 7, p. 653-697.

Krumbein, W. C., and Sloss, L. L., 1963, Stratigraphy and sedimentation (2nd ed.): San Francisco, W. H. Freeman Co., 660 p.

Lancaster, N., 1981, Grain size characteristics of Namib desert linear dunes: Sedimentology v. 28, p. 115-122.

Madden, C. T., Naqvi, I. M., Whitmore, F. C., Jr., Schmidt, D. L., Langston, W., Jr., and Wood, R. C., 1979, Paleocene vertebrates from coastal deposits in the Harrat Hadan area, Al-Taif region, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission Project Report 269, 29 p.

McBride, E. F., 1971, Mathematical treatment of size distribution data, in Procedures in sedimentary petrology, R. E. Carver, ed.: New York, Wiley-Interscience, p.109-127.

McClure, H. A., 1976, Radiocarbon chronology of late Quaternary lakes in the Arabian desert: Nature, v. 263, p. 755-756.

McClure, H. A., 1978, Ar Rub al Khali, in Al-Sayari, S. S., and Zötl, J. G., eds., Quaternary Period in Saudi Arabia: New York, Springer-Verlag, p. 252-263.

McClure, H. A., 1980, Permian-Carboniferous glaciation in the Arabian Peninsula: Geological Society of America Bulletin, v. 91, p. 707-712.

Philby, H. St. John, 1933, The Empty Quarter: London, Constable, 433 p.

Powers, R. W., Ramirez, L. F., Redmond, C. D., and Elberg, E. L., Jr., 1966, Geology of the Arabian Peninsula--Sedimentary Geology of Saudi Arabia: U.S. Geological Survey Professional Paper 560-D, 147 p.

Saudi Arabia Ministry of Agriculture and Water, 1968, The Great Nafud sedimentary basin, Kingdom of Saudi Arabia: Parsons Basil, Consultant, Riyadh, Saudi Arabia, v. 3, 500 p.

Schmidt, D. L., Hadley, D. G., and Brown, G. F., 1982, Middle Tertiary continental rift and evolution of the Red Sea in southwestern Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-6, 56 p.

U.S. Geological Survey, 1972, Topographic map of the Arabian Peninsula: U.S. Geological Survey Saudi Arabian Project Report 135, scale 1:4,000,000.

U.S. Geological Survey and Arabian American Oil Company (ARAMCO), 1963, Geological Map of the Arabian Peninsula: U.S. Geological Survey Miscellaneous Geological Investigations Map I-270 A, scale 1:2,000,000.

Whitney, J. W., 1982, Overview of the geomorphology of western Saudi Arabia and recommendations for future research: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-6, 19 p.

Whitney, J. W., 1983, Erosional history and surficial geology of western Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record USGS-TR-04-1, 90 p.

Whitney, J. W., Faulkender, D. J., and Rubin, M., 1983, The environmental history and present condition of the northern sand seas of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-95, 39 p.

A P P E N D I X A

Sieve Analyses of An Nafud Sand Samples

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 28 APRIL 1981 Sample No. 037

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.1 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 201.1 gms

Sum of Retained Wt. 201.1 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	474.3	474.1	0.2	0.1	0.1	99.9
18 (0 Ø)	449.9	448.7	1.2	0.6	0.7	99.3
35 (1 Ø)	481.1	432.2	48.9	24.3	25.0	75.0
60 (2 Ø)	535.1	408.2	126.9	63.1	88.1	11.9
120 (3 Ø)	425.0	407.1	17.9	8.9	97.0	3.0
230 (4 Ø)	380.4	374.6	5.8	2.9	99.9	0.1
Pan	356.4	356.2	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 1 JULY 1980 Sample No. 022

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 644.3 gms

Tare Wt. 443.7 gms

Wt. of Total Sample 200.6 gms

Sum of Retained Wt. 200.5 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.8	484.8	0.0			100.0
18 (0 Ø)	476.1	471.1	5.0	2.5	2.5	97.5
35 (1 Ø)	462.3	432.8	29.5	14.7	17.2	82.8
60 (2 Ø)	479.0	399.0	80.0	39.9	57.1	42.9
120 (3 Ø)	466.7	397.9	68.8	34.3	91.4	8.6
230 (4 Ø)	380.0	365.4	14.6	7.3	98.7	1.3
Pan	418.1	415.5	2.6	1.3	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 15 DEC. 1980 Sample No. 180

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.1 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 202.1 gms

Sum of Retained Wt. 201.9 gms

Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457.6	457.6	0.0			100.0
35 (1 Ø)	473.0	433.0	40.0	19.8	19.8	80.2
60 (2 Ø)	535.2	408.9	126.3	62.5	82.3	17.7
120 (3 Ø)	407.7	389.1	18.6	9.2	91.5	8.5
230 (4 Ø)	402.9	386.1	16.8	8.3	99.8	0.2
Pan	340.2	340.0	0.2	0.1	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 15 DEC. 1980 Sample No. 185

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 569.5 gms

Tare Wt. 368.9 gms

Wt. of Total Sample 200.6 gms

Sum of Retained Wt. 200.5 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457.6	457.6	0.0			100.0
35 (1 Ø)	450.6	433.0	17.6	8.8	8.8	91.2
60 (2 Ø)	541.7	408.9	132.8	66.2	75.0	25.0
120 (3 Ø)	420.5	389.0	31.5	15.7	90.7	9.3
230 (4 Ø)	404.4	386.0	18.4	9.2	99.9	0.1
Pan	340.2	340.0	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 13 DEC. 1980 Sample No. 184

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 548.1 gms

Tare Wt. 347.1 gms

Wt. of Total Sample 201.0 gms

Sum of Retained Wt. 200.8 gms

Loss 0.2 gms

U. S. Standard Sieve Size	Retained: Wt. Sample + Sieve	Wt. Sieve	Wt. Sample	Percent Retained	Sum % Retained	Sum % Passing
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457.9	457.9	0.0			100.0
35 (1 Ø)	440.9	432.1	8.8	4.4	4.4	95.6
60 (2 Ø)	561.3	409.1	152.2	75.7	80.1	19.9
120 (3 Ø)	426.1	389.1	37.0	18.4	98.5	1.5
230 (4 Ø)	389.5	386.7	2.8	1.4	99.9	0.1
Pan	340.1	340.1	0.0	0.0	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 28 Nov 1980 Sample No. 151

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.6 gms

Tare Wt. 369.2 gms

Wt. of Total Sample 201.4 gms

Sum of Retained Wt. 201.3 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained Wt. Sample + Sieve	Retained Wt. Sieve	Retained Wt. Sample	Percent Retained	Sum % Retained	Sum % Passing
10 (-1 Ø)	494.4	494.4	0.0			100.0
18 (0 Ø)	457.6	457.6	0.0			100.0
35 (1 Ø)	441.1	432.9	8.2	4.1	4.1	95.9
60 (2 Ø)	438.9	409.1	29.8	14.8	18.9	81.1
120 (3 Ø)	458.5	388.2	70.3	34.9	53.8	46.2
230 (4 Ø)	479.3	386.9	92.4	45.9	99.7	0.3
Pan	356.7	356.1	0.6	0.3	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 15 DEC. 1980 Sample No. 181

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.5 gms

Tare Wt. 368.9 gms

Wt. of Total Sample 201.6 gms

Sum of Retained Wt. 201.5 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457.6	457.6	0.0			100.0
35 (1 Ø)	441.0	432.9	8.1	4.0	4.0	96.0
60 (2 Ø)	569.8	408.9	160.9	79.8	83.8	16.2
120 (3 Ø)	410.6	388.0	22.6	11.2	95.0	5.0
230 (4 Ø)	396.0	386.1	9.9	4.9	99.9	0.1
Pan	339.9	339.9	0.0	0.0	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 28 APRIL 1981 Sample No. 039

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.6 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 201.6 gms

Sum of Retained Wt. 201.4 gms

Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	448.7	448.7	0.0			100.0
35 (1 Ø)	440.1	432.2	7.9	3.9	3.9	96.1
60 (2 Ø)	530.8	408.2	122.6	60.8	64.7	35.3
120 (3 Ø)	465.6	407.1	58.5	29.0	93.7	6.3
230 (4 Ø)	386.9	374.6	12.3	6.1	99.8	0.2
Pan	356.3	356.2	0.1	0.1	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 2 DEC. 1980 Sample No. 152

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 542.6 gms
Tare Wt. 340.1 gms
Wt. of Total Sample 202.5 gms
Sum of Retained Wt. 202.4 gms
Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457 9	457.9	0.0			100.0
35 (1 Ø)	440.0	432.7	7.3	3.6	3.6	96.4
60 (2 Ø)	497 8	409.1	88.7	43.8	47.4	52.6
120 (3 Ø)	463 3	388.6	74.7	36.9	84.3	15.7
230 (4 Ø)	417.5	385.9	31.6	15.6	99.9	0.1
Pan	356.2	356.1	0.1	0.0	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 9 DEC. 1980 Sample No. 140

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.7 gms

Tare Wt. 368.9 gms

Wt. of Total Sample 201.8 gms

Sum of Retained Wt. 201.7 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	448.6	448.6	0.0			100.0
35 (1 Ø)	435.4	432.0	3.4	1.7	1.7	98.3
60 (2 Ø)	563.8	408.8	155.0	76.8	78.5	21.5
120 (3 Ø)	427.3	388.4	38.9	19.3	97.8	2.2
230 (4 Ø)	391.1	386.7	4.4	2.2	100.0	0.0
Pan	340.0	340.0	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 20 Nov. 1980 Sample No. 210

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 556.6 gms

Tare Wt. 355.8 gms

Wt. of Total Sample 200.8 gms

Sum of Retained Wt. 200.8 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	448.8	448.8	0.0			100.0
35 (1 Ø)	425.4	423.0	2.4	1.2	1.2	98.8
60 (2 Ø)	572.9	399.0	173.9	86.6	87.8	12.2
120 (3 Ø)	394.5	379.0	15.5	7.7	95.5	4.5
230 (4 Ø)	385.5	376.7	8.8	4.4	99.9	0.1
Pan	340.3	340.1	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 4 MAY 1981 Sample No. 170

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.8 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 202.8 gms

Sum of Retained Wt. 203.7 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	471.2	471.2	0.0			100.0
35 (1 Ø)	432.7	432.1	0.6	0.3	0.3	99.7
60 (2 Ø)	541.7	409.1	132.6	65.4	65.7	34.3
120 (3 Ø)	460.9	407.2	53.7	26.5	92.2	7.8
230 (4 Ø)	391.1	375.3	15.8	7.8	100.0	0.0
Pan	356.1	356.1	0.0	0.0		

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J. Faulkender Date 4 MAY 1981 Sample No. 036

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 569.5 gms
Tare Wt. 369.0 gms
Wt. of Total Sample 200.5 gms
Sum of Retained Wt. 200.4 gms
Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	471.2	471.2	0.0			100.0
35 (1 Ø)	432.3	432.1	0.2	0.1	0.1	99.9
60 (2 Ø)	533.6	409.1	124.5	62.1	62.2	37.7
120 (3 Ø)	473.4	407.2	66.2	33.0	95.2	4.8
230 (4 Ø)	384.7	375.3	9.4	4.7	99.9	0.1
Pan	356.2	356.1	0.1	0.0	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 23 Nov 1980 Sample No. 162

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 542.0 gms

Tare Wt. 339.9 gms

Wt. of Total Sample 202.1 gms

Sum of Retained Wt. 202.0 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.7	494.7	0.0			100.0
18 (0 Ø)	458.6	458.6	0.0			100.0
35 (1 Ø)	432.7	432.5	0.2	0.1	0.1	99.9
60 (2 Ø)	518.7	408.4	110.3	54.6	54.7	45.3
120 (3 Ø)	452.6	389.2	63.4	31.4	86.1	13.9
230 (4 Ø)	413.8	385.9	279	13.8	99.9	0.1
Pan	356.3	356.1	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 6 DEC. 1980 Sample No. 146

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 549.7 gms

Tare Wt. 347.0 gms

Wt. of Total Sample 202.7 gms

Sum of Retained Wt. 202.6 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	485.0	485.0	0.0			100.0
18 (0 Ø)	458.3	458.3	0.0			100.0
35 (1 Ø)	433.1	432.9	0.2	0.1	0.1	99.9
60 (2 Ø)	515.1	408.1	107.0	52.8	52.9	47.1
120 (3 Ø)	472.0	388.3	83.7	41.3	94.2	5.8
230 (4 Ø)	398.5	386.8	11.7	5.8	100.0	0.0
Pan	340.0	340.0	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 9 DEC. 1980 Sample No. 142

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 512.0 gms

Tare Wt. 369.1 gms

Wt. of Total Sample 202.9 gms

Sum of Retained Wt. 202.7 gms

Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.6	494.6	0.0			100.0
18 (0 Ø)	448.7	448.7	0.0			100.0
35 (1 Ø)	432.4	432.2	0.2	0.1	0.1	99.9
60 (2 Ø)	502.8	408.9	93.9	46.3	46.4	53.6
120 (3 Ø)	472.0	388.6	83.4	41.1	87.5	12.5
230 (4 Ø)	411.7	386.7	25.0	12.3	99.8	0.2
Pan	340.3	340.1	0.2	0.1	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender   Date 4 MAY 1981   Sample No. 038

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.2 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 202.2 gms

Sum of Retained Wt. 202.1 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	471.2	471.2	0.0			100.0
35 (1 Ø)	432.3	432.1	0.2	0.1	0.1	99.9
60 (2 Ø)	489.6	409.1	80.5	39.8	39.9	60.1
120 (3 Ø)		407.2	97.2	48.1	88.0	12.0
230 (4 Ø)	398.9	375.3	23.6	11.7	99.7	0.3
Pan	356.7	356.1	0.6	0.3	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 13 DEC. 1980 Sample No. 202

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 549.0 gms

Tare Wt. 347.1 gms

Wt. of Total Sample 201.9 gms

Sum of Retained Wt. 201.8 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.9	484.9	0.0			100.0
18 (0 Ø)	457.8	457.8	0.0			100.0
35 (1 Ø)	432.2	432.0	0.2	0.1	0.1	99.9
60 (2 Ø)	472.5	409.1	63.4	31.4	31.5	68.5
120 (3 Ø)	480.1	389.1	91.0	45.1	76.6	23.4
230 (4 Ø)	433.9	386.7	47.2	23.4	100.0	0.0
Pan	340.1	340.1	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 28 NOV 1980 Sample No. 150

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.1 gms

Tare Wt. 369.2 gms

Wt. of Total Sample 200.9 gms

Sum of Retained Wt. 200.9 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.3	494.3	0.0			100.0
18 (0 Ø)	457.9	457.9	0.0			100.0
35 (1 Ø)	433.0	432.8	0.2	0.1	0.1	99.9
60 (2 Ø)	471.8	409.1	62.7	31.2	31.3	68.7
120 (3 Ø)	475.1	388.5	86.6	43.1	74.4	25.6
230 (4 Ø)	438.2	387.0	51.2	25.5	99.9	0.1
Pan	356.3	356.1	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 9 Dec 1980 Sample No. 145

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 570.6 gms

Tare Wt. 369.1 gms

Wt. of Total Sample 201.5 gms

Sum of Retained Wt. 2013 gms

Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 ∅)	494.8	494.8	0.0			100.0
18 (0 ∅)	448.6	448.6	0.0			100.0
35 (1 ∅)	432.0	432.0	0.0			100.0
60 (2 ∅)	549.6	408.8	140.8	69.9	69.9	30.1
120 (3 ∅)	440.3	388.5	51.8	25.7	95.6	4.4
230 (4 ∅)	395.4	386.7	8.7	4.3	99.9	0.1
Pan	340.1	340.1	0.0	0.0	99.9	0.1

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J . Faulkender Date 6 DEC. 1980 Sample No. 144

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 549.4 gms
Tare Wt. 347.0 gms
Wt. of Total Sample 202.4 gms
Sum of Retained Wt. 202.4 gms
Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.8	494.8	0.0			100.0
18 (0 Ø)	458.3	458.3	0.0			100.0
35 (1 Ø)	432.8	432.8	0.0			100.0
60 (2 Ø)	549.4	408.1	141.3	69.8	69.8	30.2
120 (3 Ø)	437.6	388.2	49.4	24.4	94.2	5.8
230 (4 Ø)	398.5	386.8	11.7	5.8	100.0	0.0
Pan	340.0	340.0	0.0	0.0		

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J . Faulkender Date 20 Nov 1980 Sample No. 161

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 559.3 gms
Tare Wt. 356.2 gms
Wt. of Total Sample 203.1 gms
Sum of Retained Wt. 202.9 gms
Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	485.0	485.0	0.0			100.0
18 (0 Ø)	448.7	448.7	0.0			100.0
35 (1 Ø)	422.0	422.0	0.0			100.0
60 (2 Ø)	531.5	398.3	133.2	65.6	65.6	34.4
120 (3 Ø)	440.4	378.9	61.5	30.3	95.9	4.1
230 (4 Ø)	384.8	376.8	8.0	4.0	99.9	0.1
Pan	340.2	340.0	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 28 APRIL 1981 Sample No. 035

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 569.0 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 200.0 gms

Sum of Retained Wt. 200.0 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	474.1	474.1	0.0			100.0
18 (0 Ø)	448.7	448.7	0.0			100.0
35 (1 Ø)	432.3	432.2	0.1	0.0	0.0	100.0
60 (2 Ø)	520.3	408.2	112.0	56.0	56.0	44.0
120 (3 Ø)	489.7	407.1	82.6	41.3	97.3	2.7
230 (4 Ø)	380.0	374.6	5.4	2.7	100.0	0.0
Pan	356.2	356.2	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 28 Nov. 1980 Sample No. 141

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.2 gms

Tare Wt. 369.1 gms

Wt. of Total Sample 202.1 gms

Sum of Retained Wt. 202.1 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	499.2	499.2	0.0			100.0
18 (0 Ø)	457.7	457.7	0.0			100.0
35 (1 Ø)	432.9	432.9	0.0			100.0
60 (2 Ø)	524.0	409.2	114.8	56.8	56.8	43.2
120 (3 Ø)	457.8	388.5	69.3	34.3	91.1	8.9
230 (4 Ø)	404.8	387.0	17.8	8.8	99.9	0.1
Pan	356.3	356.1	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J . Faulkender Date 23 NOV. 1980 Sample No. 154

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 541.7 gms
Tare Wt. 340.1 gms
Wt. of Total Sample 201.6 gms
Sum of Retained Wt. 201.4 gms
Loss 0.2 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.6	494.6	0.0			100.0
18 (0 Ø)	458.5	458.5	0.0			100.0
35 (1 Ø)	432.3	432.3	0.0			100.0
60 (2 Ø)	494.3	408.2	86.1	42.7	42.7	57.3
120 (3 Ø)	476.4	388.9	87.5	43.4	86.1	13.9
230 (4 Ø)	413.3	385.7	27.6	13.7	99.8	0.2
Pan	356.2	356.0	0.2	0.1	99.9	0.1

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 15 DEC 1980 Sample No. 16.3

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 569.9 gms

Tare Wt. 369.0 gms

Wt. of Total Sample 200.9 gms

Sum of Retained Wt. 200.8 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	499.2	499.2	0.0			100.0
18 (0 Ø)	457.6	457.6	0.0			100.0
35 (1 Ø)	433.0	433.0	0.0			100.0
60 (2 Ø)	492.9	408.9	84.0	41.8	41.8	58.2
120 (3 Ø)	469.7	389.0	80.7	40.2	82.0	18.0
230 (4 Ø)	421.9	386.0	35.9	17.9	99.9	0.1
Pan	340.2	340.0	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 9 DEC. 1980 Sample No. 165

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.3 gms

Tare Wt. 368.9 gms

Wt. of Total Sample 202.4 gms

Sum of Retained Wt. 202.3 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	485.0	485.0	0.0			100.0
18 (0 Ø)	458.3	458.3	0.0			100.0
35 (1 Ø)	432.1	432.1	0.0			100.0
60 (2 Ø)	479.3	408.9	70.4	34.8	34.8	65.2
120 (3 Ø)	500.4	388.5	111.9	55.3	90.1	9.9
230 (4 Ø)	406.7	386.7	20.0	9.9	100.0	0.0
Pan	340.1	340.1	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 20 Nov. 1980 Sample No. 143

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 558.7 gms

Tare Wt. 355.4 gms

Wt. of Total Sample 203.0 gms

Sum of Retained Wt. 202.9 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	485.0	485.0	0.0			100.0
18 (0 Ø)	448.7	448.7	0.0			100.0
35 (1 Ø)	423.0	423.0	0.0			100.0
60 (2 Ø)	454.3	399.1	55.2	27.2	27.2	72.8
120 (3 Ø)	490.1	379.3	110.8	54.6	81.8	18.2
230 (4 Ø)	413.6	376.9	36.7	18.1	99.9	0.1
Pan	340.2	340.0	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J. Faulkender Date 16 JUNE 1981 Sample No. 238

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 557.7 gms

Tare Wt. 356.2 gms

Wt. of Total Sample 201.5 gms

Sum of Retained Wt. 201.5 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.8	484.8	0.0			100.0
18 (0 Ø)	471.1	471.1	0.0			100.0
35 (1 Ø)	432.8	432.8	0.0			100.0
60 (2 Ø)	439.7	399.0	40.7	20.2	20.2	79.8
120 (3 Ø)	541.0	397.9	143.1	71.0	91.2	8.8
230 (4 Ø)	382.9	365.4	17.5	8.7	99.9	0.1
Pan	415.7	415.5	0.2	0.1	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 13 DEC 1980 Sample No. 203

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 548.5 gms

Tare Wt. 347.1 gms

Wt. of Total Sample 201.4 gms

Sum of Retained Wt. 201.4 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	499.2	499.2	0.0			100.0
18 (0 Ø)	457.9	457.9	0.0			100.0
35 (1 Ø)	432.0	432.0	0.0			100.0
60 (2 Ø)	445.5	409.1	36.4	18.1	18.1	81.9
120 (3 Ø)	514.0	389.1	124.9	62.0	80.1	19.9
230 (4 Ø)	426.8	386.7	40.1	19.9	100.0	0.0
Pan	340.1	340.1	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 28 NOV 1980 Sample No. 164

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 571.0 gms

Tare Wt. 369.2 gms

Wt. of Total Sample 201.8 gms

Sum of Retained Wt. 201.7 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	499.2	499.2	0.0			100.0
18 (0 Ø)	457.8	457.8	0.0			100.0
35 (1 Ø)	432.9	432.9	0.0			100.0
60 (2 Ø)	443.8	409.1	34.7	17.2	17.2	82.8
120 (3 Ø)	504.4	388.4	116.0	57.5	74.7	25.3
230 (4 Ø)	437.6	386.9	50.6	25.1	99.8	0.2
Pan	356.5	356.1	0.4	0.2	100.0	0.0

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender Date 2 DEC 1980 Sample No. 153

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 558.4 gms

Tare Wt. 356.1 gms

Wt. of Total Sample 202.3 gms

Sum of Retained Wt. 202.3 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	494.8	494.8	0.0			100.0
18 (0 Ø)	457.7	457.7	0.0			100.0
35 (1 Ø)	432.7	432.7	0.0			100.0
60 (2 Ø)	435.0	408.9	26.1	12.9	12.9	87.1
120 (3 Ø)	513.0	388.6	124.4	61.5	74.4	25.6
230 (4 Ø)	437.7	385.9	51.8	25.6	100.0	0.0
Pan	356.1	356.1	0.0	0.0		

SIEVE ANALYSIS DATA SHEET
An Nafud Sand Samples

Tested by D. J . Faulkender Date 16 JULY 1981 Sample No. 218

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 557.9 gms
Tare Wt. 356.2 gms
Wt. of Total Sample 201.7 gms
Sum of Retained Wt. 201.7 gms
Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 ∅)	484.8	484.8	0.0			100.0
18 (0 ∅)	471.1	471.1	0.0			100.0
35 (1 ∅)	432.8	432.8	0.0			100.0
60 (2 ∅)	418.0	399.0	19.0	9.4	9.4	90.6
120 (3 ∅)	555.2	397.9	157.3	78.0	87.4	12.6
230 (4 ∅)	390.8	365.4	25.4	12.6	100.0	0.0
Pan	415.5	415.5	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J. Faulkender Date 16 July 1981 Sample No. 248

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 557.6 gms

Tare Wt. 356.2 gms

Wt. of Total Sample 201.4 gms

Sum of Retained Wt. 201.4 gms

Loss 0.0 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.8	484.8	0.0			100.0
18 (0 Ø)	471.1	471.1	0.0			100.0
35 (1 Ø)	432.8	432.8	0.0			100.0
60 (2 Ø)	399.6	399.0	0.6	0.3	0.3	99.7
120 (3 Ø)	568.3	397.9	170.4	84.6	84.9	15.1
230 (4 Ø)	395.8	365.4	30.4	15.1	100.0	0.0
Pan	415.5	415.5	0.0	0.0		

SIEVE ANALYSIS DATA SHEET

An Nafud Sand Samples

Tested by D. J . Faulkender　　Date 16 JUNE 1981　　Sample No. 228

Type of Sample Eolian Sand

Wt. of Total Sample + Tare 556.9 gms

Tare Wt. 356.2 gms

Wt. of Total Sample 200.7 gms

Sum of Retained Wt. 200.6 gms

Loss 0.1 gms

U. S. Standard Sieve Size	Retained			Percent Retained	Sum % Retained	Sum % Passing
	Wt. Sample + Sieve	Wt. Sieve	Wt. Sample			
10 (-1 Ø)	484.8	484.8	0.0			100.0
18 (0 Ø)	471.1	471.1	0.0			100.0
35 (1 Ø)	432.8	432.8	0.0			100.0
60 (2 Ø)	399.2	399.0	0.2	0.1	0.1	99.9
120 (3 Ø)	583.9	397.9	186.0	92.7	92.8	7.2
230 (4 Ø)	379.8	365.4	14.4	7.2	100.0	0.0
Pan	415.5	415.5	0.0	0.0	0.0	

A P P E N D I X B

Identification of Heavy Minerals from An Nafud Sand Samples by X-ray Diffraction

Identification of Heavy Minerals
from An Nafud Sand Samples

By: D. J. Faulkender Date: Rajab 2, 1401

FIELD NO.	X-RAY DIFFRACTION RESULTS
210	Dravite
210	Dravite
154	Dravite
154	Zircon
154	Dravite
161	Dravite
161	Rutile
154	Rutile
154	No Lines
154	Wilkeite
154	Wilkeite
161	Dravite
161	Rutile
161	Goethite
161	Zircon
161	Zircon
161	Dravite
154	Gorceixite
154	Dravite
161	Goyazite, Gorceixite
154	Epidote
161	Dravite

Identification of Heavy Minerals
from An Nafud Sand Samples

By: D. J. Faulkender Date: Rabi Thani 7, 1401

FIELD NO.	X-RAY DIFFRACTION RESULTS
210	Dravite
210	Hinsdalite
210	Dravite
210	Dravite
210	Zircon
210	Zircon
210	Goethite
210	Rutile
210	Hematite
210	Gahnite
210	Dravite

A P P E N D I X C

Heavy-Mineral Grain Count for 14 An Nafud Sand Samples

Heavy mineral grain count for 14 An Nafud sand samples, 200 grains per sample, ribbon method

Sample No.	Dravite	Epidote	Zircon	Goethite	Rutile	Rare Minerals	Opaque Minerals
035	71	38	25	6	8	6	46
039	4	26	103	31	4	6	26
141	80	20	36	14	8	4	38
143	54	18	42	20	16	6	44
151	14	43	29	26	18	8	62
154	22	40	21	21	8	6	82
161	84	23	47	8	4	7	27
162	24	16	48	16	14	6	76
164	101	23	16	8	8	6	38
180	72	43	41	8	10	4	22
181	80	36	25	12	0	4	44
203	43	17	32	5	0	3	100
210	84	29	35	9	4	3	36
228	81	29	31	3	3	5	48
Sub-Totals	814	401	531	187	105	74	689

Total Grains: 2800

A P P E N D I X D

Heavy-Mineral Frantz Fractions for 24 Paleozoic Sandstone Samples

Heavy mineral Frantz fractions for 24
Paleozoic sandstone samples

Sample No.	Quantity of sample used	Wt of sample in gms	Frantz Fractions (FF), Wt. in gms.							
			FF	gms	FF	gms	FF	gms	FF	gms
013	All	0.45	0.5M	0.10	1M	0.15	1NM	0.20		
032	All	0.20	0.5M	0.10	1M	0.05	1NM	0.05		
041	All	0.20	0.5M	0.05	1M	0.10	1NM	0.05		
042	All	0.80	0.5M	0.20	0.5NM	0.60				
043	All	0.25	0.5M	0.15	1M	0.05	1NM	0.05		
044	All	1.10	HM	0.10	0.5M	0.90	1M	0.05	1NM	0.05
045	1/4	3.65	0.3M	0.35	1M	0.20	1NM	3.10		
047	All	0.25	0.5M	0.15	0.5NM	0.10				
048	All	0.75	0.3M	0.05	0.5M	0.30	0.5NM	0.40		
051	All	1.90	0.2M	0.85	0.5M	0.55	0.5NM	0.50		
146	All	0.20	0.4M	0.05	0.4NM	0.15				
147	1/2	6.40	0.3M	0.35	0.6M	5.90	0.6NM	0.15		
148	1/8	11.90	0.5M	0.25	1M	1.80	1NM	9.80		
152	All	3.45	0.4M	0.70	1M	0.50	1NM	2.20		
172	All	7.95	0.3M	5.55	0.6M	1.85	1M	0.25	1NM	0.30
173	All	0.60	0.2M	0.03	0.8M	0.50	0.8NM	0.07		
211	All	0.85	0.3M	0.65	0.3NM	0.20				
281	All	0.25	0.4M	0.20	0.4NM	0.05				
301	1/16	8.50	0.25M	7.65	0.25M	0.15	0.8NM	0.65		
302	1/8	8.60	0.3M	7.95	0.3NM	0.65				
304	All	0.20	1M	0.15	1NM	0.05				
311	1/2	5.60	No	separates on Frantz						
312	All	0.20	0.5M	0.15	0.5NM	0.05				
1844203	All	0.40	0.5M	0.10	0.5NM	0.30				

HM - Removal by Hand Magnet
M - Magnetic current amperes
NM - Non-magnetic

APPENDIX E

Identification of Minerals from Paleozoic Sandstone Samples by X-ray Diffraction

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Rajab 10, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS Major Minerals	Minor Minerals	Trace Minerals
013	0.5 M	Dravite	Goethite, Rutile	Quartz, Epidote
013	1 M	Quartz	Dravite	Rutile, Epidote
013	1 NM	Quartz	Zircon	Rutile, Dravite
032	0.5 M	Dravite, Chromite	Mica (Muscovite? Phlogopite?)	Quartz, Kaolinite 1Md, Rutile
032	1 M	Quartz, Dravite	Kaolinite 1Md, Mica(Muscovite? Phlogopite?)	Rutile, Anatase
032	1 NM	Quartz	Rutile	Zircon, Kaolinite 1Md
041	0.5 M	Dravite, Chromite	Quartz, Rutile	Anatase, Hornblende, Mica(Muscovite?) Kaolinite 1Md
041	1 M	Dravite	Mica (Muscovite?), Quartz, Rutile	Zircon, Kaolinite 1Md, Hematite, Anatase
041	1 NM	Quartz	Rutile, Kaolinite 1Md	Zircon, Mica (Muscovite?), Epidote, Dravite, Hematite, Anatase
042	0.5 M	Dravite, Chromite	Quartz	Rutile, Kaolinite 1Md, Anatase
042	0.5 NM	Anatase	Rutile, Quartz	Zircon, Kaolinite 1Md, Ilmenorutile

M = magnetic NM = nonmagnetic

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Shabar 23, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS Major Minerals	Minor Minerals	Trace Minerals
043	0.5 M	Goethite	Anatase, Kaolinite 1Md	Quartz, Dravite, Rutile
043	1 M	Calcite, Kaolinite	Anatase, Quartz, Goethite, Rutile	Hematite, Dravite, Gorceixite
043	1 NM	Quartz	Kaolinite 1Md, Calcite	Anatase, Rutile, Dravite
044	HM	Goethite	Quartz	Kaolinite 1Md, Hematite
044	0.5M	Kaolinite 1Md, Goethtite	Anatase, Quartz	Quartz, Rutile
044	1 M	Kaolinite 1Md	Quartz, Rutile	Anatase, Zircon, Calcite, Dravite
044	1 NM	Quartz	Kaolinite 1Md, Zircon	Rutile, Calcite
045	0.3 M	Goethite, Anatase		Hematite, Quartz, Rutile, Dravite, Kaolinite
045	1 M	Anatase	Kaolinite, Quartz	Goethite, Rutile, Hematite
045	1 NM	Anatase	Quartz, Kaolinite 1Md	Rutile, Zircon
047	0.5 M	Dravite	-	-
047	0.5NM	Quartz	-	Dravite, Flourapatite

M = magnetic NM = nonmagnetic HM = hand magnet

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Ramadan 5, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS		
		Major Minerals	Minor Minerals	Trace Minerals
048	0.3 M	Anatase	Dravite	Goethite, Quartz, Muscovite, Rutile
048	0.5 M	Dravite	Anatase, Quartz	Rutile, Mica (Muscovite?)
048	0.5 NM	Quartz, Rutile	Titanite, Anatase, Zircon	Hematite, Siderrite, Dravite
051	0.5 M	Quartz, Kaolinite 1Md	Hematite, Anatase	Rutile, Calcite
051	0.2 M	Quartz	Kaolinite, Hematite	Anatase, Rutile
051	0.5 NM	Anatase, Quartz	Rutile, Kaolinite	Dravite, Chromite, Zircon, Calcite
147	0.6 M	Kaolinite 1Md, Dickite 2 M1	Mica (Muscovite), Hematite, Rutile	-
147	0.6 NM	Quartz	Kaolinite, Goethite, Hematite, Rutile	Calcite, Anatase
147	0.3 M	Goethite	Quartz, Kaolinite, Hematite	Zircon, Dravite, Anatase
148	0.5 M	Anatase, Rutile	Diopside, Dravite, Chromite	Dolomite, Quartz, Mica (Muscovite)
148	1 M	Dolomite	Calcite	-
148	1 NM	Dolomite	Calcite	-

M = magnetic NM = nonmagnetic

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Ramadan 5, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS		
		Major Minerals	Minor Minerals	Trace Minerals
281	0.4 M	Dravite	Quartz	Goethite Hematite Kaolinite Muscovite
281	0.4 NM	Quartz, Rutile Kaolinite	Zircon, Anatase, Dravite	Hematite Gorceixite
301	0.25 M	Goethite	Quartz, Hematite	Dravite
301	0.8 M	Goethite	Quartz, Hematite	Calcite Kaolinite Dravite
301	0.8 NM	Quartz	-	Calcite, Hematite, Zircon
302	0.3 M	Quartz, Goethite	Kaolinite	Dravite
302	0.3 NM	Quartz, Goethite	Kaolinite, Hematite	Dravite
304	1 M	Quartz, Hematite	Kaolinite, Rutile, Anatase, Goethite	Muscovite, Dravite, Calcite
304	1 NM	Quartz, Anatase	Rutile	Muscovite, Kaolinite, Calcite, Dravite, Zircon, Hematite, Goethite
311	0.5 M	Quartz	Calcite, Goethite	Kaolinite, Hematite
312	0.5 M	Goethite	Quartz, Dravite	Hematite, Rutile, Anatase, Calcite
312	0.5 NM	Quartz, Rutile	Anatase, Zircon	Goethite Hematite Dravite

M = magnetic NM = nonmagnetic

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Ramadan 5, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS: Major Minerals	Minor Minerals	Trace Minerals
152	1 M	Quartz	Flourapatite, Goethite	Dravite, Gorceixite, Calcite, Flourite
152	0.4 M	Quartz, Goethite	Dravite, Chromite	Gorceixite, Anatase, Hematite
152	1 NM	Flouropatite	Quartz	Hematite, Zircon, Goethite
172	1 M	Quartz, Anatase	Rutile, Goethite	Hematite Kaolinite Dravite
172	0.3 M	Quartz, Goethite	Kaolinite, Rutile	Anatase, Dravite
172	0.6 M	Quartz, Goethite	Kaolinite, Rutile	Anatase, Dravite
172	1 NM	Quartz, Zircon	Flour patite	Rutile, Anatase, Hematite
178	0.2 M	Goethite, Hematite	Kaolinite	Zircon, Zoisite
178	0.8 M	Quartz, Goethite	Kaolinite	Muscovite, Dravite, Hematite, Anatase, Zircon
178	0.8 NM	Quartz	Zircon, Kaolinite, Rutile, Titanite	Dravite, Anatase, Muscovite, Hematite
211	0.3 M	Dravite, Hematite	Quartz, Kaolinite	Muscovite, Zircon, Rutile, Anatase
211	0.3 NM	Albite	Morderite?	Hematite

M = Magmetic NM = nonmagnetic

Identification of Minerals from
Paleozoic Sandstone Samples

By: D. J. Faulkender Date: Ramadan 5, 1403

Field No.	Frantz Fraction	X-RAY DIFFRACTION RESULTS Major Minerals	Minor Minerals	Trace Minerals
146	0.4 M	Dravite, Chromite	-	Quartz Kaolinite Titanite Anatase, Muscovite
146	0.4 NM	Quartz, Anatase	Kaolinite, Rutile	Dravite Goethite Muscovite Zircon
184	0.5 M	Dravite, Chromite	Quartz, Kaolinite,	Muscovite Calcite Horneblende
184	0.5 NM	Quartz, Anatase	Rutile, Kaolinite, Zircon	Calcite Hematite Dravite

M = magnetic NM = nonmagnetic

SOURCE OF SAND FOR AN NAFUD SAND SEA,

KINGDOM OF SAUDI ARABIA

by

DeWayne J. Faulkender

B.S., Kansas State University, 1959

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1986

An Nafud sand sea covers about 70,000 km^2 in north-central Saudi Arabia. Major dune forms of An Nafud include linear, transverse, barchanoid ridge, and massif (superimposed star dunes). An Nafud sand-sheet forms a wedge of sand that lies on the gently northeast-dipping Phanerozoic surface.

An Nafud sand sea is composed dominantly of a stable dune system. Both the stability of the major dune system and the small percentage of active dunes in the modern environment indicate a significant decrease in the average velocity and frequency of sand-moving winds since the time of stable-dune deposition. Comparison of modern wind directions with dune trends indicates that the southwesterly and westerly winds responsible for dune formation in An Nafud sand sea are no longer prevailing winds.

Radiocarbon dating of calcareous lake deposits defines at least two episodes of pluvial activity and minimal eolian activity: between about 32,000 yrs and 24,000 yrs BP and during the Holocene between about 8,500 yrs and 5,000 yrs BP. The main dune system overlies the 32,000 yrs to 24,000 yrs BP lake deposits, whereas Holocene lake-beds are found in modern interdune environments.

Paleozoic sandstone strata lie to the west and southwest of An Nafud sand sea. Results from the study of dune orientation, sand thickness, An Nafud sand samples in relation to sand-grain size and sorting values, and heavy mineral distribution within An Nafud sand sea support the concept that the dune-forming wind was from the west-southwest.

All Paleozoic sandstone formations are quartz arenites. The best correlation between An Nafud heavy mineral suite and each Paleozoic sandstone formation heavy mineral suite is with the heavy mineral suite identified in the Tabuk Sandstone. The exposure of the Tabuk Sandstone is larger in areal extent than the other Paleozoic sandstone formations, and this large area of exposure lies to the west and west-southwest of An Nafud sand sea.

The conclusions from this study are: (1) the evidence strongly suggests that the primary source of sand for An Nafud sand sea was the Tabuk Sandstone, (2) the dune-forming wind was from the west-southwest, (3) An Nafud sand sea began to develop during the late Pleistocene, (4) the average wind velocity has decreased in the recent past, and (5) An Nafud sand sea is, at the present time a stable sand sea.