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RECONNAISSANCE REPORT ON THE GEOLOGY AND HYDROLOGY OF THE WESTERN PART OF THE PROVINCE OF FEZZAN, UNITED KINGDOM OF LIBYA

by

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Not Reviewed for Conformance with Standards and
Nomenclature of the Geological Survey

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By H. A. Whitcomb

ABSTRACT

The area described in this report comprises the western part of the Province of Fezzan, United Kingdom of Libya. It lies almost entirely within the Libyan Sahara and covers about 450,000 square kilometers (175,000 square miles) of barren sand and rock. The Fezzan occupies a large erosional basin in which the climate and topography are typical of an arid desert environment. The report contains a map showing the major physiographic features. The population of the Fezzan, about 50,000 persons, is concentrated in the few isolated oases which form long, thin, broken lines diametrically across the region.

The Fezzan basin is underlain by a great thickness of sedimentary rocks which range in age from Cambrian to Quaternary and lie on gneisses and crystalline schists of Precambrian age. Geologic information obtained from reconnaissance studies of the region indicates some major breaks in the stratigraphic sequence due to the absence of, or inability to distinguish, late Paleozoic and early Mesozoic strata. The stratigraphic section is composed for the most part of clastic deposits ranging from marine claystones to continental sandstones and conglomerates. Chemical sediments, limestones and marls, make up only a small part of the sequence. The stratigraphic section is best exposed in the northern and southwestern parts of the map area where older rocks, elevated by monoclinal flexures, are exposed in escarpments carved by erosion of wind and water. The report includes a map showing the location, areal extent, and relationships of geologic formations occurring in the Fezzan. The basal stratigraphic unit consists of a thick series of sandstones and conglomerates, apparently of continental origin. Because of the absence of definitive fossils, these deposits are assigned a Cambrian and Early Silurian (Ordovician) age. Upper Silurian (Silurian) strata are preponderantly marine claystones with alternating thin shaly sandstones and claystones in the uppermost part. Overlying the marine clays is a second thick sequence of sandstones and conglomerates which are considered to be in

part marine and in part continental in origin. This series is tentatively assigned to the Upper Devonian. Lower Carboniferous (Mississippian) limestones, sandstones, marls, and clays comprise the uppermost unit of the Paleozoic deposits. The Mesozoic is represented by the Lower Cretaceous Nubian series, continental deposits of interbedded conglomeratic sandstones and claystones, and Upper Cretaceous marine limestones, sandstones, and marls. Middle Eocene limestones and marls are the youngest consolidated sediments in the map area. Quaternary deposits consist of alluvium in the uadi valleys, eolian sands of the dune and sand-plain areas, and the gravels of the stony deserts.

The major source of water at the present time in the western part of the Fezzan is the Quaternary sand and gravel which compose the alluvium of the uadi valleys. The major undeveloped sources of water in the Fezzan are the consolidated sandstones and conglomerates of Cambrian and Early Silurian (Ordovician) and Devonian ages and the Nubian series of interbedded conglomeratic sandstones and clays of Early Cretaceous age. Water encountered is generally under considerable artesian pressure which, in some places, is sufficient to cause water to flow at the surface. The report includes a map showing areas in which water may be obtained from artesian aquifers by relatively shallow drilled wells.

The rocks underlying the Fezzan form a large, nearly circular structural basin, the northern, eastern, and southwestern margins of which generally coincide with the corresponding borders of the geologic map. This basin forms a great artesian reservoir the center of which is believed to lie near the south-central border of the map. Recharge into the aquifers is from rare precipitation falling upon the upturned edges of strata which form the higher elevations of the region and generally mark the perimeter of the basin. Areas of recharge are extensive, and a large part of the rainfall reaching their surfaces is quickly absorbed into the permeable soil cover and thence, in part, moves downward into the underlying sandstones.

Supplies of surface water are practically lacking in the Fezzan; consequently, the only dependable source of water is the subterranean supplies occurring in unconsolidated alluvial deposits and artesian water in the deeper lying consolidated aquifers. This water is customarily obtained by digging relatively shallow wells in the alluvium or by drilling into the deeper artesian aquifers. Water in the dug wells is generally raised by means of a rope and bucket. Many of the drilled wells flow, and, because of lack of control, are a means of great waste of ground water in some areas. The artesian water is used for both irrigation and domestic purposes.

The quality of ground water in the alluvium varies appreciably both regionally and locally; however, in most places it is suitable for both domestic use and irrigation. Water in the artesian strata, where it is not contaminated by leakage of alluvial water into the well, is generally good to excellent for all purposes according to commonly accepted standards. A comparison of the quality of water occurring in the three major artesian aquifers shows that water from the Cambrian and Lower Silurian (Ordovician) sandstones has a very low concentration of all dissolved minerals. The Devonian sandstones of the Chatti valley contain water that is quite similar chemically to that in the Cambrian-Lower Silurian (Ordovician) series, except for an appreciable increase in the chloride content. Water in both aquifers is considered excellent for domestic and irrigation use. Water in the Lower Cretaceous Nubian series, in some places, contains concentrations of dissolved minerals that are too great to be desirable in potable water. It is believed, however, that this is due to the infiltration of highly saline alluvial water into the sampled well, and that the water contained in Nubian sandstones is generally of good quality for all purposes.

Ground-water supplies are adequate almost everywhere in the Fezzan for the present needs of its inhabitants. Increased supplies may be developed in most areas by the construction of additional dug or relatively shallow drilled wells. The yields of many existing wells probably can be increased by cleaning and deepening. In most areas the development of ground-water supplies can be substantially expanded with little effect upon the water table in the alluvium or the head of the artesian aquifers. However, careful supervision and control of future large-scale developments would be necessary to prevent overdevelopment in areas where ground-water supplies may be limited. Possible means of control of flowing wells in one of these areas, the Chatti Valley, are outlined. A limited program of exploratory drilling would be of value in the development of healthful and dependable community water supplies. The hydrologic information obtained in such a program could be used to determine the feasibility of drilling for irrigation water in each area tested.

INTRODUCTION

LOCATION OF AREA

Libya is the name given by the Italians to the formerly separate and autonomous states of Tripolitania, Cyrenaica, and Fezzan after their seizure from the Turks in 1911. The country was governed by the Italians from the provincial capitols of Tripoli, Benghazi, and Sebha, respectively. In November 1950, the three provinces, by common consent, joined together to form the United Kingdom of Libya under the sovereign rule of King Idris I. On December 24, 1951, Libya was declared an independent nation under the sponsorship of the United Nations.

Libya lies between Egypt on the east and Tunisia and Algeria on the west. It is bordered on the north by approximately 2,000 kilometers (km.) - 1,250 miles (mi.) - of Mediterranean coastline; its unmarked southern border lies some 1,500 to 2,000 km. (950 to 1,250 mi.) to the south within the confines of the Sahara Desert. (See figure 1.) The area of the country is estimated to be about 1,500,000 sq. km. (575,000 sq. mi.).

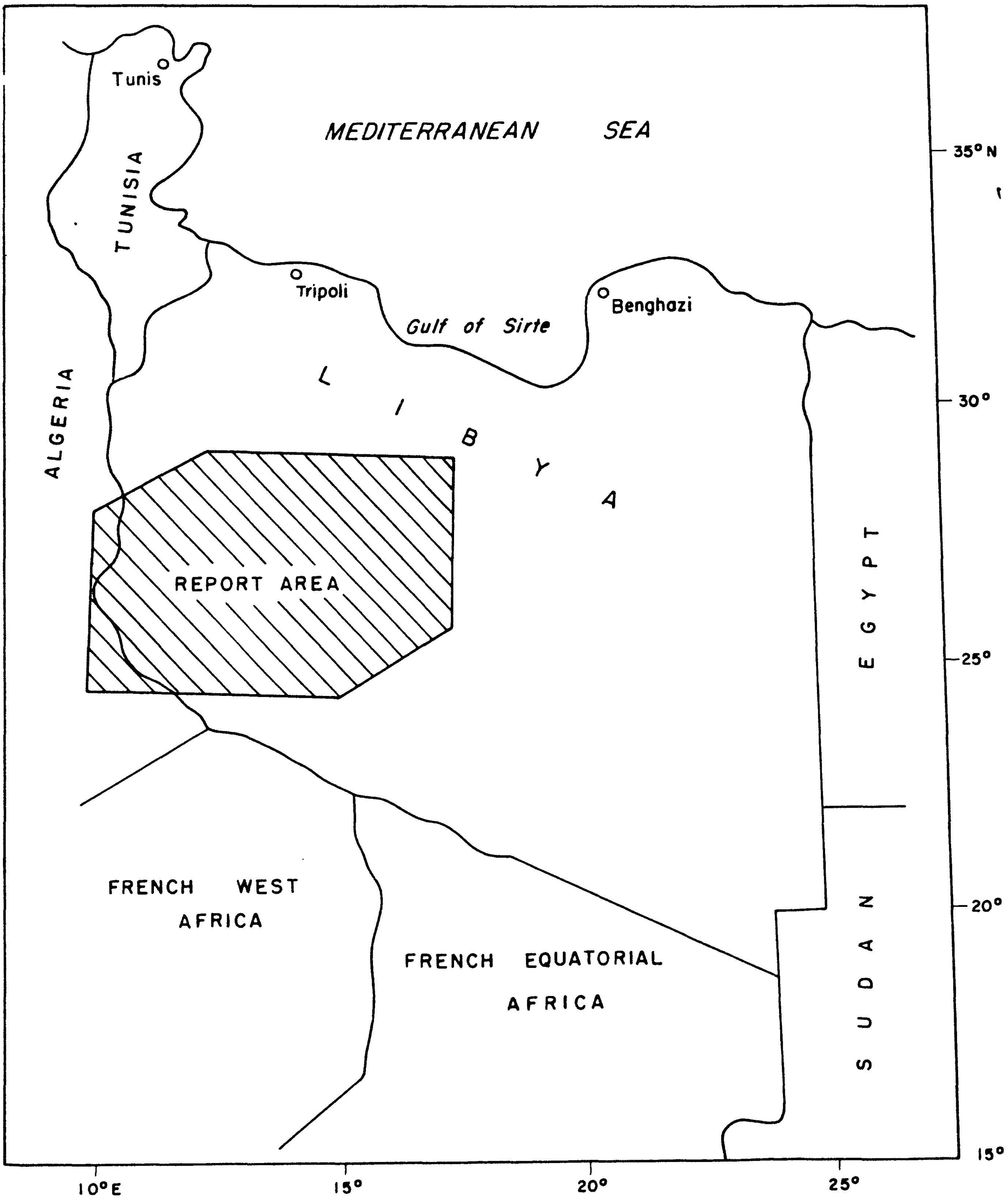

Figure I.— Regional map showing area included in report.

PURPOSE AND SCOPE OF INVESTIGATION

Early in 1952 the United States Government sent a small group of technical advisors to Libya to aid in the reconstruction of the country and promote its future economic development. During the ensuing years the amount of economic and technical assistance was increased greatly under the direction of the United States Operations Mission (USOM). It was not until the latter part of 1955, however, that the program of ground-water development of the USOM Division of Natural Resources was expanded to include the remote areas of the Province of Fezzan.

At the request of the governor of the Province of Fezzan, a brief visit was made in July 1955 to the oasis of Sebha, the provincial capital, for the purpose of discussing with government officials a program for the development of ground-water resources in areas where water was either lacking or unsuitable. Plans were formulated for a reconnaissance study of the area. Work was started immediately but, because of the extremely high temperatures prevailing during the summer months, intensive field work was postponed until late October of that year. Between October 1955 and May 1956 a total of approximately 3 months was spent in a reconnaissance study of the geology and hydrology of the western part of the Fezzan Province. Owing to the great distances involved, rigorous traveling conditions and attendant mechanical deterioration of vehicles, acute problems of supply of gasoline and repair parts, and occasional difficulties in obtaining qualified personnel, a relatively small portion of this time was devoted to the unhindered study of geologic and hydrologic conditions.

The work was under the general supervision of A. N. Sayre, Chief, Ground Water Branch, U. S. Geological Survey, and T. E. Eakin, Chief, Overseas Programs, Ground Water Branch, U. S. Geological Survey, and under the immediate supervision of D. J. Cederstrom, Chief of the Geological Survey field party serving as technical advisors on geologic and hydrologic studies to the USOM to Libya.

PREVIOUS STUDIES

The Fezzan has been visited several times in the past 100 years by persons who were interested in the natural and geologic history of the area. These earlier observers in the Fezzan have contributed much to the general geologic and hydrologic knowledge of the region. Desio (1936), in his work for the Italian Government during the Italian occupation of Libya prior to World War II, with the help of others, laid the basic ground work for the further study of the geology of southern Libya. Geologic knowledge was further augmented by the paleontologic studies of the late Dr. Chiesa, for many years director of the Libyan Museum of Natural History at Tripoli. A recent report on the geology and hydrology of the Fezzan by Muller-Feuga (1954) is of considerable value, and the information included in it has been used by the writer of this report to increase his knowledge of geologic and hydrologic conditions in areas that time did not permit visiting. A report by Le Franc (1956) published by the Libyan Public Development and Stabilization Agency, Tripoli, contains detailed hydrologic data on the oases of the southwestern Fezzan.

ACKNOWLEDGMENTS

M. Demenais, engineer representative at Sebha, Fezzan, of the Libyan Public Development and Stabilization Agency (LPDSA), was generous with both his time and extensive knowledge of the region and supplied the author with all available records on past ground-water developments in the Fezzan. He also made available to the author aerial photographs of the major oases areas.

Cavalieri Viali, chief of the Well Boring Section of the Libyan Department of Agriculture, provided the writer with much pertinent and interesting information from his vast store of knowledge of the Fezzan.

The writer wishes to acknowledge the friendliness and hospitality with which he was greeted by the government officials and people of the Fezzan and to extend his thanks to those who did much to make his work easier and his stay more pleasant.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

The province of Fezzan is a poorly defined and relatively unknown region which occupies the southwestern part of the Kingdom of Libya; it comprises more than one-third of the total area of the country. (See figs. 1, 2.) The major portion of the Fezzan lies between 22° and 28° north latitudes and between 10° and 18° east longitudes. It is bordered on the north by Tripolitania, on the east by that part of Cyrenaica designated on maps as the Libyan Desert, on the south by French Equatorial Africa, on the southwest by French West Africa, and on the west by Algeria. The area discussed in this report consists of that part of the Fezzan lying west of 16° east longitude and between 24° and 28° north latitudes and comprises about 450,000 sq. km. The place names mentioned in the text that follows can be found by referring to fig. 2 or to plates 1 and 2.

Lying almost entirely within the vast area designated as the Sahara Desert, the Fezzan is essentially a land of sand and barren rock where the monotony is broken only rarely by the welcome green of desert oases.

A relatively small part of the Libyan Sahara is composed of sandy desert. The major portion consists of broad, flat areas commonly carpeted by angular rock debris or sand-polished, rounded pebbles. The sandy deserts consist of the "edeien," areas where the sand forms a nearly flat or gently undulating surface, and the "ramla," areas in which the sand has been heaped into dunes and dune masses. (See figures 3 and 4.) The differences in topography are probably due to variations in texture of the sands, the amount of sand available, and the direction and force of the prevailing winds. Rocky deserts (hamada) occur in areas where the bedrock is exposed and generally form the high, flat-lying surfaces of the region. (See figure 5.) The fragmental rock cover is derived from weathering and disintegration of the underlying strata. Wide expanses of flat, smooth desert pavement (serir) generally are found in areas where the underlying alluvium consists of clastics of a wide range of grain sizes. (See figure 6.) Strong desert winds sweep away the lighter fine-grained material leaving a closely packed skim of small rounded pebbles carpeting the surface. (See figure 6a.) The surface is

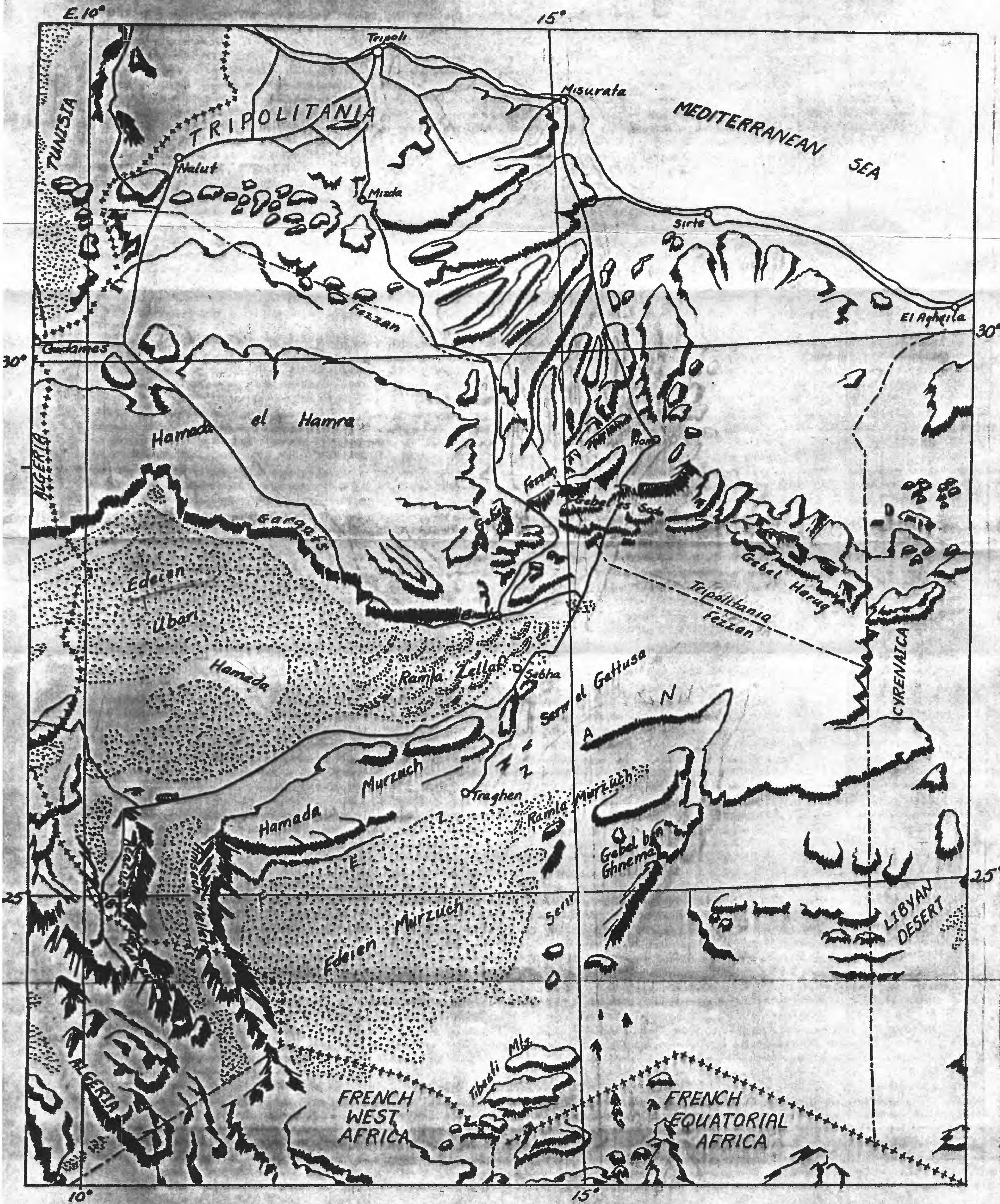

Figure 2.--Map showing major physiographic features of western Libya.

(Adopted by H. A. Whitcomb from World Aeronautical Charts, U.S. Air Force, ed. of 1948, rev. 1951; and Carte Michelin Sahara, no. 152.)

Figure 3.--The smooth, rolling surface of the "edeien" is excellent for motor travel in some areas. However, relatively high speeds must be maintained and stops made only when absolutely necessary.

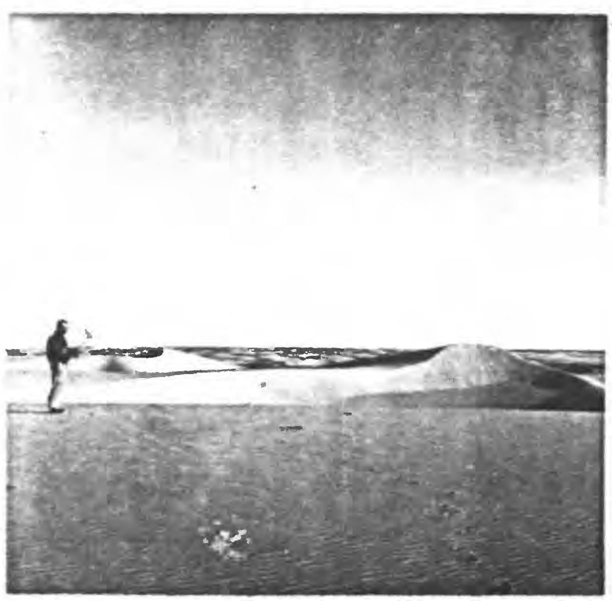

Figure 4.--Dunes of the "ramla" are constantly moving in the direction of the strong prevailing winds. The ramla is traversed only by camel or on foot.

Figure 5.--The hamada surface generally is rough and rocky and hard on both vehicles and occupants.

Figure 6.--The flat smooth surface of the serir provides an excellent automobile route several kilometers wide.

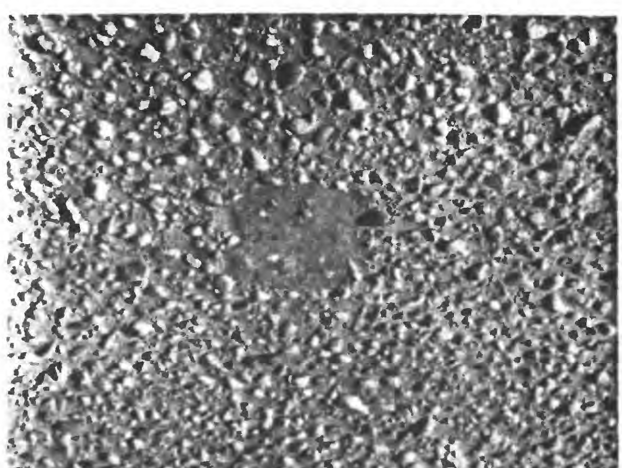

Figure 6a.--A close-up photograph of the gravelly surface of the serir.

firm and forms a broad highway, several miles wide in places, that is ideal for automobile travel. However, frequent shallow drainage channels or areas of deflation are a menace to the unwary driver traveling across the serir at high rates of speed.

The sand areas occur as two elongated lobes oriented generally northeast-southwest, lying near the center of Fezzan province. One, Edeien Ubari, and its eastern extension, Ramla Zellaf, lies between Brach and Ubari, and the other, Edeien Murzuch, lies south of Ubari and Murzuch. The two sand regions are separated from each other by an elevated rock and pebble-strewn plateau, the western part of which is called Hamada Murzuch, and the eastern part Serir el Gattusa.

Hamada el Hamra occupies approximately the northern third of the Fezzan and extends with almost unbroken horizon from the eastern to the western border. Two more or less contiguous lava-capped masses, Gebel es Soda and Gebel Fezzan, dominate the south-central part of the hamada and rise nearly 400 meters (m.) or 1,350 feet (ft.) above its surface. Hamada el Hamra is separated from Edeien Ubari and Ramla Zellaf by a generally east-west-trending escarpment known as the Gargafs, which extends from a point east of Brach westward beyond the limits of the mapped area.

The eastern part of the map area is dominated by Gebel Harug, which stands nearly 300 m. above the surrounding plateau.

South of Edeien Ubari a second line of escarpments separates the sandy desert from Hamada Murzuch. The escarpment extends in an almost unbroken line from Sebha west southwestward nearly 400 km. to a point where it is incised by the north-trending valley of Uadi Tannezzoft. Here the escarpment trends sharply to the south to form the easterly dipping cuestas which comprise the steep western flanks of gebels Acacus and Tadrart. West of the Acacus-Tadrart Mountains, and separated from them by the valley of Uadi Tanezzoft, lie the highlands of Tassili n Ager.

The western part of the region is composed essentially of broad sandy and stony deserts which extend westward into Algeria and northwestward into southeastern Tunisia.

Flanking the sand areas and, in places, lying within them are found the oases, the only permanently inhabited areas in the Fezzan. The oases consist of isolated areas of vegetation generally arranged in long, relatively narrow broken lines having a predominantly east-west orientation. They occur where the water table is sufficiently near the surface of the land to support the growth of date palms and to permit digging shallow wells to supply water for the irrigation of a limited variety of cereal and vegetable crops and to support a small number of domestic animals.

Perhaps the heaviest concentration of population in the Fezzan is in the oases which occupy the valley of Uadi Chatti which extends from Debdeb, east of Brach, to Uenzerich. Second in importance are the oases in that part of Hofra and Cherguya valleys lying between Murzuch and Traghen. A long line of oases extends along the southern margin of Edeien Ubari, occupying the valley of Uadi el Agial. Several large oases lie west of the road from Sebha to the intersection with the road leading to Brach. In the southwest corner of the Fezzan are the oases of Gat and el Barcat. There are several small isolated oases lying within the confines of both Edeien Ubari and Edeien Murzuch. These oases are inaccessible except on foot or by camel.

In areas where the level of the ground water is sufficiently close to the land surface to permit the movement of water upward into the zone of evaporation, large tracts of salt flats (sebhkas) are formed. The salt flat in the vicinity of Edri covers over 50 sq. km. Large sebkhas also occur in the Hofra-Cherguya valleys between Murzuch and Traghen. There is a large deposit of salt a short distance south of Gat on the road to el Barcat. The sebkhas are the source of most of the salt used by the natives of the Fezzan.

Altitudes in the Fezzan, established barometrically by the French Military Engineers, are based upon an arbitrary altitude of 400 m. for a point near the airport at Sebha. From this reference point altitudes have been established at frequent intervals along the main routes of travel. Altitudes of strategic points along the road traversing the Chatti valley range from 313.12 m. at Brach to 295.87 m. at Gorda and to 340.90 m. at Edri. Altitudes along the road between Sebha and Murzuch reach a high of 464.22 m. about 20 km. south of Sebha, and from this point gradually decline to 413.58 m. at Murzuch. In the Hofra-Cherguya valleys altitudes decline eastward from Murzuch to 383.38 m. at Traghen and then increase slightly to 389.15 m. at Umm el Araneb. The altitude at Zuila is approximately equal to that at Traghen. The range of altitudes in the valley of Uadi el Agial is only about 20 m., from 420.76 m. at el Abiad to 443.64 m. at Ubari. The height of the land surface along the road from Sebha northward to the junction with the road to Brach gradually declines to an altitude of 345.64 m. a short distance north of Umm el Abid. The altitude is approximately 650 m. where the road passes over the Acacus Mountains about 25 km. west of Serdeles. From this high point altitudes gradually decline to about 650 m. at Gat in the southern end of the valley of Uadi Tanezzoft. On the crests of the Tassili n Ager and the Tadrart Mountains altitudes of 1,900 and 1,500 m., respectively, have been recorded.

The Fezzan is a part of the great interior drainage basin which comprises much of the Sahara Desert. Centuries of scanty rainfall have resulted in the abandonment of former drainage systems to destruction and concealment by the erosional and depositional action of strong desert winds. Vestiges of an old drainage system are still apparent in the western part of the Fezzan. The orientation of the drainage channels indicates that surface runoff, at one time, moved generally to the east or east-northeast. No perennial drainage exists within the Fezzan at the present time; intermittent runoff seldom occurs except at the higher elevations near the crests of the Tassili n Ager and the Acacus-Tadrart and Tibesti Mountains where there are occasional heavy, but generally short-lived, rainstorms. However, this runoff seldom reaches the floor of the encompassing desert basin.

CLIMATE

The climate of the Fezzan is arid. Rain falls only at rare intervals and varies both as to location and time of year. Some areas report that no rain has fallen in several years, whereas records kept at Fort Leclerc, Sebha, reveal that usually some rain falls each year, generally during March, April, and May. For the 5 years during which these records were kept the annual precipitation ranged from a maximum of 101 mm. (4 in.) to a minimum of 15 mm. (0.5 in.) and averaged 68 mm. (approximately 3 in.). The relative humidity of the Fezzan is extremely low, probably averaging less than 20 percent; however, observations made at Sebha and Brach indicate a surprisingly high humidity, with average maximum of 42 percent and average minimum of 21 percent. At times the humidity rises as high as 90 percent and, on rare occasions, heavy fogs have been reported in the Sebha and Brach Oases. Undoubtedly, the high humidity occurring in some of the oasis areas is due to the transpiration of relatively heavy growths of vegetation supplemented by evaporation from the surfaces of water in open wells, irrigated plots, and, in the case of Sebha, perennial saline lakes.

According to Muller-Feuga (1954, p. 15), temperatures in the western Fezzan range from about 40°C. (105°F) average maximum during the summer to about 2°C (35°F) during the winter months. Differences between the day and night temperatures are extreme and the strong desert winds usually increase the discomfort caused by these extreme temperatures. Winds blowing from the great desert area lying to the south are intensely hot during the summer months and are often piercingly cold in the winter.

PEOPLE

The inhabitants of the Fezzan are of several racial stocks which have become somewhat intermixed throughout the years. The Tuaregs and the Berbers have been supplemented by Negroes, who have come voluntarily, or have been brought involuntarily as slaves, from French Equatorial and French West Africa. The Tubus from the "Ghost Mountains" of Tibesti make seasonal journeys northward to Gatrun and Murzuch to trade handicraft and animals for articles manufactured locally or shipped in from Tripoli. Governed as they are by a desert environment, and dependence upon an oasis economy, there is little opportunity for the inhabitants to lead the nomadic life common in Tripolitania and northern Cyrenaica. Each oasis is almost completely self-sufficient, raising its own grain, vegetables, and a few animals and occasionally manufacturing simple handicraft articles for trade between villages.

According to the census of 1948 the population of the Fezzan is estimated to be between 40,000 and 50,000. Since World War II apparently there has been a migration of a large percentage of the male population northward, drawn by the inviting opportunities offered by the expanding economy of Tripolitania. As a result, the women are left at home to care for the small farms. It is reported that in the oases of Murzuch and Traghen, the present population is nearly 80 percent female.

The people are friendly, courteous, and hospitable. They are eager for help and receptive to anything that will improve their present situation. However, their cooperation is somewhat limited by their lack of experience and technical understanding, adherence to customs and traditions, and natural resistence to change.

GEOLOGY

DESCRIPTION OF STRATIGRAPHIC UNITS

Rocks exposed in the western part of the Fezzan range in age from the Precambrian gneisses and schists found in the Tibesti Mountains and the Tassili highlands to the unconsolidated Quaternary sands and gravels which form much of the desert basin.

The sedimentary rocks throughout the Fezzan are preponderantly sandy and are considered to be predominantly continental in origin. A generalized description of the age, thickness, and water-bearing character of the geologic formations in the Fezzan is shown in table 1. The areas of outcrop of the formations exposed in the Fezzan are shown in plate 1.

Table 1.--Generalized section of the sedimentary deposits and their water-bearing characteristics, western part of the province of Fezzan, Libya.

(After Desio, 1939; Muller-Feuga, 1954; and LeFranc, 1956.)

ystem 1/	Series 1/	Thickness (meters)	Physical characteristics	Water-bearing character
aternary	Recent and Pleistocene (?) Unconformity	0-30+	Unconsolidated sands and gravels of uadi deposits; moving sands of dune areas; dormant sands of sand plains; residual gravels of gravel plains; loosely consolidated sands, clays and marls of lacustrine origin.	Yield generally small (2 cubic meters per hour, or 2 mc/hr) to moderate (10 mc/hr) amounts of water to shallow dug wells. Major source of water for existing wells in Fezzan. Quality of water generally suitable for domestic use, but poor in some areas.
ertiary	Middle Eocene Unconformity	0-30+	Marine sandy limestone, clay, marl, and thin calcareous sandstone; interbedded.	Probably unproductive. No wells in area known to penetrate Eocene deposits.
retaceous	Upper Cretaceous	0-50+	Marine limestone and marls, interbedded, and some thin sandstone and gypsum.	Probably unproductive. No wells in area known to penetrate Upper Cretaceous deposits.
	Lower Cretaceous (Nubian series) Unconformity	300-500+	Continental deposits of conglomeratic sandstone and clay, interbedded.	Yield moderate (10 mc/hr) to large (100 mc/hr) amounts of water to dug and shallow drilled wells. Drilled wells in eastern part of Hofra valley flow. Quality of water generally good to excellent for all uses.

Table 1.--Generalized section (Con.)

System 1/	Series 1/	Thickness (meters)	Physical characteristics	Water-bearing character
Carboniferous: Lower Carboniferous (Mississippian)	Visean (Upper Mississippian)	0-200±	Marine limestone, sandstone, clay and marl, interbedded, and some gypsum.	Probably relatively unproductive. No wells known to penetrate Visean series.
	Tournasian (Lower Mississippian)	100-150±	Marine and continental sandstone and clay, interbedded, and extensive ferruginous beds.	Yield moderate supplies of water to deep dug wells in the Chatti Valley. Quality of water is generally suitable for domestic use.
	Unconformity(?)			
Devonian	Upper(?) Devonian	200-300	Marine(?) and continental sandstone and conglomerate and some clay, interbedded.	Yield large amounts of water to drilled wells in the Chatti Valley. Water generally flows. Quality of water good for all uses.
	Unconformity(?)			

Table 1.--Generalized section (Con.)

	System 1/	Series 1/	Thickness (meters)	Physical characteristics	Water-bearing character
Cambrian to Silurian	Upper Silurian (Silurian)		250±	Marine clay containing graptolites; continental sandstone and clay, interbedded, in upper part.	Upper sandstones may transmit some water, but generally lie below practicable drilling depth.
	Lower Silurian (Ordovician) and Cambrian		400-600	Continental(?) sandstone and conglomerate, interbedded claystone in lower part.	Yield moderate supplies of water to shallow dug wells in Gat-el Barcat area. Water generally rises to, or a short distance below, land surface. Will probably flow in large amounts from relatively shallow drilled wells in low-lying areas. Quality of water is excellent for all uses.

1/ European terminology given priority, American enclosed in parentheses.

SEDIMENTARY ROCKS

Cambrian and Lower Silurian (Ordovician) Systems

The thick sequence of sandstone which immediately overlies the Precambrian basement rocks is well exposed in the Gat area and on the eastern flank of the Tassili n Ager uplift to the west. It is reported to lie in discordant contact upon the Precambrian gneisses and schists. The sandstone is overlain with apparent conformity by the Upper Silurian clays. The sandstone is generally white to pale reddish brown on the fresh surface, and dark brown to nearly black on weathered surfaces. The texture differs greatly from place to place, the sand grains grading, both horizontally and vertically, from fine to coarse. In places the deposits are coarsely conglomeratic. Under the hand lens the grains appear to be generally subangular to subrounded. The cement is commonly calcareous, ranging from fairly firm to weak, but, in places, the cement is siliceous. The sandstone is thick-bedded and massive in its upper part and thin-bedded to shaly below. Thin beds of claystone are interbedded with the sandstones of the basal section. Cross-bedding is apparent throughout most of the formation, and ripple marks and shrinkage cracks are common.

In the Gat area, with the exception of the sandstone butte upon which the fort is built, the Cambrian and Lower Silurian (Ordovician) sandstones weather to form a relatively smooth undulating surface, generally covered by a layer of sand of varying thickness. However, photographs taken of Cambrian and Lower Silurian deposits exposed in the Tibesti area show them forming steep high cliffs and rounded knobs above the underlying Precambrian. (See Figure 7.) The sandstone series has been estimated to be between 400 and 600 m. thick. Readings taken on the overlying Upper Silurian (Silurian) clays indicate a regional dip of 2° to 3° to the northeast.

In more recent studies than those of Desio, Muller-Feuga (1954, p. 23) and Le Franc (1954, p. 10) have both placed the age of these deposits as Early Silurian (Ordovician). In the absence of fossil evidence, there appears to be little basis for a distinction between Cambrian and Lower Silurian (Ordovician) strata. In this report the sandstone series lying between the Precambrian gneisses and the Upper Silurian (Silurian) clays are designated as undifferentiated Cambrian and Lower Silurian (Ordovician) deposits.

The upper sandstones in this series yield water to shallow wells in the Gat-el Barcat area.

Figure 7.--A view of Cambrian-Lower Silurian (Ordovician) sandstones exposed south of the map area in the vicinity of Uau el Chebir. Interbedded clays appear in the lower slope near base of series.

Upper Silurian (Silurian) System

The shaly marine clays of the Upper Silurian (Silurian) underlie much of the broad valley of Uadi Tanezzoft and, with the overlying Upper Silurian and Devonian sandstones, form the steep western flank of the Acacus-Tadrart Mountains. The clays are generally variegated, ranging in color from dark-gray to greenish-gray and grayish-purple. Where examined closely, they were found to be nearly pure clay with little or no admixed sand or silt. In the upper part, however, the clays grade upward into sandy shales and shaly sandstones which become progressively more massive. (See figure 8.) The clays are shaly and usually brittle on exposed surfaces. Thin bands and stringers of gypsum are common throughout the formation. Where not protected by overlying sandstone, the clays weather to form smooth gently rounded surfaces carpeted with fine fragments of shale. Because of the abundance of fossils in these clays they were commonly referred to by early writers as "schists with graptolites".

The Upper Silurian sandstones, classically known as the "sandstones with Harlania" (Harlania halli: Geop), comprise the upper part of the Silurian system and are considered to be a continental facies of this stage of deposition. Because of their inaccessible position in the face of the escarpment of the Acacus-Tadrart, they were not examined closely by the writer. Their lithology is typical of that of continental deposits. The texture varies from sandstone to conglomerate within short distances. Generally lenticular in structure, massive beds grade laterally into thin-bedded sandstones and shales. Large scale cross-bedding is generally characteristic and ripple marks are common. In the upper part the sandstone again becomes more shaly, and thin beds of sandy clay appear. This gradational zone is considered to mark the contact between the Silurian system and the overlying Devonian sandstones. The contact is based upon fossil evidence only, and is placed at the highest horizon at which Harlania occurs. (Muller-Feuga, 1954, p. 26)

The thickness of the Upper Silurian system exposed in the western escarpment of the Acacus-Tadrart Mountains is estimated to be approximately 250 m.

The sandstones in the upper part of the Silurian system probably will yield water to wells but in most places lie at too great a depth to be considered as an important source of water in the Fezzan.

Figure 8.--Exposure of Upper Silurian (Silurian) clays in escarpment of Acacus mountains. Capping unit composed of "sandstones with Harlania" overlaid by Upper (?) Devonian sandstone which forms knobs and pinnacles on the skyline.

Devonian System

The sandstones of Late(?) Devonian age are best exposed at the top of the high escarpment forming the western flank of the Acacus-Tadrart Mountains. They overlie the Upper Silurian "sandstones with Harlania" with a gradational contact. The Devonian is exposed also in the Gargafs escarpment of the Chatti Valley north of Tarut where it forms much of the surface of the southern part of the Hamada el Hamra. In both areas the Upper(?) Devonian series are overlain with apparent conformity by the sandstones and clays and, in places, limestones of the Lower Carboniferous (Mississippian) system.

The few poorly preserved fossils found in these deposits do not permit a precise determination of their age; however, they are generally considered as having been deposited sometime during the period between the Late Silurian and the Early Carboniferous, the majority of opinion favoring the Late Devonian (Muller-Feuga, 1954, p. 36; or Borghi, 1938). Desio subdivides the Devonian into Lower, Middle, and Upper series. He includes the underlying "sandstones with Harlania", which are now accepted as being Late Silurian in age; and the uppermost sandstones and clays which have been placed in the Lower Carboniferous by Muller-Feuga (1954, p. 37). For the purpose of this report the Devonian is mapped and described as a single, essentially massive sandstone unit and is considered to include those deposits lying between the Upper Silurian (Silurian) sandy shales and the Lower Carboniferous sandstones and clays.

The sandstones are generally pale reddish-brown in color on the fresh surface although the occasional more ferruginous zones are somewhat darker. The texture ranges from very fine- to very coarse-grained with frequent conglomeratic zones. The finer grains are angular to subangular while the coarser grains are subrounded to rounded. Throughout the section examined there was little evidence of selective sorting; usually the texture observed was a haphazard mixture of grain sizes. The cementing material is primarily calcium carbonate; however, there are zones where the calcareous cement has been replaced by ferruginous and siliceous cement.

The sandstones are massive and thick-bedded. Medium scale cross-bedding, with accompanying ripple marks and shrinkage cracks, is common throughout the series. The beds are blocky and weather to form knobs and pinnacles with pitted and gnarly surfaces. (See figure 9.) In the Acacus-Tadrart Mountains the thickness of these strata is estimated to be about 200 m. Muller-Feuga (1954, p. 33) estimated the thickness of the Devonian in the Chatti Valley to be 300-350 m.

Both continental and marine facies of the Devonian series have been recognized in the western Fezzan. The upper part of the series, as seen in exposures in the Gargafs north of Tarut, appears to be continental in origin. Characteristically these beds exhibit intricate cross-bedded structure, poor sorting of the clastic material, ripple marks and shrinkage cracks, and apparent complete absence of fossils. Here 37 m. of massive cross-bedded sandstone was measured.

Following is a description of the upper part of the Devonian sandstone exposed in the escarpment 3 km. north of Tarut. The dip of the strata in this area is 1 1/2° S 30° E.

		Thickness (meters)
Upper Crestaceous marls		
Upper(?) Devonian series:		
Sandstone,	grayish orange-pink, fine-to very coarse-grained, calcareous cement, hard brittle, thick-bedded, cross-laminated, jointed; weathers grayish-brown to nearly black, smooth and shiny; forms resistant ledge......	3
Sandstone,	pale reddish-brown, medium-grained, well sorted, ferruginous cement, friable, cross-laminated; weathers brownish-gray, gnarly; forms slope..........	6
Sandstone,	similar to uppermost sandstone..............	10
Sandstone,	pale brown, fine to coarse-grained, conglomeratic in places, calcareous cement, friable, thick-bedded, cross-laminated, jointed; weathers light-brown to nearly black; blocky, gnarly; shows ripple marks and shrinkage cracks.....	15

Figure 9.--Photograph of pinnacle of Devonian sandstone showing intricate cross-bedding and honeycomb type of weathering.

Siltstone,	banded reddish-orange and light-purplish-gray; friable, thin-bedded, cross-laminated; contains conglomeratic lenses...............	2
Sandstone,	medium-gray, medium-grained, fairly well sorted, coarser grains along planes of cross-lamination; ferruginous cement, friable, thick-bedded, cross-laminated; weathers grayish-brown, blocky; contains vertible tubules filled with calcite........	1
	Total measured..............................	37

The sandstones in the Upper Devonian series are the aquifers which supply water to the flowing wells in the Chatti Valley.

Carboniferous (Mississippian and Pennsylvanian) System

Lower Carboniferous (Mississippian) System

Carboniferous deposits are known to occur in only two areas in the western Fezzan, in the southwest in the vicinity of Serdeles and in the northern part where they form the escarpment of the Gargafs. They overlie the Devonian sandstones from which they are differentiated by their fossil fauna and depositional characteristics.

The Carboniferous deposits were divided into Upper and Middle Carboniferous series by Desio (1936, p. 319-356). These included only those sediments which are preponderantly calcareous in character and contain marine fossils of Carboniferous age. Later work by Muller-Feuga (1954, p. 37) leads him to place these and the underlying interbedded sandstones and clays in the Lower Carboniferous (Mississippian). They are considered to be of Early Carboniferous (Mississippian) age in this report.

Tournasian (Lower Mississippian) series.--Tournasian deposits occur in both the southwestern part of the map area and in the Chatti Valley. Depositional features and lithology appear to be similar in both places. Characteristically, the deposits consist of alternating beds of silty sandstones and clays with occasional bands of gypsum. (See figure 10.) Ferruginous zones are common, particularly in the Chatti Valley near Brach, where thick hematitic and limonitic bands persist for many kilometers along the base of the Gargafs.

The Tournasian series of the Serdeles area was not examined by the writer, but descriptions by other writers (Muller-Feuga, 1954, p. 38) indicate that deposits similar to those found in the Chatti valley occur there.

Muller-Feuga (1954, p. 43-47) basing his conclusions on fossil evidence, subdivides the Tournasian into two marine stages separated by a continental stage. Again, for reasons of brevity and simplicity, no attempt will be made to describe them separately since, lithologically, they are practically indistinguishable.

A section exposed in the escarpment 3 km. northeast of Brach, measured by the writer, comprises approximately the upper two-thirds of the Tournasian series, and is thought to be typical of the Tournasian of the Chatti Valley. The strata dip 1 1/2° S 20° E.

	Thickness (meters)
Upper Cretaceous "limestone"	
Tournasian (Lower Mississippian):	
Sandstone, light-brown, very fine-grained, ferruginous cement, firm, thin-bedded, slabby, flat-bedded; shows ripple marks and shrinkage cracks; weathers dark reddish-brown to black, blocky	1.80

Figure 10.--View of the interbedded sandstones and shales of the Tournasian series exposed in the Gargafs north of Brach. The capping unit is Upper Cretaceous limestone.

Claystone, pinkish-gray, sandy, contains thin beds of shaly sandstone near top; firm, brittle, thin-bedded, flat-bedded; weathers light-gray..........8.00

Claystone, banded, light-gray, grayish-yellow, grayish-green; laminated, flat-bedded; weathers to form slope; contains occasional thin seams and bands of hematite 18.00

Siltstone, grayish-orange, micaceous, ferruginous cement, firm, thin-bedded, flat-bedded, slabby; shows ripple marks and shrinkage cracks; weathers light-brown; forms ledge; contains thin bands of hematitic clays...............................15.00

Claystone and interbedded thin sandstones: light-gray, sandy, firm, laminated, shaly, flat-bedded; weathers to form alternating slopes and ledges; contains 80 cm. hematitic band with several thinner bands...............................10.00

Siltstone, similar to siltstone above...........3.00

Claystone and interbedded thin sandstones: similar to claystone and interbedded sandstone above; contains many hematitic bands ranging from 5 cm. to 30 cm. in thickness...............................10.00

Siltstone, similar to siltstone above...........3.00

Claystone and interbedded thin sandstones: similar to claystone and interbedded sandstone above...............................2.00

Total measured..................................70.80

Thicknesses of the Tournasian sediments are estimated at approximately 125 m. near Serdeles and 100 m. in the Chatti Valley. The sandstones of the series supply water to most of the dug wells in the Chatti Valley and, possibly, to some of the drilled wells. Because of their lithologic characteristics the sandstones are not sufficiently permeable to be considered a major source of water, however.

The Tournasian of the Serdeles area is overlain by the alternating sandstones, limestones, and clays of Visean (Late Mississippian) age. There are no known deposits in the Chatti area of Visean age. Here the Tournasian series are disconformably overlain by Upper Cretaceous limestones and marls.

Visean (Upper Mississippian) series.--Visean deposits are found only in the southwestern part of the mapped area where they occupy a zone lying just east of Serdeles. Exposures along the road are poorly defined and the rocks are generally concealed beneath the sands and gravels weathered out of the overlying Nubian series. There was insufficient time to visit the outcrops in the escarpment south of the Ubari-Serdeles road; however, the following section described by Rossi (1939, pp. 185 to 247) is probably characteristic of the Visean limestones, sandstones, and clays. Rossi did not record the thicknesses of strata exposed.

Sandstone,	blood-red and yellow, quartzitic with net-like structures.
Discordance	
Limestone,	banded gray and white, sandy; with barite and gypsum.
Sandstone,	gray, quartzitic; with some petrified wood.
Discordance	
Limestone,	yellowish-gray, compact; contains some fragments of crinoids and corals.
Marls,	pink and green, some gypsum; contains numerous ferruginous beds with small gastropods.
Sandstone,	brown, quartzitic.
Limestone,	gray and brown; some brachiopods and fragments of crinoids.
Limestone,	white, oolitic.
Clays,	greenish; shells of spirifers and large fragments of crinoids.

Alternating beds of clay and sandstone: greenish.

Concealed.

The Visean series exposed in the southern part of the map area is overlain with apparent conformity by the sandstones and clays of the Lower Cretaceous (Nubian) series. Its thickness in the southeastern Fezzan, outside the mapped area, is estimated by Muller-Feuga (1954, p. 51) to be about 200 m.

The author knows of no wells penetrating Visean deposits; however, it is doubtful that these strata can be considered a dependable source of water in the western Fezzan.

Cretaceous System

Lower Cretaceous (Nubian) series

The Nubian series, which overlies Visean deposits in the southern part of the map area and Tournasian strata in the northern part, is the most widely exposed stratigraphic unit in the western part of the Fezzan. It can be traced from Sebha westward nearly to Serdeles and northward from Sebha to the junction with the road to Brach. The broad plateau of Hamada Murzuch extending from Sebha to Murzuch is underlain by Nubian deposits. Isolated buttes capped by resistant Nubian sandstones are seen throughout nearly the entire length of the Hofra-Cherguya Valleys from Murzuch to Zuila. It comprises much of the surface of the southern part of Hamada el Hamra. The Nubian series is overlain by Upper Cretaceous limestones, sandstones and clays in the northern part of the map area and by middle Eocene limestones and marls in the eastern section.

The Nubian series is of continental origin and lacks definite fossils; hence, there is some uncertainty as to its geologic age. The upper part of the series has been accepted generally as Lower Cretaceous (Muller-Feuga, 1954, p. 54), but there is a difference of opinion among writers as to the age of the lower part. In this report all the Nubian series is considered to be of Early Cretaceous age.

Wherever seen, the Nubian deposits are characteristically and consistently a series of interbedded conglomeratic sandstones and clays. (See figure 11.) The members are usually lenticular and change lithologically in short distances both horizontally and vertically. The sandstones in the sequence generally consist of sand grains of a variety of sizes, ranging from very fine to very coarse grained. (See figure 11a.) The grain size of the conglomerates ranges between very coarse sand and gravel. Both the sandstones and conglomerates are usually firmly cemented and are often silicified on weathered surfaces. They are thick-bedded and almost invariably show large scale cross-bedding. Ripple marks and shrinkage cracks are common. The sandstones and conglomerates weather dark reddish-brown to black and, at a distance, are easily mistaken for remnants of lava flows. The black blocky debris which characteristically covers the slopes of buttes capped by Nubian sandstones heightens the impression of an igneous origin. A section of the Nubian

Figure 11.--Exposure of Nubian series along road east of Serdeles showing lava-like appearance of outcrops. Dip of strata is apparent in bands crossing the road.

Figure 11a.--Close-up photograph of texture of conglomeratic sandstone in the Nubian series.

series was measured by the author in the butte upon which For Leclerc is built at Sebha. The strata exposed apparently lie near the top of the Nubian series. Dips could not be measured with any degree of certainty, but it is believed that the beds are either flat-lying or dipping very gently to the southeast.

Section of the Nubian series exposed at Fort Leclerc, Sebha.

	Thickness (meters)
Nubian series:	
Sandstone, pinkish-gray, very fine- to fine-grained, coarse-grained to conglomeratic in upper part; calcite cement, firm; thick-bedded, cross-laminated; occasional thin bands of variegated siltstone along planes of cross-lamination; weathers to form cliff	6
Concealed, probably clay	8
Sandstone, pale yellowish-brown, predominantly fine-grained with some coarse to very coarse grains; calcite cement, weak; thick-bedded, cross-laminated; weathers to form smooth slope	2
Concealed, probably clay	3
Sandstone, grayish-pink, very fine- to fine-grained, ferruginous cement, weak; thin-bedded, cross-laminated, friable; forms slope	2
Sandstone, banded dusky-red, pale red, and black; medium-grained with coarser grains along bedding planes; ferruginous cement, weak; upper part silicified; thin-bedded, cross-laminated; forms slope	2.5
Concealed, probably clay	3
Conglomerate, variegated dusky-red, yellowish-gray, and moderate yellow; thick-bedded, cross-laminated; forms slope	4

Claystone, variegated purples, grays, and yellows; sandy, weakly cemented, thin-bedded, flat-bedded; contains some hematitic stringers and concretions; forms slope 5

Sandstone and conglomerate, variegated grayish-red and greenish-gray; fine-grained to gravel, ferruginous cement, weak; in places calcareous or siliceous; thick-bedded, cross-laminated; forms slope 6

Concealed

Total...41.5

The thickness of Nubian deposits is not known because nowhere is the entire section exposed. The greatest apparent thickness was measured at el Greifa, 25 km. east of Ubari, where a well was drilled to a reported depth of 350 m. without reaching the base of the series of interbedded sandstones and clays. A few kilometers south of el Greifa approximately 200 m. of the Nubian series is exposed in the escarpment which forms the southern boundary of the valley of Uadi el Agial. Apparently, the Nubian series is at least 550 to 600 m. thick at this point and perhaps even thicker eastward.

The sandstones of the Nubian series yield water to most of the dug wells at Sebha, to the flowing wells at Traghen and, probably, to many of the shallow wells in Uadi el Agial and Hofra-Cherguya valleys.

Upper Cretaceous Series

The limestones and marls of the Upper Cretaceous have been examined by the writer only where exposed along the road from Brach northward to Mizda. According to Desio (1939 map), Upper Cretaceous strata are exposed over most of the area lying between Gebel es Soda and the gebel escarpment of Tripolitania 700 km. to the north. In the area included in this report, they are seen capping the crests of the Gargafs north of Brach (fig. 10), where they lie disconformably on the Lower Carboniferous sandstones and clays, and again the the extreme northern part of the map area where limestones and marls are exposed at the base of Gebel es Soda and Gebel Fezzan. Upper Cretaceous deposits are overlain disconformably by middle Eocene limestones and marls in the northeastern part of the map area.

A general description of the Upper Cretaceous series indicates it consists primarily of interbedded marine limestones, sandstones, and clays. At the top of the escarpment north of Brach, the Upper Cretaceous consists of a single limestone member underlain by clays of Carboniferous age. (See figure 10.) The contact is sharp and one of angular unconformity. The limestone is white, fine-grained and very hard and brittle. It is generally sandy and appears to be oolitic in places. Thick-bedded and massive, it forms a heavy protective cap above the soft underlying clays. The limestone weathers to a light-brown color and disintegrates into large rectangular blocks which form a coarse talus at the foot of the slope. Fossils are either non-existent or rare. The exposed thickness of the limestone member is approximately 5 m.

Muller-Feuga (1954, p. 57) measured a section of Upper Cretaceous deposits near Auinet-Uennin at the western end of the Chatti valley. It is not known if the entire Upper Cretaceous is exposed here but the outcrop is probably representative of the series in the western part of the Fezzan. His description of the strata exposed at this location is as follows:

	Thickness (meters)
Upper Cretaceous series:	
Marls and limestones, thick, interbedded........	12

Sandstone, yellowish, often coarse-grained, siliceous, cross-bedded...............8

Marls and limestones, white, interbedded.........6

Marls and shaly limestones.......................4

Limestones, light-yellow and gray, compact.......5

Marls: gray, some gypsum.........................5

Sandstones, white, calcareous....................2

Limestone, white, compact, hard..................0.2

Sandstone, white, siliceous......................5

Upper Devonian

Total measured...................................49.2

Muller-Feuga considers the limestone exposed in the Gargafs north of Brach to be not of Late Cretaceous age, but somewhat younger than those described above, either late Eocene or early Quaternary. The writer can offer no opinion based upon personal examination, so includes all the limestone deposits in the Chatti area in the Upper Cretaceous.

Tertiary System

The middle Eocene series disconformably overlies the Lower Cretaceous Nubian series in the eastern part of the map area and the Upper Cretaceous series in the northeastern part. Middle Eocene strata east of the area of the report are overlain by upper Eocene limestones and clays. The only deposits of known Eocene age in the western part of the Fezzan are found in the extreme northeastern part of the area, where they form the surface of the broad plateau dominated by the lava-capped mass of Gebel Harug. Desio (1936, p. 341-342) assigns a middle Eocene age to these sediments. The strata consist of alternating beds of sandy limestones, marls, sandy clays, and calcareous sandstones, with interbedded zones of gypsum. West of this area of finer clastics, and forming a crescent around its western border, is a thick sequence of limestone conglomerate. Desio considers the conglomerate to have been deposited by a transgressive Cretaceous-Eocene sea. However, in this report it is considered to be of the same age as the limestones and marls lying to the east.

Limestone and marl deposits which are similar lithologically to the middle Eocene strata described above occur in the vicinity of Murzuch. The rare, poorly preserved fossils found in the sediments do not permit a precise determination of their age. Desio (1939 map) placed them in the Jurassic, but other workers (Muller-Feuga, 1954, p. 80) who have examined the deposits indicate a preference for a somewhat later period of deposition, sometime between Early Cretaceous and Quaternary. Lithologically, the deposits are very similar to both the Upper Cretaceous limestones and marls of the Chatti valley and the middle Eocene limestone and marl series occurring in the extreme eastern part of the map area. The deposits are only local in extent, and nowhere do they appear to exceed a few meters in thickness. There is no evidence that the region has experienced crustal disturbance of sufficient magnitude to cause deep-lying Jurassic strata, if they exist at all in the western Fezzan, to be exposed at the surface. Nubian outcrops in the area generally dip gently and persistently south-eastward. In the absence of any fossil evidence, these deposits are considered to be not older than middle Eocene and, perhaps, younger.

The writer was unable to examine the Eocene deposits, consequently, the description given was obtained entirely from published reports by Desio (1936, p. 340-342) and Muller-Feuga (1954, p. 59-60).

Quaternary System

Quaternary deposits comprise the unconsolidated sediments produced by the action of desert weathering and wind and water erosion upon desert rocks, and semiconsolidated deposits resulting from the deposition of evaporites and wind- and water-borne material deposited in highly saline bodies of water. The unconsolidated deposits include the more or less fixed sands of the areas designated in the western Fezzan as "edeien," the moving sands of the "ramla", the thin sheets of gravel covering the "serir," and the sands and gravels of the uadis.

Semiconsolidated strata commonly consist of generally impure evaporite deposits interbedded with marls and weakly cemented sand and clay. These sediments mark the sites of former lakes which have become dry as a result of the increased rate of evaporation and decreased recharge caused by progressively greater aridity. The deposits are generally local in extent and are found within the dune areas as well as along their margins. Deposition of evaporites is taking place at the present time inthe few isolated saline lakes lying within Edeien Ubari and Edeien Murzuch.

A second type of evaporite deposition occurs in areas where ground water is sufficiently close to the surface of the land to permit water to be brought to the surface by capillary action. The water is evaporated off, leaving the soluble salts as a thin crust on the land surface. Sodium chloride deposited in these "sebkhas" is the major source of domestic salt in the Fezzan.

The thickness of unconsolidated deposits undoubtedly differs greatly from place to place and probably is greatest in the dune areas. An examination of drillers' logs of 10 wells drilled in the Fezzan since 1950 indicates that the alluvium in the eastern part of the Hofra-Cherguya valleys may be as much as 33 m. thick. In the Chatti Valley drilled holes penetrated alluvium ranging in thickness from 3 to 13 m. Few dug wells reveal the character and thickness of the alluvium because slumping of the walls generally conceals the character of the material penetrated.

Quaternary sediments yield water to dug wells in areas where there is occasional surficial recharge from precipitation, or where these deposits immediately overlie discharging artesian aquifers. The quantity and quality of the water may vary greatly between areas and, in some places, between adjacent wells. These deposits are the major source of ground water in the Fezzan at the present time.

Metamorphic Rocks

The gneisses and crystalline schists of the Tassili n Ager in the southeast corner of themap are the only known metamorphic rocks in the western part of the Fezzan. Similar outcrops occur in the Tibesti Mountains at the extreme southern border in Libya. The writer was unable to visit the areas in which the metamorphic rocks are exposed. Desio described these rocks and assigned them to the Archaeozoic (Precambrian).

Igneous Rocks

The masses of Gebel Fezzan, Gebel es Soda, and Gebel Harug which occupy much of the northeastern corner of the map area, are composed of sedimentary strata capped by a thick layer, or layers, of basalt flows. The source of these flows is not known but it is probable that Gebel es Soda encompasses the center of a formerly active volcanic area. The age of the volcanics is considered to be post-Eocene and, perhaps, as late as Quaternary.

STRUCTURE

The "Fezzan Basin" has long been recognized by geologists who have studied the geology and structure of the area. An examination of the geologic map by Desio, supplemented by reconnaissance studies in the field by the writer, indicates the presence of a large structural basin, or rather two adjacent basins separated by an east-west-trending anticlinal fold occupied by the plateau of Hamada Murzuch and Serir el Gatuzza. (See plate 1.) The composite basin underlies most of the area included in the map of the western part of the Fezzan. Its northern, eastern, and southwestern margins generally coincide with the corresponding limits of the map. Its southern border lies outside the map area, as does the lobate north-eastern extension. Westward the outline of the basin is concealed beneath alluvial deposits of Edeien Ubari. The center of the basin is believed to lie within Edeien Murzuch some distance south of the Hofra Valley.

The northern rim of the basin is formed by the southeasterly dipping beds of a monoclinal fold which carries the Devonian strata exposed in the Gargafs of the Chatti Valley deep beneath the surface of Ramla Zellaf and Hamada Murzuch. (See figure 12.) South of the Zellaf, between Sebha and Murzuch, the exposed Nubian strata appear to assume a nearly horizontal position, only to be depressed again to the south and southeast along a line generally coinciding with the axis of the Hofra-Cherguya valleys. The dips of the sediments exposed in the eastern part of the Hofra-Cherguya valleys indicate the presence of a secondary anticlinal structure imposed upon the regional dip.

The eastern and southern edges of the basin are delineated by a semicircular outcropping of strata of the Nubian series. Structural sections drawn by Muller-Feuga indicate strata dipping gently westward in the vicinity of Gebel ben Ghnema with the direction of dip changing gradually to the north as the Nubian outcrops are traced to the southwest. The Tassili highlands mark the extreme southwestern border of the Fezzan Basin. Here the sediments dip steeply to the east, or slightly north of east, away from the Tassili n Ager and toward the deeper part of the basin. (See figure 11.) Two secondary synclinal structures, one in the northeastern part of the basin, the other in the northwestern part, break the continuity of the structural basin and form lobar extensions which disappear

Figure 12.--Photograph showing southeasterly dip of Tournasian strata in Gargafs north of Brach. The Upper Cretaceous limestone is the very thin uppermost unit, just barely discernible, lying discordantly on the Tournasian sandstones and clays.

beneath the Eocene sediments to the east and Quaternary deposits to the west.

Minor folding and faulting of strata are not uncommon in the western Fezzan, but apparently major displacements are rare or are concealed beneath surficial deposits.

GROUND-WATER RESOURCES

PRINCIPLES OF OCCURRENCE OF GROUND WATER

Ground water may be defined as that water occurring below the surface of the earth in the zone of saturation. It is any water below the land surface that may be recovered by wells or appears at the surface in the form of springs or seeps. Practically all the rocks that comprise the earth's outer crust contain water in some quantity. The amount of water contained in a saturated rock is determined by the porosity of the rock. If the pore spaces are interconnected, the water can then move through the rock, and the rock is said to have permeability. If the pore spaces are relatively large, as in a coarse sand or sandstone, the resistance to the movement of water through the material is not great, and the rock is said to have a high permeability. However, if the pore spaces are small, as in clay and claystone, the resistance to the movement of water is very great, and the rock is said to have a low permeability.

Ground water under normal conditions is in constant motion laterally, in the form of a broad sheet, from areas of recharge at relatively high elevations to areas of discharge at relatively low elevations. Only under very special conditions does ground water move in well-defined underground streams or channels. In the Fezzan, discharge is into natural (saline lakes) and artificial (wells) bodies of surface water and into the atmosphere by evaporation from land surfaces and transpiration by desert vegetation. Recharge is from rainfall which, though occurring rarely, has resulted in the accumulation in underground reservoirs of large amounts of water during the past several thousand years. The rate of movement of ground water from recharge to discharge areas is generally very slow, often much less than a kilometer a year, and in places perhaps only a meter or two a year.

Any rock layer or stratum that will yield water in sufficient quantity to supply a well or create a spring is called an aquifer. Aquifers often extend over wide areas and transmit water many kilometers. The water flowing from the wells at Traghen probably started as rain falling on the crests of the Acacus and Tadrart Mountains many years ago. If the water in an aquifer is not confined by impermeable strata above, the water is said to occur under water-table conditions. Water confined in an aquifer by an overlying impermeable stratum is generally under pressure that will cause the water to rise above the top of the aquifer where it is penetrated by a well. The water is said to occur under artesian conditions, and the pressure that causes it to rise in the well is called artesian or hydraulic pressure. The term "artesian" is used whether or not the water rises enough to flow at the land surface.

Withdrawal of water from the aquifer by wells causes a lowering of the water table in unconfined material or a decrease in the pressure within artesian strata. If the rate of withdrawal is excessive, the yield of wells will be reduced. Recharge and discharge of ground water in a desert environment are generally in rather delicate balance; consequently, great care is necessary to prevent overdevelopment of the ground-water resources. The generally low rate of recharge may be exceeded easily by concentrated withdrawals from wells, and water lost from storage is replaced only very slowly.

PRINCIPAL AQUIFERS AND THEIR WATER-BEARING CHARACTERISTICS

The western part of the Fezzan, in spite of its desert environment, contains, perhaps, the largest reserve supplies of underground water in Libya. Accumulated evidence indicates that most of the region is underlain by water-bearing sandstones in which water is under sufficient artesian pressure to cause it to flow in drilled wells or to rise to within a practicable pumping distance of the land surface, except on the highest ground. The unconsolidated deposits of the oasis areas generally are saturated and contain water that is easily obtained by constructing relatively shallow wells, most of which are dug.

In the western Fezzan there are four major ground-water provinces in which water is obtained from four entirely different and more or less separate reservoir systems. These systems are, in order of geologic age, the Cambrian and Ordovician sandstones of the Gat-el Barcat area; the Devonian sandstones that underlie the Chatti Valley; the sandstone members of the Nubian series of Early Cretaceous age which are exposed at, or lie only a short distance below, the surface of most of the eastern half of the map area; and the unconsolidated deposits of sand, gravel, and marl which generally underlie the surface of the broad valleys bordering the great sand areas.

Cambrian and Ordovician Sandstones

The interbedded sandstones and conglomerates of Cambrian and Ordovician age underlying the Gat-el Barcat area in the southern part of the valley of Uadi Tanezzoft have all the characteristics of an excellent artesian aquifer. The strata are massive and thick bedded and are persistent over wide areas. The total thickness is estimated to be 400 to 600 m. The regional dip is generally to the northeast away from the relatively impermeable metamorphic rocks which form the crests of the Tassili n Ager Mountains, on the flanks of which the upturned edges of the sandstones are exposed in a broad encircling band. Precipitation falling on the Tassilian highlands is almost entirely absorbed into these sandstones, and a part of it percolates to the zone of saturation. The underlying gneisses and schists and the overlying thick clay sequence form confining layers above and below the aquifer. The permeable texture of the sandstones and conglomerates readily permits water to move through them, and the water migrates from the area of recharge on the flanks of Tassili n Ager eastward toward the center of the Fezzan basin.

Unfortunately the importance of this series of strata as an aquifer is reduced by the fact that only a relatively small portion of the Fezzan can benefit from the water contained in them. Except for the area lying within the valley of Uadi Tanezzoft, the Cambrian and Ordovician sandstones lie too deep for economic exploitation under present conditions.

A few wells in the Gat-el Barcat area apparently yield water from Recent eolian deposits, but most of the water is obtained from the underlying consolidated sandstones. It is believed, however, that much of the water in the dune deposits has its origin in the sandstone reservoir. A common method of constructing wells here is to sink a shaft on a low rise of land so that the water in the underlying artesian aquifer will rise to an elevation higher than that of the surrounding land surface. Canals are then trenched from the well to the irrigated plots, to which the water is carried by gravity. These canals are often lined and covered with stone slabs to protect them from drifting sand. Water in the Gat-el Barcat area is used primarily for irrigation of small garden patches and orange and fig groves, though it is of sufficiently good quality to be used for all domestic purposes. A crude measurement of the flow of one dug well indicated a yield of approximately 40 mc/hr (175 gpm). The flow from a second well, similarly determined, was found to be about 16 mc/hr.

The village of Gat obtains its domestic water from a large dug well that was originally constructed to supply the French fort. Water is pumped to the fort, and the overflow is carried by gravity through a covered canal to a community tank where it is used by the local inhabitants for domestic purposes. The well is reported to have been originally 25 m. deep, but a tape measurement indicated a present depth of only 6.5 m. It is about 6 m. in diameter and cased and covered with concrete. It was impossible to obtain an accurate measurement of the well's flow because of the frequent pumping required to supply water to the fort. At the time of the writer's visit to Gat the overflow of the well was estimated to be about 15 mc/hr. The level of the water in the well is reported to decline slightly during the summer months, but no recorded data were available to substantiate this report.

Devonian Sandstones

Devonian sandstones which crop out in a broad east-west band along the southern border of Hamada el Hamra are downwarped to the south-southeast and pass beneath the Chatti Valley at inclinations ranging from 1 1/2° to 2°. In the southwestern part of the map area Devonian strata are exposed over most of the dip slope of the north-south-trending cuesta which forms the Acacus and Tadrart Mountains. In both areas the Devonian sandstone is considered to be a potential source of large supplies of ground water. The great expanses of outcrop area generally are covered by a thin carpet of sand or pebble alluvium that rapidly absorbs any precipitation falling upon its surface. The portion of the water that is not evaporated or transpired readily percolates downward into the underlying sandstones.

The contact between the Devonian series and the underlying Silurian clays, as seen in the escarpment of the Acacus-Tadrart, is not exposed in the Chatti region. However, it is probable that the thick clay sequence persists as far north as the Chatti Valley and forms a more or less impermeable layer at the base of the massive sandstones. The interbedded clays and siltstones of the overlying Carboniferous series provide a confining layer above.

The thickness of Devonian strata is estimated to be approximately 100 m. in the Chatti Valley and about 125 m. near Serdeles at the northern tip of the Acacus Mountains. The sandstones and conglomerates generally appear to be quite permeable. Evidence obtained from the flowing wells in the Chatti Valley indicates that ground water apparently moves through these strata rather freely. The movement is probably to the southeast in the direction of the regional dip. It is doubtful that any of the dug wells at Serdeles enter Devonian sandstones. It is believed that the direction of ground-water movement in this area is generally to the east.

Data contained in the following tabulation was obtained from drillers' records of wells drilled in the Chatti Valley; they permit a brief comparison of the hydrologic and geologic conditions encountered. Drillers' logs of these wells are shown in table 2.

Location of well	Elevation of land surface 1/ (meters)	Depth to Devonian 2/ (meters)	Depth of well (meters)	Water level relative to land surface (meters)	Yield (mc/hr)
Debdeb	311	40	90	+10.75	72
Brach					
LPDSA well	304	50	91	+16.00	72
Ain Bizanti	300	--	94	+16.00(?)	200
Guhgum					
Ain Neucf	308	55	65	+15.50	130
Zelluase	335	20	93	+ 2.00	5.5
Agar	330	75(?)	100	+ 6.00	50
Maharuga	318	40	90	+ 6.50	45
Gorda	296	20	66.50	+19.50	80
el Gotta	300	55	100	+16.00	52
Berghen	337	18	82	------	1.2
Uenzerich	321	60(?)	82	+21.00	50
el Hatia	345	9	150	- 5.60	-----

1/ Benier N., Repeves de Nivellement, Territoire Militaire de Fezzan: Algiers, 1952. Altitudes relative to that of reference point (400 m.) at Fort Leclerc airfield.

2/ Interpretations by author.

Depths to Devonian strata were determined from a study of the driller's description of the types of rocks penetrated during the drilling and the depths at which they were encountered. The accuracy of the interpretations is dependent to a large extent upon the accuracy of the drillers' descriptions and the care exercised in collecting the rock samples.

A comparison of the recorded static levels in the wells indicates that there is a general, though irregular, decline of the piezometric surface eastward. It stands at an elevation of about 340 m. at el Hatia and at approximately 315 m. at Gorda. The elevation of the piezometric surface rises east of Gorda to a high of 337 m. at Zelluase and declines again to 322 m. at Debdeb. (See plate 2.) The possible errors involved in determining artesian pressures and surface elevations may account for some of the irregularities.

There is no evidence of any regional progressive differences in amounts of water produced by the wells studied. The observed differences are probably due to local variations in the hydrologic characteristics of the aquifer and possibly to differences in drilling and developing techniques and method of measuring the flow. In addition to the 12 drilled and cased wells tabulated above, there are many flowing wells in the Chatti Valley which consist of an uncased hole drilled into the bottom of a former dug well. It is estimated there are about 40 such wells throughout the valley, most of them concentrated in oases in the vicinity of Brach. Seventeen wells were visited within a radius of 7 km. of Brach. Depths of the wells range between 23 and 101 m., and flows, measured and estimated, ranged from 4 to 93 mc/hr. The average depth of these wells is approximately 45 m. and average flow about 22 mc/hr.

Pumping tests were made at the oasis of Zelluase on 2 wells whose flows were reported to have decreased during the past 3 years. Bir Duega is a dug well 23 m. deep, and Bir Omar Lazuni is a combination dug and drilled well 77 m. deep. The flows of these wells at the time of the tests were approximately 4 and 10 mc/hr, respectively. It was found by pumping that Bir Duega has a specific capacity (the number of cubic meters of water a well will yield each hour for each meter of drawdown) of 5.7 mc/hr and Bir Omar Lazuni a specific capacity of 10.7 mc/hr.

Lower Cretaceous (Nubian) Series

The sandstones and clays of the Lower Cretaceous (Nubian) series are exposed over most of the eastern half of the map area. They yield water to wells in the Sebha oasis, the Hofra-Cherguya Valleys, and the valley of Uadi el Agial. Consequently, Nubian aquifers are one of the major sources of existing water supplies in the Fezzan.

The sandstones, where exposed at the surface, are generally thickbedded. The outcrop area is extensive and is commonly covered by a porous layer of sand or gravel derived from the disintegration of the sandstone and conglomerate members of the series. The thickness of the Nubian series in the southern part of the map area is estimated to be in excess of 550 m. Regional dips, generally to the east or southeast, indicate the presence of a large structural basin, the center of which apparently lies some distance south of Murzuch in Edeien Murzuch. In the areas where the Nubian series yields water to shallow dug wells, or is a potential source of water for deep drilled wells, the movement of the ground water is believed to be generally to the east or southeast. There is little evidence upon which to base conclusions concerning the permeability of the sandstones in the Nubian series. The generally poor sorting of clastic materials characteristic of continental deposits and the tendency of the depositional units to be lenticular in structure and gradational in composition suggest that the rate of movement of water through the aquifers will vary from place to place and at different horizons. Hydrologic data available on wells dug and drilled into the Nubian sandstones and clays appear to support this conclusion.

Oases occupying the valley of Uadi el Agial obtain water from shallow dug wells which generally range from 5 to 8 m. in depth. It is probable that some of the wells penetrate the Nubian series, because Nubian strata are exposed in isolated outcrops over most of the surface of this area. However, in most places rock encountered in the wells is generally concealed beneath the debris accumulated from the slumping of the walls.

There are no recorded data on the productivity of wells in the valley of Uadi el Agial, but landowners and water raisers generally reported adequate supplies of water for present needs. These reports were verified in some areas where wells were observed to yield enough water to permit the operation of two, and sometimes three, dallu buckets. One of the deeper wells (9 m.) at el Griefa is equipped with a centrifugal pump powered by a diesel engine. However, the pump, which discharges about 110 gallons of water a minute, lowers the water level 2.5 m. to the bottom of the suction column in about 2 hours of pumping. Recovery to static level was reported to require about 4 hours.

The oasis of Sebha obtains its water from dug wells which range from 8 to 10 m. in depth. The bottoms of the wells are seldom more than 2 m. below static water level. Nearly all of them penetrate sandstones of the Nubian series. Some of the wells are sufficiently productive to permit irrigating grain and forage crops, but others have been abandoned because of meager yields. The discharges of two irrigation wells equipped with pumps were measured at 24 mc/hr and 26 mc/hr. In both wells the drawdown of the water level was approximately 2 m. The owners reported that, when necessary, the wells are pumped 12 hours a day without exhausting the supply of water. There are several other wells in the oasis that appear to be equally productive.

Two wells recently dug about 3 km. west of the fort at Sebha are 11 and 18 m. deep, respectively. The shallow well is about 600 m. west of the deeper well and 5m. lower in elevation. The static water level in the deeper well is about 16 m. below the surface; that in the shallower well stands only 3 m. below the surface. The results of pumping tests indicate that the shallow well will yield 10-12 mc/hr, while the deep well produces less than 2 mc/hr. The different hydrologic conditions encountered by wells in the Nubian series within relatively short distances of each other is not uncommon.

Community supplies for the Sebha oasis are obtained from several different sources. Military-owned wells supply water to Ft. Leclerc and the homes of French officers and civilians. A dug well owned by the Tunis Automobile Transport Co. is also used for a domestic source of supply. A dug well equipped with a small turbine pump supplies water to the local native population and is hauled in tank trucks to the homes and offices of government officials in the el Gorda section of the oasis. However, in spite of these widespread sources of water, there are frequent shortages of supply. Attempts are being made to develop additional supplies of water in the el Gorda area from dug wells.

Throughout the Hofra-Cherguya Valleys water is usually found at depths ranging from 6 to 8 m. Except for the flowing wells at Traghen, the water is obtained from shallow dug wells equipped with a dallu tower or well sweep.

Some of these wells are believed to penetrate the underlying Nubian series where it lies sufficiently close to the surface.

The three wells recently drilled at Traghen encountered water in the Nubian sandstones at depths ranging from 33 to 35 m. The hydraulic head is reported to be approximately 2 m. above the land surface. The wells were reported to flow 40, 44, and 47 mc/hr, when completed. During the approximately 7 years since the wells were completed, 2 of them have become filled to within a few feet of the land surface with what appears to be fine gravel, and the flows have decreased to about half the original volume.

There have been few attempts to explore the deeper strata of the Nubian series outside areas where water under sufficient artesian pressure to flow is known to exist. Exploratory wells ranging from 100 to 350 m. deep were drilled at the oasis of el Greifa in the valley of Uadi el Agial, at Tuila, and Umm el Araneb in the Hofra-Cherguya Valleys and at el Gorda in the Sebha oasis. Test holes were started at el Abiad, Murzuch, and Zuila but were abandoned before completion. All are reported to be less than 40 m. deep. Water was found in most of the wells, and static water levels were generally only a short distance below the land surface. All the wells were considered unsuccessful, perhaps because they did not flow, and apparently were never used. There are no records to show that the yields of these wells were ever tested by pumping.

The well at el Greifa is reported to be 350 m. deep. The static water level when the well was completed was 13.50 m. below the surface. A driller's bailing test, conducted when the well was partially finished, indicated that it might yield approximately 11 mc/hr for each meter of drawdown. The quality of the water is reported to be unusually good. If the recorded and reported data are reliable, there is reason to believe that there are supplies of water in the el Greifa area which may be obtained at relatively shallow depths. The artesian pressure probably is sufficient to bring the static water level to within easy pumping distance of the surface.

A pumping test was made on an abandoned drilled well located about 200 m. west of the police fort at Murzuch. The depth of the well measured at the time of the test was 10.40 m., and static water level stood at 4.10 m. below the surface. There is no record of the original depth of the well or amount of casing installed. However, it is thought, as a result of comparison of chemical analyses of water encountered, that the well obtains most of its water from the Nubian series.

The specific capacity of the well was determined to be 8.60 mc/hr for each meter of drawdown. It is believed that the yield of the well will increase with continued pumping, and may be further improved by cleaning.

The well at Tuila, about 20 km. east of Traghen, is reported to be 150 m. deep, and the water level stands 5.90 m below the surface. The yield is not known, as there is no record of any pumping test on this well. That the well did not flow probably is due to the fact that the elevation of the land surface at Tuila is nearly 8 m. higher than that at Traghen, and the artesian pressure is insufficient to lift the water to the surface. At the time of the writer's visit the well was found to be filled to within 1 m. of the land surface with rocks and sand.

A well drilled at Umm el Araneb, about 35 km. east of Traghen, is reported to be 150 m. deep, but a measurement made at the time of the writer's visit indicated a depth of only 55 m. It is possible that debris caving from the walls of the uncased section of the hole has partially filled it. The water level stands at 9.50 m. below the surface of the ground. There is no record that the yield of the well was ever tested.

The only deep well on record in the Sebha oasis was drilled at el Gorda about 5 km. northwest of F. Leclerc. It is reported to be 100 m. deep, and the recorded static water level is 4.50 m. below the surface. The hole entered the Nubian series at, or only a short distance below, the surface. The driller reported that the well produced 100 mc/hr by pumping with very little drawdown. The quality of the water is reported to be excellent. Because the well did not flow it was considered unsuccessful and abandoned. It has since become filled, or plugged, with rocks and sand.

Quaternary Deposits

Alluvial Deposits

The alluvium that covers the floors of the broad valleys that border Edeien Ubari and Serir el Gattusa is the major present source of water in the western Fezzan. Water is generally found at relatively shallow depth throughout the valleys of Uadi el Agial, Hofra-Cherguya, and Chatti. In composition the alluvial deposits range from relatively coarse and permeable sands to very fine-grained silty sands and sandy marls. These variations in lithology often occur within relatively short distances with the result that two adjacent wells may be completely dissimilar in quantity and quality of water obtained. It is thought that in most places throughout the western part of the Fezzan the alluvium is recharged in large part by leakage from the underlying artesian aquifers. There is little evidence of declining water tables in the region in spite of relatively heavy withdrawals in the more populous areas.

Depths to the water table range from only a few centimeters in parts of the Chatti and Hofra-Cherguya Valleys to as much as 12 m. in the western part of the valley of Uadi el Agial. However, water levels in most parts of the Fezzan are at depths that require the use of a dallu tower to operate the well efficiently.

Chatti Valley

The water levels of the dug wells in the western end of the Chatti Valley are generally very near, or, in some places, at the surface. The wells are seldom more than 3 to 5 m. deep. It was discovered by the native farmers that if a well is constructed on slightly elevated ground the water often rises high enough in the well to flow by gravity through shallow ditches to the area to be irrigated. This method of well construction is quite common in the Edri-el Hatia area. The yield of these wells usually is not great, and it is often necessary to build a storage reservoir nearby to permit the water to accumulate during the night. In this way, the flow of the well is sufficient to irrigate small garden plots. The community well at Edri is constructed in this manner and supplies the populace with both domestic and irrigation water. A typical example of this method of construction is the well which, for some unaccountable reason, was dug directly in the center of the road leading from Edri to el Hatia.

In the central Chatti Valley from Uenzerich to Esckhida there are several dug wells yielding large flows of water. The diameters of the larger wells range from 5 to 10 m. The three wells, Ain Kebir, Ain Bru, and Ain Auinette, that supply the oasis of Brach with domestic and irrigation water are reported to flow 135, 65, and 20 mc/hr, respectively. The community well at Esckhida about 20 km. east of Brach is recorded as yielding 120 mc/hr. The depths of the wells at Brach are not known, but Ain Gdima at Esckhida has less than 2 m. of water standing in it when the discharge gate is open. The artesian heads of the wells at Brach are only a few centimeters above the land surface. The static water level in Ain Gdima is actually below the immediate land surface, but the well is located near the crest of a high sand mass which overlooks the village. The overflow is led to the cultivated land below through a channel cut deeply into the sand by the rapid flow of the water.

It is likely that the water in these wells is derived from upward leakage from the underlying Devonian sandstones. The quality of the water in the dug wells at Brach is similar to that obtained from the deep drilled wells penetrating the Devonian and indicates a similar source of supply. The water from Ain Gdima contains a somewhat higher concentration of chloride and sulphate but an appreciably lower concentration of magnesium than the water in the deeper strata, and thus suggests a different source than the Devonian sandstone.

Hofra and Cherguya Valleys

Throughout the broad Hofra-Cherguya Valleys extending from Murzuch to Zuila the oases villages are supplied with water obtained from shallow wells dug into alluvium. These wells range from 6 to 8 m. in depth. In some places, as in the Chatti Valley also, the water level is very near the surface. The water occurs in interbedded fine sands and sandy marls. It is reported that the yields of the wells differ appreciably throughout the area, as does the quality of the water. Some of the wells are able to support 2 or 3 dallu towers which indicates that they are quite productive. Farmers who were interrogated confirmed the apparent fact that there are ample supplies of water for present needs, though there was some adverse criticism of the quality.

Valley of Uadi el Agial

There are many shallow dug wells in the inhabited oases that lie in a broken line from Ubari to el Abiad. The wells range from 5 to 12 m. in depth and generally extend 1 to 1 1/2 m. below the water table. The water occurs in the fine alluvial sand which underlies the valley floor. Only a few of the deeper wells reach bedrock. Recharge into the alluvium is undoubtedly in part from upward leakage from the underlying Nubian sandstones. Since the wells are not cased, the walls generally slump and cave until, in some cases, diameters are 6 to 8 m. However, the additional storage capacity thus provided is sometimes an advantage. In conversation with the owners and water-raisers it was generally reported that the wells supplied an adequate amount of water for present needs. As elsewhere, there was occasional adverse criticism of the quality of the water.

Eolian Deposits

The few isolated oases lying within Edeien Ubari and Ramla Zellaf are accessible only by camel-back or on foot. They occupy the narrow valleys separating the high northeast-southwest-trending ridges of dunes characteristic of the western Zellaf. (See figure 13.) It is thought that the high ridges are a reflection of the former erosional topography which has subsequently been buried beneath a relatively thin layer of windblown sand. At the bottom of the depressions Nubian sandstones lie close to the surface and yield large amounts of water into the overlying sand deposits.

The oases lying within these depressions generally surround small highly saline lakes, the surface levels of which mark the approximate elevation of the water table in the valley. (See figure 14.) The source of the water in the lakes and in the alluvium is believed to be the underlying Nubian sandstone supplemented by infrequent meager precipitation. Some of the lakes are perennial, while others are reported to become dry during the late summer. At the time of the writer's visit in early December the water levels of the lakes in the oases of Gbr Oun and Maaten Truna were reported to be at or near maximum elevation. (See figure 14a.) However, the level of the water at Maaten Truna subsides during the summer until, by early fall, the concentration of salts reaches a point of saturation, and sodium chloride and sodium carbonate are precipitated on the bottom of the lake. These salts are harvested annually during the late summer, primarily for the sodium carbonate, and are transported to Sebha by camel caravans to be trans-shipped by truck to Tripoli. The water level of the lake at Gbr Oun reportedly has only a slight seasonal fluctuation.

The wells at Maaten Truna range from 4 to 5 m. in depth and the static water level is sufficiently near the surface of the ground to permit drawing water with well sweeps. The yield of the wells is not indicated by the size of the irrigated plots, because the population of the oasis is small, and the demand for water is not great. There appeared to be abundant water in the wells at the time of the writer's visit, but it was reported by the Sheik of Maaten Truna that water levels sometimes decline dangerously during the late summer.

Figure 13.--Oasis of Gbr Oum accentuates height of dune mass behind it.

Figure 14.--Oasis of Maaten Truna surrounds saline lake.

Figure 14a.--Collecting sample of water from lake at Matten Truna. Although level of lake was near maximum height, saline concentration of water was very high.

Along the caravan route from Maaten Truna to Sebha, shallow wells have been dug at strategic points to supply water to the camels and their drivers on the 8-day trek across the sands. The wells must be re-excavated each time the caravan passes because of incursion of the drifting sand.

UTILIZATION OF GROUND WATER

In the Fezzan, as in other parts of Libya, water plays a major role in the local economy. Its quantity and quality determine what crops may be cultivated, how large a proportion of these crops survive the desert heat, what animals may be raised for their products, and the extent to which the water can be used for domestic supply. The quality of the public supply also greatly affects the physical health of the community.

Supplies of water from rainfall occur rarely and are soon lost through evaporation and by absorption into the porous sandy or rocky cover which blankets the surface of much of the area. The only other source of water in this arid land is that obtained from wells, most of which are dug into unconsolidated alluvial deposits or, in some places, the deeper lying consolidated strata. Most of the water thus obtained is used for irrigating small garden plots; relatively little of the water is diverted to domestic use, though of course the water so used is vital.

The traditional method of constructing a well in the Fezzan is to dig a circular or rectangular hole to a depth of 1 to 2 m. below the water table or through the confining layer that in some areas overlies an artesian aquifer. The depth to which the well can be dug below the water table is generally determined by the rate at which the workers can bail out the water, relative to the rate of water inflow. The wells are seldom curbed; hence, in loosely consolidated sediments, the walls tend to collapse. The removal of the debris gradually increases the diameter of these wells. Some of the wells visited had attained diameters of 15 to 20 m. The difficulty of raising water from such wells often leads to their eventual abandonment.

Where the water level is sufficiently close to the surface, 3 to 4 m., water for irrigation is generally raised by means of a woven fiber basket attached to the end of a well sweep counterbalanced by a large rock. The work is laborious, and the rate of withdrawal of water is generally low. Water is drawn from greater depths by constructing a tall headframe, or tower (dallu), over the well. (See figure 15.) A large leather bucket, generally made of camel or goat hide, is attached to one end of a long rope which passes over a pulley at the top of the tower; the other end of the rope is usually attached to a donkey, cow or camel. The bucket is raised by leading the animal

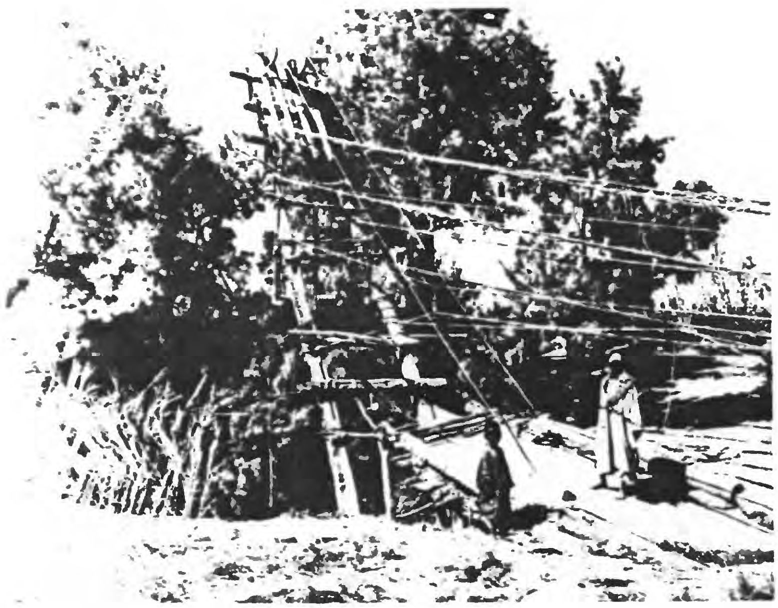

Figure 15. --Dallu tower typical of those used in the western Fezzan. Wells generally attain large diameters with slumping of walls, and towers must be moved periodically to prevent their collapse.

away from the well down an excavated incline. A second rope extending from bucket to the animal causes the bucket to spill into a palm-log trough upon reaching the surface. The water is then led through a system of dirt canals to irrigated plots. The animal is led back to the head of the well in order to return the empty bucket to the water. It has been estimated that the average rate of withdrawal of water by the dallu method is between 2 and 3 mc/hr.

The Italians devised a system of ropes and pulleys employing two dallu buckets, which permitted raising water on the return trip to the well also. Because of the lack of stamina of the draft animals or the intricacies of the system of ropes, or both, the method was never adopted by the native farmer. Attempts to introduce the Persian wheel method of raising water were unsuccessful in the Fezzan. Invariably the wheel was dismantled and the owner of the well reverted to the time-tested dallu tower or well sweep.

The work of raising water is customarily done by men who own no land of their own and apparently have no other means of making a living. They receive a small share of the crops irrigated in payment for their labor. On several occasions, owing to the lack of draft animals, these men were seen to be raising water by toiling up and down the incline themselves.

In the oases of Gat and el Barcat, in the extreme southwestern part of the Fezzan, several flowing wells have been constructed by digging. (See figure 16 and 16a.) This is true also of the region around Edri and el Hatia, in the northwestern part of the map area. In both these areas artesian aquifers are sufficiently close to the surface to be penetrated by hand tools. As a rule the hydraulic head of the water in these wells is low and the flow is not large. The water customarily is impounded in a collecting reservoir during the night for use the following day.

The drilling method of constructing wells has only recently been adopted in the Fezzan and dates from the French occupation during the early part of World War II. Most of the drilling has been confined to areas where there are known supplies of artesian water at relatively shallow depths, and has been devoted to the construction and development of flowing wells to supply water for irrigation projects.

In areas where flowing wells have been constructed by drilling, the drilled hole generally has been continued below the bottom of a previously dug well. (See figure 17.)

Figure 16.--Flowing well near el Barcat dug into Cambrian-Lower Silurian (Ordovician) sandstone. Tunnel leads to cultivated plots to which water flows by gravity. Flow of well is about 16 mc/hr.

Figure 16a.--Flowing well at el Barcat dug into alluvium. Flow was measured at 40 mc/hr.

Figure 17.--Flowing well constructed near el Gotta by drilling hole in bottom of former dug well. Well is uncased and completely uncontrolled.

Casing is seldom used, and the wells are permitted to flow unchecked. The top of the dug well is elevated by rock curbing to raise the level of the water at the well sufficiently to permit it to be led off by means of canals to the surrounding cultivated plots. Wells of this type are numerous, in the Chatti Valley especially. Large quantities of water are wasted, and the unique construction of these wells makes any attempt to control them extremely difficult and expensive once they are completed.

There is little evidence that the owners of these flowing wells have attempted to increase appreciably their area of cultivation to utilize the additional water available. Also, there appear to have been few places where the water has been shared with neighbors.

During the past 6 years 12 flowing wells have been drilled in the Chatti Valley to supply water for the establishment of large-scale community irrigation projects. The wells are 65 to 100 m. deep and their flows range from 2 to 200 mc/hr. They are generally cased to the top of the major aquifer, the Devonian sandstone, and the casing cemented in place. The drilling program was begun by the French Military government of the Fezzan and has been continued by the Libyan Public Development and Stabilization Agency (LPDSA). One large project is in operation at Brach and a second is being planned and constructed under the direction of USOM technicians. Projects at the oases of Gughum, Agar, el Gotta, and Uenzerich have been producing crops on a large scale for about 4 years. In spite of modern methods of construction all the wells are flowing free, and a large amount of water is being wasted. A similar situation exists at Traghen where two of three flowing wells, drilled in 1948, are still uncontrolled.

Village water supplies in the western part of the Fezzan are generally obtained from shallow dug community wells from which water is drawn by means of a rope and bucket. At Brach and Traghen, where flowing irrigation wells are located near the village, water is transported to the homes in jugs carried on the heads of women and children.

CHEMICAL CHARACTER OF THE GROUND WATER

There is a wide variation in the chemical character of ground water in the western part of the Fezzan. Its quality ranges from excellent for domestic uses to acceptable only for the irrigation of plants having high salt tolerance.

The determination of the chemical quality of the water is based primarily upon the chemical analysis of water samples collected by the author in late 1955 and early 1956. Analyses were made by the USOM Agriculture-Natural Resources Laboratory, Sidi Mesri, Tripoli, Libya. The results of analysis of water from wells that were abandoned after completion, and in which the water is no longer accessible, were obtained from the report by Muller-Feuga.

CAMBRIAN AND ORDOVICIAN SANDSTONES

Samples of water were taken for analysis from what are believed to be representative wells in the Gat-el Barcat area. The results of the analyses, shown in the table below, indicate that water in the Cambrian and Ordovician sandstones, though moderately hard to hard, is of excellent quality for all uses. The sample from the water-table well contained a somewhat higher concentration of soluble salts than those from the flowing wells, but the similarity of chemical constituents suggests that the source of the water is principally upward leakage from the underlying artesian aquifers, with some contribution from the alluvium.

Parts per 1/ million	el Barcat (flowing well)	Gat (flowing well)	Gat (water-table well)
pH	6.6	6.7	6.9
Hardness as $CaCO_3$	85	75	125
Ca	11	11	21
Mg	12	7.0	7
CO_3	4	None	4
HCO_3	42	56	79
SO_4	19	53	82
Cl	18	30	44
Temp. (°C)...	30	33	25 1/2

1/ Analyses by USOM Agriculture - Natural Resource laboratory, Sidi Mesri, Tripoli, Libya.

The depths of the wells are 3,6.50 (reported depth 25 m.), and 4 m., respectively, and diameters range from 3 to 8 m. The well at el Barcat flows at a rate of about 40 mc/hr. and the well at Gat about 15 mc/hr.

The low temperature of the water in the water-table well illustrates a phenomenon common to dug wells in which the water has not been disturbed for some time.

The cooling effect of the high rate of evaporation lowers the temperature of the water in the well several degrees below that in adjacent wells which are in use. Undoubtedly, the lower atmospheric temperatures of late fall also contributed to the depression of temperatures of exposed water surfaces. The abnormally high temperature of the water in the flowing well at Gat is probably due in part to the accumulation of heat in the thick concrete roof which covers the well, combined with a reduction of the cooling effect of evaporation at the water's surface.

DEVONIAN SANDSTONES

The quality of the water in the Devonian aquifers is inferior in some respects to that found in the Cambrian and Ordovician sandstones at Gat, but it is excellent for irrigation and suitable for domestic use. However, the chloride concentration in the water from the wells at Uenzerich and el Hatia is somewhat high and gives the water a slightly salty taste. Water temperatures range from a low of 26°C to a high of 37°C; the average is about 30°C. In the following table are given the results of chemical analysis of samples of water from drilled and cased wells in the Chatti Valley. It is believed that the samples obtained are representative of the water occurring in the Devonian sandstones which underlie the area. The LPD and SA well at Brach was chosen as representative of wells in the eastern part of the Chatti Valley, and the well at Berghen as representative of wells in the central part. The wells at Uenzerich and el Hatia are the only drilled and cased wells in the western part of the Chatti Valley.

Parts per million	Brach 1/ (LPDSA well)	Berghen 2/	Uenzerich 1/	el Hatia 1/
pH.............	6.8	7.3	6.6	8.5
Hardness as $CaCO_3$	95	-----	130	90
Conductance (meas. at 25°C)....	755	-----	-----	1,146
Al	Trace	-----	Trace	Trace
Fe	Trace	-----	Trace	Trace
Ca	14	13	27	18
Mg	15	5	15	20
Na+K	116	124	185	------
CO_3	None	48	None	------
HCO_3........	58	-----	135	------
SO_4........	17	28	48	154
Cl	175	165	385	315
Total solids	411	402	797	774
Temperature	28°C	26°C	-----	------

1/ Analyses by USOM Agriculture - Natural Resources Laboratory, Sidi Mesri, Tripoli, Libya.
2/ Analyses from report by Muller-Feuga, 1954, p. 144.

The LPDSA well is 90 m. deep and is cased to 50 m. Its flow is reported to be 75 mc/hr. The well at Berghen is 102 m. deep and is cased to 22 m. The flow is reported to be 2.1 mc/hr. The well at Uenzerich is 82 m. deep and cased to 60 m. The flow when the well was completed was 50 mc/hr. The abandoned well at el Hatia is reported to be 150 m. deep but a tape measurement indicated a depth of only 115 m. During the years of disuse debris falling from the walls probably has partially filled the hole. The yield of the well is not known.

A comparison of analyses of water obtained from wells in the eastern part of the Chatti Valley show the chemical composition to be remarkably consistent. The increase in concentration of salts found in the water samples taken from the wells at Uenzerich and el Hatia may or may not indicate a trend toward greater concentrations westward. The water characteristically has a slight hydrogen sulfide odor which disappears with aeration. Colloidal iron and silica in the water generally form a thin brown scum over the bottom and sides of containers after standing a short while.

LOWER CRETACEOUS (NUBIAN SERIES)

The quality of the water found in the Nubian series is rated as good to excellent for irrigation use and is generally acceptable for most domestic purposes. In areas where water is reported unsuitable for domestic use the poor chemical quality is believed to be the result of contamination by highly saline water in the alluvium overlying the Nubian series.

Analyses of samples of water taken from wells that are thought to obtain all, or most, of their water from the Nubian series are given in the following table.

Parts per million	el Gorda[1]	el Greifa[1]	Umm el Araneb[2]	Traghen[2]	Traghen[2]
pH	7.1	7.1	6.7	7.05	7.1
Hardness as $CaCO_3$..	---	---	---	154	88
Ca	39	14	24	----	---
Mg	8	5	9.3	----	---
Na	16	26	216	----	---
CO_3.......	22	10	---	----	---
SO_4.......	76	40	92	132	94
Cl	28	36	215	354	223
Total solids.	190	150	581	848	584
Temperature (°C)	26	---	---	26 1/2	26 1/2

1 Analyses from report of Muller-Feuga, 1954, p. 146.
2 Analyses by USOM Agriculture - Natural Resources laboratory, Sidi Mesri, Tripoli, Libya.

There are only a few drilled wells in the Fezzan which penetrate the Nubian series. The author was able to obtain water samples from only the wells at Umm el Araneb and Traghen. The wells at el Greifa and el Gorda have been filled, or plugged, with rocks and sand since they were completed. The chemical analyses of the water from these wells were obtained from the report by Muller-Feuga. The well at el Gorda is reported to be 100 m. deep, the well at el Greifa 350 m., the well at Umm el Araneb 150 m., and the wells at Traghen approximately 35 m. deep.

QUATERNARY DEPOSITS

The water obtained from wells dug in the alluvium of the western part of the Fezzan varies in quality from place to place and, in some areas, between adjacent wells. It is believed that the poor quality of water encountered in some wells in both the Chatti and Hofra-Cherguya Valleys is due to the presence of local evaporite deposits which contribute salt to the ground water. In places, such as the valley of Uadi el Agial, the eastern part of the Chatti Valley, and the Sebha oasis, where the water table is generally some distance below the surface of the land, the quality of the ground water is generally good.

The quality of the alluvial water in the Chatti Valley is generally excellent for agricultural use; however, the chloride content is a little high to permit rating it as excellent for domestic consumption. Except for a few wells in the western part of the valley that yield water unsuitable even for irrigation, the chemical composition of the water in the alluvium is generally comparable to that of the two representative samples shown in the table below.

	Parts per million[1]	Brach (Ain Kebir)	Maharuga (Aioune)
1	pH	7	7.1
2	Ca	19	26
3	Mg	10	10
4	Na	110	147
5	CO_3	57	115
6	SO_4	17	109
7	Cl	170	170
	Total solids	340	550

1 Excerpts from analysis by Muller-Feuga, 1954, p. 144-145.

The quality of the water found in the Hofra and Cherguya Valleys varies considerably from place to place and, in some areas, even between adjacent wells. The chloride content of the water is often too high to be desirable for human consumption, although the local inhabitants use it. The excessive hardness causes the water to be generally unsatisfactory for other domestic uses. It is classified as good for agricultural purposes and is used for irrigation of vegetables, grain, and fodder crops. Following are the results of analyses of representative samples of water obtained from dug wells in oases in the Hofra - Cherguya Valleys.

Parts per million [1]	Murzuch (irrigation) well	Murzuch (community) well	Traghen	Umm el Araneb	Tuila	Zuila
pH	7.15	7.3	7.05	6.8	7.4	7.1
Hardness as $CaCO_3$....	400	280	660	740	195	540
Ca	139	94	----	301	42	261
Mg	85	63	----	71	22	62
CO_3........	2	7	----	7	None	4
SO_4........	108	173	645	247	192	77
Cl	895	1,400	766	920	490	625
Total solids	-----	---	2,440	---	1,230	---

1 Analyses by USOM Agriculture - Natural Resources Laboratory, Sidi Mesri, Tripoli, Libya.

Samples of water taken from wells in the oases of Ubari and el Greifa in the valley of Uadi el Agial were found to be similar in chemical composition. The water in the el Greifa well is somewhat higher in hardness and concentration of sulfates than the water in the well at Ubari, but it still qualifies as good for both agricultural and domestic use. There is some variation in the quality of the water locally in the valley of Uadi el Agial, but no wells were reported to yield water unfit for human consumption. The chemical analyses of the water from the Ubari and el Greifa wells are shown below.

Parts per million [1]	Ubari	el Greifa
pH	6.9	7.4
Hardness as $CaCO_3$.....	130	225
Ca	79	87
Mg	19	16
Na	---	---
CO_3..................	4	None
HCO_3	28	11
SO_4	86	154
Cl	145	152
Total solids	---	---

1 Analyses by USOM Agriculture - Natural Resources Laboratory, Sidi Mesri, Tripoli, Libya.

Samples of water from dug wells in the oases of Maaten Truna and Gbr Oun, in the midst of Ramla Zellaf, were obtained with some difficulty. The 200 km. round trip was made by camel caravan and required 5 days of travel. Owing to a miscalculation in the amount of time required for the camels to retrace the route up the steeper leeward slopes of the dune masses against strong headwinds, it was necessary to consume some of the water collected as samples; consequently, insufficient water was salvaged to permit a complete chemical analysis. The results of analyses of water from the lake at Maaten Truna and an adjacent well and water from a well at Gbr Oun are shown in the following table.

Parts per million	Maaten Truna 1/ (lake)	Maaten Truna 2/ (well)	Gbr Oun 2/ (well)
pH	8.4	7.6	7.5
Hardness as $CaCO_3$	--	65	175
Ca	71	18	54
Mg	104	7	21
Na	51,300	--	--
CO_3	19,000	4	2
HCO_3	19,000		

1/ Analysis by Muller-Feuga.
2/ Analysis by USOM Agriculture-Natural Resources Lab., Sidi Mesri, Tripoli, Libya.

It is interesting to note that the water obtained from the wells in these oases is of good quality in spite of the close proximity of highly saline lakes. This can be seen by a comparison of the quality of the water from the well at Maaten Truna with that obtained from the nearby lake. The well is only about 200 m. from the lake shore.

CONCLUSIONS AND RECOMMENDATIONS

The development of ground water in the Fezzan presents two entirely dissimilar problems. One is the development of additional supplies of water in areas where inadequate or inferior supplies exist; the other is the control of water in areas where wasteful over-development of the artesian aquifer has occurred.

POSSIBILITIES OF DEVELOPING ADDITIONAL SUPPLIES OF WATER

Gat-el Barcat Area

The possibilities of developing additional water supplies in the southern part of the valley of Uadi Tanezzoft are very favorable. Water in the Cambrian and Ordovician rocks is generally encountered at depths of 4 to 6 m. and almost everywhere in the area rises to within a few centimeters of the land surface. Flowing wells have been excavated in the rather soft and friable sandstones with hand tools. Relatively shallow drilled wells will probably yield large amounts of water under considerable artesian pressure. It is believed that existing wells are withdrawing only a small part of the large supply of water contained in the aquifer, and that a substantial increase in development by the construction of new wells or the deepening and cleaning of present wells will have little effect upon the artesian reservoir. However, care should be taken in the location of additional wells to prevent local overconcentration of withdrawal and a resulting decrease in yields of wells in such areas. Chemical analyses indicate that the water is of suitable quality for both irrigation and domestic use.

Chatti Valley

The writer believes that the development of additional supplies of water from the Devonian sandstone in the Chatti Valley is feasible and, if carefully supervised, will have no serious effect upon the artesian pressure in the aquifer. This opinion is based upon the assumption that the flows of existing wells may be controlled, or more efficiently utilized, and that future drilling in the area will be regulated as to location and method of well construction. In the western part of the Chatti Valley, where the artesian pressure is insufficient to cause water to flow at the surface, large supplies of water can probably be obtained at relatively shallow depths from wells equipped with pumps. Wells that obtain water from the alluvium generally can be improved by deepening and cleaning. In the absence of evidence of a declining water table, it is believed that additional water can be safely withdrawn from the alluvium by constructing new wells.

Valleys of Uadi el Agial and Hofra - Cherguya Valleys and oases between Sebha and Umm el Abid

In the Uadi el Agial and Hofra - Cherguya Valleys and the oases extending from Sebha to Umm el Abid the deeper wells generally obtain water from the underlying Nubian series. Because the Nubian series is preponderantly of continental origin the water-bearing sandstone members may change laterally, in both composition and thickness, and wells dug or drilled into these strata are apt to meet with varying success. It is believed, however, that moderately shallow drilled wells penetrating the Nubian series to depths ranging from 30 to 50 m., in most places, will yield relatively large amounts of water by pumping. Data obtained from records of earlier exploratory drilling in the region indicate that, except for the eastern part of the Hofra Valley, much deeper drilling (perhaps 200-400 m.) will be required to encounter water under sufficient pressure to flow at the surface.

It is believed that a large part of the recharge of water into the alluvium of the oases is from the underlying Nubian sandstones. Consequently, additional water probably can be obtained by deepening and cleaning existing wells or digging new ones without seriously affecting the water table.

CONTROL, UTILIZATION, AND IMPROVEMENT OF PRESENT SUPPLIES OF WATER

It is apparent that, if the ground-water supply is to be effectively conserved and utilized, some method will have to be devised to regulate the uncontrolled flow of wells in the Chatti Valley, especially in the Brach area. The present drain upon the artesian aquifer may, in time, seriously reduce the pressure in the ground-water reservoir to such an extent that wells in some areas may cease to flow. There are about 50 flowing wells in the Chatti Valley, more than half of which are concentrated in the vicinity of Brach. (See figures 18 and 19.) The depths of these wells range from 23 to 101 m., and their flows range from less than 10 to nearly 200 mc/hr. It was computed from discharge measurements made on 25 flowing wells in the vicinity of Brach that about 21,000 cubic meters (about 5,500,000 gallons) of water is discharged daily from the Devonian sandstones through the flowing wells in that area. (See figure 20.) It is estimated that nearly one-third of this amount is wasted. The five largest wells in the areaaccount for nearly half the total withdrawal and practically all the waste. The water from these large wells is used for irrigation only during the daylight hours; consequently, water is wasted during the night. During the time since these wells were constructed, the evaporation of large amounts of water has resulted in deposition of excessive quantities of salts in the soil, with the result that large areas are now unsuitable for cultivation, and the soil may be permanently damaged. (See figure 21.)

It is understood that attempts will be made to control the flow of these wells by setting steel casing which will extend from the land surface several meters into the drilled section of the well. (See figure 22.) When in place the casing will rest on a flange which will form a more or less tight seal between the drilled hole and the dug section. Hydraulic cement will be run into the bottom of the dug hole to form a concrete plug about 1 m. thick. The hole will then be packed to within 1 m. of the surface with clay and gravel to reinforce the plug and stabilize the casing. A second concrete plug will fill the remainder of the hole to reduce the possibility of upward seepage of water. A "T" connection at the top of the casing will permit the installation of two shut-off valves to control and direct the flow of the well. It is realized that there are problems involved in this method of control that will require the services of a skilled

Figure 18.--Flowing well (Ain Neucf) drilled by French 3 km. west of Brach. Well is cased, but control valve has been removed. Flow is about 100 mc/hr.

Figure 19.--Ain Bizanti at Brach is reportedly cased, but flow is uncontrolled. Flow is nearly 200 mc/hr. Drilled hole is in center of concrete basin.

Figure 20.--Measuring flow of water through one of two main canals at Ain Bizanti, Brach oasis, with a 90° V notch weir.

Figure 21.--Example of soil impregnated with salt deposited by waste water from wells in Brach oasis.

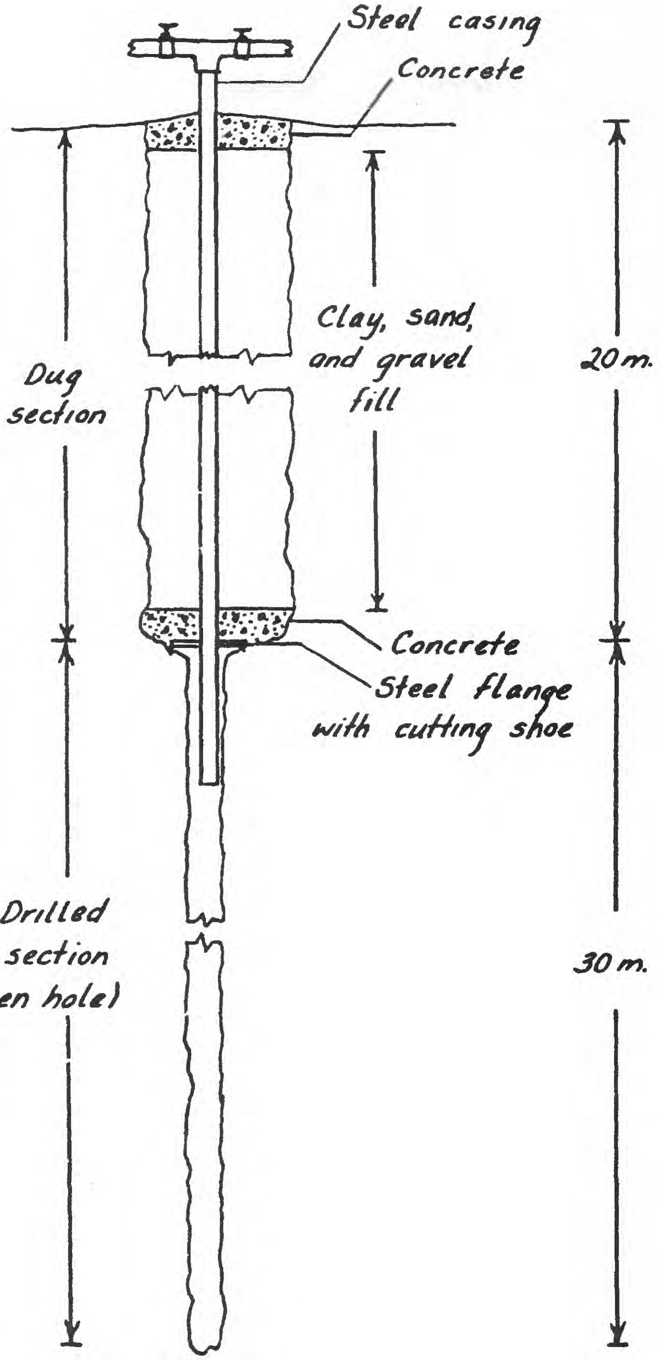

Figure 22.--Sketch of proposed method of controlling flow in a typical well in the Chatti Valley.

well driller and equipment and material that is not yet available. However, it is believed that benefits to be derived from the control of the flow of these wells would warrant the expenditure of the necessary time and money.

In the event this method of control is unsuccessful, the only alternative is to lead the excess water out of the area through lined impermeable canals and store it in excavated tanks for use on adjacent land. This method will not reduce the amount of water being withdrawn from the aquifer but will permit a wider use of the water available, and reduce the amount of salt being deposited in the soil by waste water that migrates laterally through the walls of the existing soil-lined ditches.

In conjunction with the program of control of the flow of wells, a system of drainage ditches could be installed in areas where excess amounts of salt have already been deposited in the soil. Where the soil is not permanently damaged, much land may be recovered by carefully supervised irrigating and the resulting flushing out of the salt into the drainage ditches. The "jdula" system of irrigating, which permits the water to stand in small plots, generally 2 by 3 m., until it is absorbed into the soil, is conducive to rapid concentration of salt in the water and subsequent deposition of salt in the soil. The crust of salt thus formed beneath the surface further retards absorption of the water by the soil, with the result that ever increasing amounts of water are lost through evaporation and proportionately greater amounts of salt are deposited. More modern methods of irrigation, which would cause the water to flow through the cultivated area, would eliminate much of the salt deposition.

During the past 4 or 5 years, there have been reports of decreasing flows in several wells in the Brach area. The flows of two wells are reported to have failed completely during one night, the water level in the wells dropping several meters below the surface. The fact that the reportedly failing wells are in areas where neighboring wells were unaffected suggests that the difficulty is the result of faulty construction rather than a general decline in water levels. The interbedded clays encountered in drilling through the Carboniferous series perhaps collapsed into the hole and sealed off the artesian aquifer, and the water level in the wells declined to the level of the water table in the surrounding surficial material. It is believed that the yields of these wells may be recovered by cleaning them out with a simple hand-operated tripod and sand bucket.

There is much work that could be done to improve existing dug wells. The yield of many could be increased by cleaning and deepening. The installation of concrete or rock caissons would prevent the slumping and caving of the walls of the wells. Rock curbings would reduce the amount of surface contamination of existing wells and prevent much of it in new wells.

NEED FOR FUTURE HYDROLOGIC STUDIES

As a result of the present study it is concluded that there are large amounts of water in the Fezzan that may be obtained from relatively shallow depths by pumping. (See plate 2.) A study of comparative costs may reveal that it is more economical in some areas to drill shallow wells and install pumps than to attempt to reach deeper aquifers that might yield flowing water. The installation of centrifugal pumps on several irrigation wells at Sebha, at least 2 at Murzuch, 1 at el Greifa, and possibly others elsewhere indicates that there are local farmers who feel it is feasible to pump water where adequate supplies are available and there is sufficient cultivatable land upon which to utilize the water.

Attempts should be made to evaluate the yields of representative dug wells in the oases of the western Fezzan and to advise interested farmers of the type of pump that will meet their needs. (See figure 23.) Some of the pumps that are in operation are much too large for the yield of the wells, so that their installation and operation have been unnecessarily costly.

Detailed hydrologic studies should be made in areas where existing supplies of water are inadequate or unsuitable for irrigation or human consumption. Such studies should begin with an investigation of any deep drilled wells that were abandoned, apparently because the water encountered was not under sufficient artesian pressure to flow. It is believed that most of these wells will yield appreciable amounts of water from relatively shallow depths by pumping. For example, the test made on the abandoned shallow drilled well at Murzuch indicates it will yield approximately 7 mc/hr for each meter of drawdown, or about 23 mc/hr from a depth of 7.50 m. The drilled wells at Umm el Araneb and el Hatia should be similarly

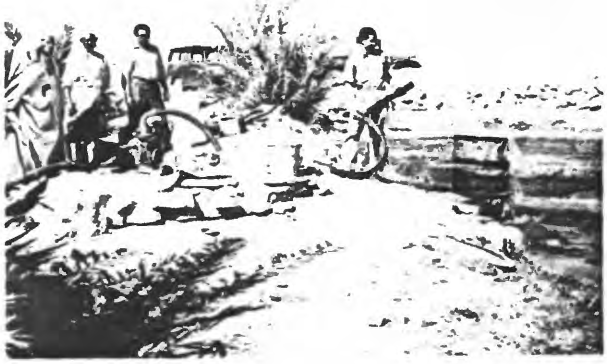

Figure 23.--Measuring yield of well (Bir Omar Lazuni) at Zellouaze oasis with centrifugal pump. Flow of 9 mc/hr reportedly about half the yield of well when completed. Pump produced 11 mc/hr with 1.10 m. drawdown of water level.

tested to determine their yield. The well at el Hatia is reported by local residents to have produced a large amount of water when completed. The deep well at el Gorda in the Sebha oasis is reported by the driller to have produced 100 mc/hr by pumping from a depth of about 5 m. The deep well at el Greifa, tested by bailing when completed, yielded 11 mc/hr for each meter of drawdown. Unfortunately, these wells have become filled with sand since completion and cannot be tested.

A limited test-drilling program would be warranted to explore the possibilities of developing wells in areas where there is an urgent need for dependable supplies of water suitable for domestic use. Such supplies can best be insured by the construction of properly cased drilled wells. Casing will shut out the shallow alluvial water, which is generally inferior in quality to the water in deeper aquifers. It will also greatly reduce the possibility of contamination of the water from the surface and from the migration of contaminated water into the drilled well from nearby dug wells.

Well drilling in the Fezzan, for obvious reasons, is expensive, and the maintenance of pumping equipment is a serious problem in a region where few people understand even the most rudimentary mechanical principles. Under present conditions, therefore, drilling projects can be expected to be economically feasible only when the water obtained is suitable in quality for a community supply or adequate in quantity for a large-scale community irrigation system.

It is believed that the most efficient plan would be to direct any drilling program toward the development of community supplies. The hydrologic information resulting from test drilling, and from actual use of the water, may be used to determine the feasibility of developing water later for irrigation.

In the opinion of the writer, dug wells are, and will remain for some time, the most practicable method of obtaining water for irrigation by the small farmers. They are inexpensive to construct, and water can be raised with a minimum of mechanical equipment. The quantity of water that can be raised by the dallu tower or well sweep is generally adequate to irrigate the small plots of land the individual families are able to plant and cultivate. The quality of the water in most places is suitable for the small variety of staple crops which comprise the major part of the diet of the native Fezzanese and is generally acceptable for domestic use.

DRILLERS' LOGS OF WELLS DRILLED IN THE WESTERN PART OF THE FEZZAN

Table 2 contains descriptions of the character and thicknesses of the rock units encountered in 10 wells drilled in the western Fezzan. Nine of the wells are in the Chatti Valley and one, the well at Tuila, is in the Hofra Valley. Other wells have been drilled in these areas, but logs of only the 10 tabulated below are available. The descriptions were obtained from logs prepared by the drillers and were translated from the French by the author. The terminology used is essentially that of the driller. Stratigraphic interpretations are by the author. The wells were drilled during the French military occupation of the Fezzan after World War II. Drilling was by the rotary method.

Table 2.-- Drillers' logs of wells drilled in the western part of the Fezzan

	Thickness (meters)	Depth (meters)
Well at Debdeb		
Quaternary		
Sand, clays, and gypsum, with stringers of sandstone	7.80	7.80
Lower Carboniferous		
Tournasian		
Clay, yellowish, slightly sandy	2.60	10.40
Clay, red and brown, very compact	2.10	12.50
Clay, gray, compact	13.70	26.20
Clay and sandstone, interbedded, gray, hard	10.95	37.15
Sandstone, gray, very hard	0.35	37.50
Clay, gray, compact	2.20	39.70
Devonian		
Sandstone, gray, hard	5.10	44.80
Clay, gray, compact	2.10	46.90
Sandstone, gray, hard	4.60	51.50
Sandstone, conglomeratic, coarse-grained, quartizitic	6.00	57.50
Sandstone, white, soft, fine-grained	10.20	67.70
Sandstone, hard, clayey	2.30	70.00
Sandstone, soft, clayey	1.20	71.20
Clay, white, sandy, with interbedded sandstones, red	2.40	73.60
Sandstone, white, soft	1.10	74.70
Sandstone, white, hard	0.90	75.60
Clay, white, sandy	1.40	77.00
Sandstone, white, hard, fine-grained; some clay layers	13.00	90.00
Bottom of hole		

Table 2.--Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters
Well at Zellouaze		
Quaternary		
Sand	0.50	0.50
Lower Carboniferous		
Tournasian		
Clay, maroon, very sandy	5.50	6.00
Clay, maroon and yellow	4.00	10.00
Clay, gray and yellow, grading into sandstone, yellow, soft	10.00	20.00
Devonian		
Sandstone, gray, hard	36.00	56.00
Sandstone, blue, clayey	12.50	68.50
Sandstone, yellow, very hard	0.80	69.30
Sandstone, yellow, soft	11.00	80.30
Sandstone, yellow, with clayey zones	6.50	86.80
Sandstone, clayey	7.00	93.80
Bottom of hole		
Well at Guhgum		
Quaternary		
Sand, some shell fragments	1.20	1.20
Lower Carboniferous		
Tournasian		
Clay, yellow and red, with stringers of sandstone	1.00	2.20
Sandstone, grayish, rather hard	0.80	3.00
Sandstone, grayish, with their layers of clay, red, brown, sandy	4.70	7.70
Clay, red and brown, sandy	0.80	8.50
Clay, gray, red and yellow; sandy	7.20	15.70
Sandstone, gray and black, very hard	1.00	16.70
Clay, gray, sandy, with layers of harder sandstone, gray ,	7.70	24.40
Clay, gray, rather sandy	24.20	48.60
Sandstone, gray, fine-grained	3.40	52.00
Clay, gray, rather sandy	10.00	62.00
Devonian		
Sandstone, white, soft	3.00	65.00
Bottom of hole		

Table 2.--Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters)
Well at Mahruga		
Quaternary		
Sand, with sandstone stringers	1.00	1.00
Sandstone, dark-brown, hard	0.50	1.50
Lower Carboniferous		
Tournasian		
Clays, variegated, red, gray and yellow, sandy	11.50	13.00
Sandstone, yellowish, soft	2.90	15.90
Sandstone, brown, hard	0.40	16.30
Clay, gray, sandy	2.40	18.70
Clay, gray, sandy; interbedded with sandstone, gray, fine-grained	3.80	22.50
Sandstone, whitish, fine-grained	2.00	24.50
Clays, sandy	10.50	35.00
Sandstone, yellowish	1.00	36.00
Clay, gray, sandy	2.50	38.50
Devonian		
Sandstone, white, soft, fine-grained	13.00	51.50
Clay, gray, sandy	2.40	53.90
Sandstone, white, soft, fine-grained	6.90	60.80
Sandstone, white, soft, coarse-grained	1.60	62.40
Sandstone, white, soft, fine-grained	3.60	66.00
Clays, variegated gray and red, slightly sandy	8.90	74.90
Sandstone, hard	0.80	75.70
Clay, white and red, sandy	2.50	78.20
Sandstone, white, soft	4.50	82.70
Clay, red, white and yellow; sandy	3.70	86.40
Sandstone, yellowish, clayey	0.80	87.20
Sandstone, black, very hard	0.10	87.30
Sandstone, white, soft	0.30	87.60
Clay, gray	1.00	88.60
Sandstone, red, clayey	1.40	90.00
Bottom of hole		

Table 2.--Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters)
Well at Gorda		
Quaternary		
Sand and gypsum	1.20	1.20
Lower Carboniferous		
Tournasian		
Clay, compact, and sandstone, greenish	5.00	6.20
Clay, gray, with thick stringers of sandstone, brown	9.30	15.50
Clay, gray, sandy	2.00	17.50
Devonian		
Sandstone, whitish	2.00	19.50
Sandstone, whitish, soft	6.50	26.00
Sandstone, gray	1.00	27.00
Sandstone, gray, clayey	1.30	28.30
Sandstone, white, soft	4.20	32.50
Sandstone, gray, clayey	3.00	35.50
Sandstone, hard, and clay, gray	1.20	36.70
Sandstone, grayish, clayey	1.00	37.70
Clay, gray	0.80	38.50
Sandstone, gray, very clayey	9.50	48.00
Sandstone, whitish, little clay	1.50	49.50
Sandstone, white, very soft, with layers of harder sandstone and white clay	17.00	66.50
Bottom of hole		
Well at Agar		
Quaternary and Lower Carboniferous,		
Undescribed	75.00	75.00
Lower Carboniferous		
Sandstone, yellow, fairly hard	1.00	76.00
Clay, gray, sandy	3.00	79.00
Sandstone, gray, hard	1.00	80.00
Clay, gray, yellow and red; rather hard	11.00	91.00
Devonian		
Sandstone, yellow, soft; with layers of white coarse-grained sandstones	5.50	96.50
Sandstone, yellow, soft	0.20	96.70
Clay, gray, slightly sandy; with layers of compact red clay	3.70	100.30
Bottom of hole		

Table 2.--Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters)
Well at Berghen		
Quaternary		
Sand, yellow, clayey, with stringers of sandstone	8.40	8.40
Sand, gray	2.10	10.50
Lower Carboniferous		
Tournasian		
Clay, gray, sticky	1.50	12.00
Clay, red, compact	6.00	18.00
Devonian		
Sandstone, white, very hard	24.00	42.00
Sandstone, yellow, clayey	1.30	43.30
Sandstone, gray, soft	7.50	50.80
Sandstone, very hard	9.20	60.00
Clay, gray, sandy, grading into sandstone, yellow and white, soft	8.00	68.00
Sandstone, gray, very hard, clayey	28.00	96.00
Sandstone, clayey	6.00	102.00
Bottom of hole		

Table 2.-- Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters)
Well at el Gotta		
Quaternary		
Clay, yellow and gray	0.60	0.60
Sand, clay and gypsum	1.40	2.00
Lower Carboniferous		
Tournasian		
Clay, gray and reddish, very compact	7.50	9.50
Clay, light-gray	1.00	10.50
Clay, gray, sandy	2.30	12.80
Clay, light-gray	2.90	15.70
Sandstone, very hard	0.60	16.30
Clay, gray, sandy	6.70	23.00
Sandstone, white, coarse-grained	4.80	27.80
Sandstone, gray, very hard	0.45	28.25
Clay, gray, sandy	5.45	33.70
Sandstone, gray, clayey	2.40	36.10
Sandstone, gray, very hard	1.70	37.80
Clays, interbedded, gray, and sandstones, white, clayey	1.40	39.20
Sandstone, white, with layers of sandstone, hard	3.20	42.40
Clay, gray, very compact	5.55	47.95
Clay, gray, sandy, very compact, with interbedded sandstones, hard	0.85	48.80
Clay, gray, sandy, very compact, with interbedded sandstones, hard	5.70	54.50
Devonian		
Sandstone, gray, clayey, very compact	1.20	55.70
Sandstone, white, soft	0.30	56.00
Sandstone, white, soft, porous	4.70	60.70
Sandstone, white, clayey	2.10	62.80
Sandstone, very hard	0.20	63.00
Sandstone, gray, clayey	3.50	66.50
Sandstone, yellow, soft, porous	6.20	72.70
Sandstone, hard	1.50	74.20
Sandstone, very clayey	1.80	76.00
Clay, variegated white, pink and yellow, sandy	21.10	97.10
Sandstone, white, porous	3.20	100.30
Clay, gray, sandy	0.50	100.80
Bottom of hole		

Table 2.--Drillers' logs of wells drilled in the western part of the Fezzan - Continued

	Thickness (meters)	Depth (meters)
Well at el Hatia		
Quaternary		
Sand, yellow	0.40	0.40
Lower Carboniferous		
Tournasian		
Sandstone, gray and yellow	2.80	3.20
Clay, red and yellow, rather sandy	5.90	9.10
Devonian		
Sandstone, yellow, rather hard; contains coarse grains of white silica	87.50	96.60
Sandstone, white, moderately hard	7.40	104.00
Clay, gray, sandy, and sandstone, white, moderately hard	6.80	110.80
Sandstone, white, soft, ...	39.20	150.00
Bottom of hole		
Well at Tuila		
Quaternary		
Sand, yellow	21.65	21.65
Sand, yellow, coarse-grained, somewhat consolidated; contains hard layers	11.45	33.10
Lower Cretaceous		
Nubian Series		
Sandstone, red, hard, clayey	2.20	35.30
Sandstone, yellow, conglomeratic, and gravel conglomerates; harder below 46 m.	34.70	70.00
Sandstone, yellow, conglomeratic, with lenses of gravel conglomerates, soft	80.00	150.00
Bottom of hole		

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