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GROUNDWATER RESOURCES OF THE SAHEL, WEST OF SUDAN

by

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1. INTRODUCTION

The ground-water resources of the Sahelian zone west of Sudan are outlined from information derived from existing publications and reports.

The recent drought (1965 - 1973) has stimulated research into the development of reliable supplies of ground water, but the results of much of this work have not yet been published.

Due to the former great extent of French colonial influence in this part of the world the vast majority of available literature is in French and has not been translated. Many references are obtainable only in Paris or in the country concerned.

1.1 GEOGRAPHY (Figure 1)

Roche et al (1976) define the Sahel as the semi-arid to savannah zone between the 300 mm and 750 mm average annual isohyets. This is quite a restricted latitudinal belt where rainfall is sufficient only to maintain pastoralism. Other authors consider that the Sahel extends south to the latitude of the Gulf of Guinea, and this area has been used for the purpose of this report. Since the major sedimentary basins of the Sahel extend north into the Sahara their borders have been used to define the northern limit of the area under consideration.

The region defined above occupies the greater part of the 'bulge' of the African continent. The area is approximately 4,000 km east-west by 2,500 km north-south, lying between latitudes 17°W and 23°E and between longitudes 5°N and 25°N. The countries within the region are: Benin (formerly Dahomey), Chad, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. Parts of Algeria, Cameroon, Central African Republic and Sudan are also included.

1.2 MORPHOLOGY AND DRAINAGE

The morphology of the region is dominated by a westward tilted Tertiary plateau surface which has resulted in flat-topped massifs such as Ahaggar and

Tibesti. The highest peaks are in the order of 1000 m in Tibesti and Darfu (Sudan) in the east, falling to 500 m in the Fouta Djallon.

There are three major areas of low-lying country: the Djouf (Taoudeni) and Chad basins and the coast of the Gulf of Guinea and Atlantic Ocean. The basins range from 150 m to 460 m above sea level and are areas of inland drainage for ephemeral wadi flows. There are also several perennial streams which flow into Lake Chad from the more humid south: the largest of these is the Chari which drains the Ubangi Plateau (Central African Republic). The Djouf basin also drains to the central Niger. Drainage systems leading to the coast are perennial, the most northerly being those of the Rivers Senegal and Niger. The course of the Niger is doubtless influenced by river capture: it is hypothesised (Blij, 1964) that before Africa broke away from America during Mesozoic lifting, all drainage on this part of Gondwanaland was to interior basins resulting in the northeasterly direction of the upper reaches of the Niger. After separation coastal drainage became more vigorous and cut back northwards along a NW-SE fault zone to capture the Niger, thus diverting its course towards the sea.

1.3 CLIMATE (Figure 1)

The climates of the region range from desert in the north through latitudinal belts of semi-desert and savannah to tropical along the coast.

The desert climate of the Sahara is hot and dry with occassional and unpredictable rainfall. Temperatures may reach 54°C during the day, dropping to 12°C at night. Long term average precipitation is less than 100 mm per annum, and evapotranspiration in the order of 3,000 mm per annum. In the semi-desert (steppe) zone there is sufficient rainfall to support scattered grass. It does not usually exceed 500 mm annually.

In the Savannah average annual precipitation is in the order of 1,200 mm, but there is a distinct dry season between November and March. Average annual temperature is about 25°C with a range usually less than 8°C. Bathurst (Gambia) is typical of this climate; with a total annual rainfall of 1209 mm:

	J	F	M	A	M	J	J	A	S	O	N	D
T°C	23.3	23.9	24.4	24.4	25	26.7	26.7	26.1	26.7	30.6	26.1	23.9
Pmm	0	0	0	0	5.1	73.7	276.9	497.8	254.0	94.0	5.1	2.5

Savannah landscapes are typified by scattered trees and tall grasses.

The climate of the coastal tropical belt is determined by the convergence of hot, dry air from the Sahara with warm moist air from the South Atlantic. In the west there are two monsoonal peaks of precipitation separated by a short dry season, while in the east there is only one peak. Annual precipitation can be more than 4,000 mm. Axim (Ghana) and Freetown (Sierra Leone) are examples of different patterns of precipitation in this zone:

Average Precip. mm

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Axim	50.1	61.0	127.0	142.2	419.1	533.4	154.9	53.3	83.8	203.2	190.5	88.9	2108
Freetown	15.2	12.7	27.9	137.2	375.9	541.0	934.7	990.6	825.5	386.1	134.6	33.0	4430

There is a small enclave of drier conditions along part of the Ghana-Togo coast, but elsewhere general moist, warm conditions prevail throughout the year. The high humidity is occassionally relieved by dry hot winds (Hartmattans) from the Sahara.

Potential evapotranspiration is usually estimated by Thornthwaite's method (Thornthwaite, 1948) since there are few, if any, climatalogical stations where parameters necessary for Penman's (1948) method are recorded. The potential rate increases with average annual temperature from north to south, from less than 1,000 mm in the south to over 3,000 mm in the Sahara. Actual rates of evapotranspiration vary with the amount of available moisture and thus increase from north to south, where actual evapotranspiration rarely falls below the potential rate.

Roche et al (1976) have examined the available climatic data for the region and conclude that droughts of similar intensity to the recent one recur in the order of once every 50 years.

2. GEOLOGY

All periods of geological history, from the Pre-Cambrian to Recent are represented in this part of Africa.

The more arid regions have been least explored due to difficult access, and to the extensive cover of sand dunes which obscure the solid geology. Much of the original research and mapping of results was undertaken by the colonial powers of France, Great Britain, Portugal and Belgium.

The broad outline presented below is taken largely from Furon (1963) and from maps at a scale of 1 : 5,000,000. Further details are available from various symposia (e.g. The Granites of West Africa, Unesco 1968), and from publications of the geological surveys of the constituent countries and the countries mentioned above. Publications containing references to hydrogeological surveys listed in the bibliography often contain a substantial amount of geological information.

2.1 TECTONICS AND STRUCTURE

West Africa is part of the stable African plate and has therefore been little disturbed tectonically.

The basement lies at or near the surface where it has been upwarped, and these outcrops form the present higher land. Volcanoes have developed locally (as in the Tibesti massif along lines of faults in these regions of updoming.

Sedimentary basins have formed in regions of subsidence, usually in tectonic troughs bounded by major faults. They have been subject to Hercynian, Alpine and Recent tectonic undulation. The locations of the major basins are shown in Figure 2.

The major fracture systems are oriented NW-SE and NE-SW, cutting almost at right-angles. These structures have been reactivated throughout the sedimentary history. There are also N - S structures of Pre-Cambrian age (such as the horst of the Air massif) which have not affected the sedimentary cover.

Many geological maps of the region have been published at various scales. Of those seen the International Tectonic Map of Africa (UNESCO, 1968) at a

scale of 1 : 5 million gives the clearest picture of the geology and structure of the region. Other maps published up to 1963 are listed by Dixey (1963).

2.2 PRE-CAMBRIAN

The crystalline Pre-Cambrian basement complex crops out over almost one third of the surface area of West Africa. The most extensive outcrops are a wide band from Sierra Leone to Nigeria, the Cameroon mountains and Ubangi-Chari divide, the Chad-Sudan border area in the east, and in Mauritania in the west. It also forms the central Saharan massifs of Tibesti and Ahaggar.

In Nigeria and Hadjer al Hamis (immediately south-east of Lake Chad) the Pre-Cambrian has not been sub-divided (up to 1960). In Nigeria the basement complex of gneisses, mica-schists, schists and amphibolites which crops out over half of the country has been invaded by batholiths of "Older Granites". In the Bauchi Plateau on the left bank of the River Niger are younger biotite and riebeckite granites. Rhyolites are characteristic of Hadjer-el-Hamis.

In most areas three divisions are generally recognized: Lower, Middle and Upper Pre-Cambrian. The lithologies of each division are fairly consistent from place to place but the nomenclature is variable.

2.2.1 Lower Pre-Cambrian

This group is generally known as the Suggarian in the Sahara region, while to the south it is usually called the Dahomeyan. In some Pre-Cambrian terrains it has not been positively identified, as in the 'bend' of the Niger, in Ivory Coast and Upper Volta.

The rocks are predominantly schistose, consisting of gneisses, mica-schists, quartzites, marbles and amphibolites which have all been cut and migmatised by the Older Granites. In Togo and Benin basic intrusives are more important.

In the Ahaggar massif the Suggarian is at least 20,000 m thick. The basal Arechchoum Series is composed of biotite and amphibole gneisses with intercalations of marble and quartzite. These form the western and eastern zones of Ahaggar, outcropping widely in Tanezrouft and Adrar des Iforas. Above comes the Egere

Series which is richer in quartzites and marbles. Intense regional metamorphism has resulted in migmatisation of all the lower units. This was followed by folding and intrusion of granites, the folds being aligned N-S. A charnokite zone some 20 km wide known as the In Ouzzal Series extends 600 km from Tanezrouft to Adrar des Iforas.

In Adrar des Iforas the Suggarian appears in a north-south horst with submeridional ranges of quartzites, marbles and amphibolites associated with foliated gneisses. The folds are symmetrical and rarely overturned.

The Tazizlet Series constitutes the major part of the Air massif and is equivalent to the Suggarian of Ahaggar, with similar rock types and tectonic history.

In western Mauritania the Amsaga Series is also equivalent to the Suggarian of the central Sahara. A variety of gneisses, often ferruginous, are intercalated with mica-schists, quartzites, marbles and amphibolites. They have been tilted vertical, folded and intruded by granites.

In Senegal the Dahomeyan seems to be represented by the Thiagnaf Mica-schists on the right bank of the Senegal River.

In Sierra Leone the Lower Pre-Cambrian is represented by the 'Kasila System' and by the Kambui and Sula Schists which are cut by pegmatites.

In Guinea and south-eastern Ghana the Dahomeyan consists largely of granites and garnetiferous gneisses. The assemblage is intensely folded.

The Atacora Range extends more than 1,000 km in a SSW-NNE direction from the Accra region of Ghana, through Togo and north-west Benin into western Nigeria. The Dahomeyan outcrops over a wide area in the centre and east of this range, and consists of granites, gneisses and micaschists. The gneisses are affected by NNE-SSW folds.

The Lower Pre-Cambrian of Cameroon consists of highly tectonised crystalline schists and Older Granites. In the Ubungi-Chari Divide a great variety of gneisses outcrop.

2.2.2 Middle Pre-Cambrian

The Middle Pre-Cambrian follows with major unconformity. In the Sahara it is called the Pharusian and Akjoujt while to the south it is known as the Atacorian and Birrimian. The group consists of folded and granitised series in many places, the main rock types being schists, quartzites, and stromatolite marbles. Metamorphism is less intense than in the Lower Pre-Cambrian.

Pharusian deposition of Ahaggar was accompanied by intense volcanic activity so that conglomerates, quartzites and stromatolitic marbles accumulated with acid volcanics a thickness of 15,000 m. The series has been metamorphosed, and folded along N-S axes. The oldest granite intrusions are migmatitic or in concordant batholiths. There is a later group of discordant granites and finally alkaline granites sometimes associated with rhyolites as at In Zize. Similar conditions pertained in the Phurusian of Adrar des Iforas, where outcrops are east and west of the Suggarian horst. The andesitic volcanics occur mainly in the basal 1,000 m. In the Air massif the Middle Pre-Cambrian is known as the "Proche-Tenere" Series.

The Akjoujt Series of Mauritania covers a large part of Inchiri. The succession contains schists, marbles and ferruginous quartzites which have also been intruded by syn-tectonic and post-tectonic granites. Folds are subdued and regular.

In Senegal, light coloured muscovite quartzites are unconformable on the Thiagnaf Mica-Schists. They may be Birrimian or more recent.

In Guinea and Sierra Leone a variety of schists and quartzites have been progressively assimilated by granite batholiths. There are also many discordant batholiths. The series is known as the Marampa Schists in Sierra Leone, while the Middle Pre-Cambrian of Guinea has been divided into three by Roques (1948): Atacorian (Simandou and Nimba quartzites); Lower Birrimian (schists, quartzites and arkoses of the Siguiri Basin); Upper Birrimian (schists, quartzites and greenstones or metamorphosed lavas). Fold directions are generally N-S. On the borders of Guinea, Liberia and Ivory Coast is an assemblage 5,000 m thick which has been little affected by granitisation.

In the bend of the Niger the Birrimian is represented by the Yatakala Series which comprises schists, quartzites and greenstones.

Much of the surface of Ivory Coast and Upper Volta is occupied by concordant granite batholiths. The garnetiferous quartzites of the Atocorian are only present as isolated remnants in the west, while Lower Birrimian schists and quartzites cover large areas of the major river basins. The Upper Birrimian comprises greenstones, schists and manganiferous quartzites. Folds are oriented NNE-SSW.

The Middle Pre-Cambrian outcrops over a sixth of the surface of Ghana, and is important for its gold, manganese and diamonds. The Lower Birrimian consists of schists, slates, phyllites and greywackes, while the Upper Birrimian consists of sandstones and schists with an abundance of greenstones. Dips are 30° to 90°, striking NE-SW. The rocks have been folded, metamorphosed and partly assimilated by granite bodies.

In Togo and Benin the Middle Pre-Cambrian is characterised by thick quartzites separated by pelitic beds. The quartzites form the major relief feature of the Atacora Range, and have been locally invaded and assimilated by granites.

In Cameroon the Middle Pre-Cambrian is represented by a number of rock groups which form a folded complex consisting of amphibolite schists, lavas and quartzites cut by granite bodies.

In many areas thick (2,000 m to 4,000 m) slightly metamorphosed sandstones and conglomerates lie on the crystalline Pre-Cambrian basement with marked unconformity. These beds are far less extensive in outcrop than the older rocks and are generally ascribed to the Upper Pre-Cambrian or less frequently to the Infra-Cambrian and even later.

Such series crop out over small areas of Ahaggar, in the Timetrine massif (West of Adrar des Iforas) and also west of Tessalit, where they are known as the Upper Pharusian or Nigritian. Similar conglomerates from the 'Crimson Series' of Ahnet. Further west in the Dorsale Reguibat detrital quartzites and conglomerates (the Akjoujt series crop out over a large part of Inchiri

and are intruded by the Aftout Granites).

Further south these conglomerates are generally called the Tarkwaian. Only a few remnants are left in Guinea and Sierra Leone, but outcrops are more extensive in Ivory Coast and Ghana. In Ivory Coast coarse arkoses are common, while in Ghana phyllites are also important and the Tarkwaian in cut by numerous acid and basic dykes.

In Cameroon the series seems to be represented by quartzites, sandstones and shales which are intruded by granites. In the Ubangi-Chari divide the Upper Pre-Cambrian as represented by schists and quartzites which are also cut by granites.

Later much of north-west Africa was covered by a stromatolite sea. The unconformity was marked by both volcanic and glacial activity which continued throughout the terminal Pre-Cambrian.

In Eastern Ghana, Togo and Dahomey this period has resulted in the following succession (Buem Series) from bottom to top:

1. Shales and arkose at base
2. Feldspathic sandstones with quartz veinlets, and conglomerates at the top.
3. Calcareous shales, limestones and tillites
4. Basalts, dolerites and some hyolites.

These occupy a strip of ground 30 km wide in the west of the Atacora Range, and pass under the Palaeozoic Voltaian sediments.

This group is equivalent to the 'Rockell Series' of Sierra Leone, which pass northward, into conglomerates and feldspathic sandstones of Guinea, and to the 'Falerrian' sandstones, shales and phtanites (Infra-Cambrian) of Senegal and Mauritania. The stratigraphic position of these is much disputed, and 'Falemian' sandstones may extend into the Ordovician.

The Palaeozoic Voltaian sediments to the west are equivalent to the 'Rockell Series' of Sierra Leone which pass northward into conglomerates and feldspathic sandstones in Guinea, and then to the 'Falemian' sandstones, shales and phtanites (? Infra-Cambrian) of Senegal and Mauritania.

The stratigraphic position of these series is much disputed, and the Falemian may even extend into the Ordovician.

Quaternary and Recent Sand-dunes (in the Sahara) and alluvium (along river beds) overlies the Pre-Cambrian terrain in large areas. The thickness of river alluvium generally increase from north to south with the increase in run off.

2.3 CHAD BASIN

The Chad Basin is a structural depression crossed by two major troughs which cut each other almost at right angles. They run NW-SE and NE-SW from Tibesti to Cameroon. The Pre-Cambrian basement crops out around most of the border giving a surface area of approximately 2,335,000 km^2. The depth of sediments increases towards the centre of the basin: a thickness of 550 m has been indicated by a seismic survey at Fort Lamy, Chad (Schneider, 1966), and over 1,300 m in the Maiduguri borehole in north-eastern Nigeria. The basement appears to be deepest in the vicinity of the chad-Niger border.

Hercynian movements caused updoming of the basement around the borders of the basin. Prior to this only the northern areas were subject to sedimentation, and these rocks do not extend far south into the basin, wedging out below the Continental Intercalary (Jurassic - Cretaceous).

At the northern margin of the basin Cambro-Ordovician sandstones some 500 m thick crop out against the crystalline rocks of Ahaggar and Tibesti. They extend eastward to the plateaux of Ennedi and Borkou. Post-Ordovician Caledonian movements did not result in unconformity but in a sharp change of facies to graptolitic shales of the Silurian.

The Silurian crops out nearer the centre of the basin and forms the major part of the Borkou plateau. Here the facies is a mottled micaceous, shaly sandstone which becomes increasingly shaly to the west in Ahaggar. These are followed by sandstones and then limestones (?Devonian). Very fine grained continental sandstones are transitional between the Devonian and Lower Carboniferous, and crop out over the Ennedi Plateau. Overlying fossiliferous limestones of the Lower Carboniferous reach 300 m north of Bilma (in north-

eastern Nigeria).

After the Hercynian orogeny the bottom of the Chad Basin was covered by deposits of the Continental Intercalary. These sandstones are 300 m thick and crop out over a broad area in the west directly overlying the Pre-Cambrian of Air, both east (Tefidet) and south (Tegama) of the horst. 200 m of Lower Cenomanian sandstones follow, and then 10 m of Upper Cenomanian and Lower Turonian limestones. In the depressed region between Ahaggar and Tibesti the Palaeozoic rocks are partly covered by these Cretaceous sediments.

Marine Turonian sediments crop out between Agadem and Bilma and as far as the northern part of Tenere while marine Senonian sediments crop out near Bilma. Marine Eocene rocks may be present in the same area, but at other localities the terminal Cretaceous - Lower Eocene are represented by continental beds (Galhama Series) of pisolitic bauxite.

In the south-east of the Chad Basin (i.e. north-west Nigeria) is a continental sequence of Eocene - Palaeocene age (Continental Terminal) called the Kerri-Kerri Formation. It consists of loosely cemented sands, grits, clayey sandstones, clays and silts with lacustrine and deltaic sediments being the most common. This formation was laid down unconformably on the basement complex and Cretaceous rocks. The sediments are generally unfolded but downwarped under the Chad Formation. They thin rapidly westwards and do not extend far to the north and east under the Chad Formation.

The major infilling of the basin occured during the Pliocene and Pleistocene when sands and clays of alluvial and lacustrine origin were deposited during different stages of the ancient Lake Chad. These Quaternary deposits are known as the Chad Formation in this basin. In the west, beds of coarse sand and gravel are well developed but to the east clays are more dominant and sandy beds are restricted to well defined zones or occur as thin, impersistent lenses. There is a shallow depositional dip from the edges of the basin towards the Lake, in the order of 1.5 m per km where the thickening is most rapid. This dip generally follows the gentle slope of the land's surface. The thickness of the whole formation probably exceeds

400 m in the centre of the basin on the Niger - Chad border.

Much of the area is covered by sand-dunes underlain either by the Chad Formation or by silts deposited in ponds during the rainy season.

2.4 IULLEMEDEN (SOKOTO) BASIN

The Iullemeden Basin is approximately 600,000 km^2 in area. The geology has not been well synthesised in comparison with the Chad Basin, but the structural and sedimentary histories are very similar.

Cambro-Ordovician sandstones are of more limited extent and only crop out over a small area in the north-east, between Air and Tassili Oua N'Ahaggar.

Between the Pre-Cambrian rocks of Adrar des Iforas and the bend of the Niger, the Geo Trough has been continuously subsiding since the Cretaceous and forms a geological link with the Taoudeni Basin in the west.

Elsewhere the crystalline rocks which border the basin are generally overlain directly by the Continental Intercalary, except in the far south where the Continental Terminal oversteps older sediments and rests directly on the basement.

The maximum determined thicknesses are:

Continental Intercalary	1,500 m
Cretaceous (marine)	400 m
Tertiary	100 m
Continental Terminal	100 m

The Continental Intercalary shales, conglomerates and sandstones are better known in this region due to their more extensive outcrop. The shales and limestones of the Tertiary are more extensive than the equivalent arenaceous Kerri-Kerri Formation of the Chad Basin, but are absent in the west. The Continental Terminal (Gwandu Formation) consists of similar heterogeneous sediments as the Chad Formation, and may be clayey throughout. It is less extensive than the Continental Terminal in the Chad Basin.

Dips are very gentle towards the centre of the basin. Outcrops of pre-Continental Terminal formations give rise to a plateau and scarp

topography. Along the line of the Wadi Azoyak there is a sharp increase in the depth of sediments due to a local syncline which follows the form of the basement.

Sand dunes overlie much of the northern part of the basin, and alluvium underlies the wadi valleys and that of the River Niger. These Quaternary and Recent superficial deposits are similar to those of the Chad Basin.

2.5 TAOUDENI BASIN

This vast cuvette is one of the largest synclines in the world (more than 1,200 km in diameter). In the north-east it is continuous with the Saoura Basin of Algeria, and in the east with the Iullemeden Basin. Elsewhere it is bound by the Pre-Cambrian basement complex.

In the north a cliff of Infra-Cambrian and Palaeozoic sediments overlooks the Dorsale Reguibat. The cliff rises to 600 m in the west and then takes a southerly direction, forming the western limit of the Palaeozoic plateaux of Amsaga and Tagant. Here the succession consists of Infra-Cambrian shales, sandstones and limestones a few metres to 15 m thick. The tillite which marks the base of the Cambrian is 40 m thick in places, and followed by over 100 m of Cambrian limestones, sandstones and shales. The Ordovician sandstones are up to 200 m thick, and are overlain by 20 to 50 m of Silurian shales and 20 to 30 m of Devonian limestones and sandstones.

To the south, the Palaeozoic beds rise to the edge of the plateau overlooking the Aoukel and the Bandiagara plateau on the right bank of the river Niger.

The Aouker is an erosion window occupying the south-west of the Taoudeni Basin. Here a depression in the Infra-Cambrian and Cambrian sediments is Covered mainly by deposits of the Continental Terminal, some 30 m of clayey-sandy sediments, and overlying sand dunes.

The Paleaozoic formations are all cut by numerous dolerite dykes, and the Cambrian in the south-east Aouker is intruded by a large dolerite laccolith (the Kaarta region).

The sea retreated from the central Sahara after Hercynian movements, so that Visean limestones continue upward in to a series of sandstones and gysiferous clays 150 m thick. These are followed unconformably by sandstones of the Continental Intercalary. The post-Palaeozoic succession is defined from the west bank of the Tilemsi valley which runs north-south adjacent to Adrar des Iforas. Here the Continental Intercalary directly overlies the Pre-Cambrian basement, Upper Cretaceous limestones are overlain by a few metres of Palaeocene sands and clays. Transgressive Lower Eocene limestones and marls pass upward into phosphatic beds. These are followed by the Continental Terminal, which reaches a maximum of 50 m thick at outcrop.

In the west of the basin flaggy sandstones of the Continental Terminal directly overlies the Continental Intercalary.

The sedimentary series dip gently to the centre of the basin, except in the far west where the Palaezoic formations are folded and in the region of Timbuctoo where the strata have been locally inverted.

Much of the area north of the River Niger is covered by sand dunes and has been little explored. The fossil delta of the Niger covers the eastern part of Aouker and a wide belt of alluvium deposited by the river abuts against the Pre-Cambrian of Upper Volta in the south.

2.6 FERLO BASIN

The sediments of this coastal basin are transgressive over the Pre-Cambrian basement which crops out in the east.

In the eastern part of the basin, the top of the basement dips westward at about 0.25° while in the west it falls more rapidly, at an angle of about 3° to a depth of 4,000 m off the coast of Mauritania. In the Trarza area there is a structural high oriented NNE which brings the Pre-Cambrian within 150 m of the surface near Lake Rkiz.

The earliest known sediments to be deposited on the basement are sands and clays of Jurassic-Cretaceous age. They are overlain by Tertiary sediments which show a facies change from littoral sands at the junction

with the basement, through limestones to argillaceous marls in the west where they are 255 m thick at Idinin (Roussell, 1968a). These series are overlapped by Continental Terminal deposits of Miocene - Pliocene age which consist of sandstones and sands with a variable clay content in east Mauritania and more than 300 m thick at Port-Etienne in the west. These are 30 m thick at Aleg in general the clay content increases westwards.

The pre-Quaternary strata dip gently seaward and thicken in the same direction. They have not been strongly folded or faulted and the structure of the basin is relatively simple. Details of the succession are only known locally since outcrops are rare except in the Senegal valley.

The Quaternary consists of large NE-SW dune chains (20 m - 30 m high) in central and northern Mauritania, with interdune hollows underlain by clays which are usually less than 3 m thick. Near the coast, old beach deposits which may be shelly, are intercalated with the sands: in Senegal 40 m of these deposits overlie marls and clays (Debuisson, 1970).

All the major river valleys are underlain by Quaternary and Recent alluvium, which is usually fine and silty.

2.7 NIGER - BENUE VALLEY

In the north-east this sedimentary basin is continuous with the Chad Basin; in the south it widens out into the Niger delta; elsewhere it is surrounded by the Pre-Cambrian basement which intersects the coast near the Cameroon border in the east and continental and marine sediments of Cretaceous age. The continental deposits consist largely of heterogeneous sandstones and are overlain by the marine and estuarine shales. Only in the Benue valley are the series noticeably folded: late Cretaceous movements resulted in long, narrow folds, and faulting has affected the entire sequence.

The basal Bima Sandstone of the Upper Benue is exposed in wide tracts adjacent to the basement outcrops and in the cores of the major anticlines where it can be as thick as 3,000 m. It is continuous with the Continental Intercalary of the Chad Basin, and is overlain in the north by the Kerri-Kerri

and Chad Formations. The Bima Sandstones is in places overlain by sandy magnesian limestones of Cenomanian - Turonian age which in turn are followed by Upper Cretaceous shales.

Immediately south-east of the confluence of the Niger and Benue rivers is a plateau of Late Cretaceous to Palaeocene sediments which dip gently to the south-west. 65 m of Upper Coal Measures are separated from a similar thickness of Lower Coal Measures by 500 m of the 'False-Bedded Sandstone'. The Coal Measures consist of siltstones, sandstones, clays and thin seams of coal. The False-Bedded Sandstone is a series of heterogeneous, poorly-cemented sandstones: these may be equivalent to the Nupe Sandstone, which is the major infilling of the Niger valley above the confluence with the Benue.

All of these sediments are diachronous, heterogeneous and subject to lateral facies changes: they are therefore poorly correlated from place to place but in general become more argillaceous from northwest to southeast in the Niger valley and from northeast to southwest in the Benue valley. Du Preez and Barber (1965) discuss the variations of lithology in more detail.

During the Palaeocene up to 1,000 m of foraminiferal shales (the Imo Shales) were deposited in parts of southern Nigeria. This series unconformably overlies the Cretaceous sediments to the north and crops out against the Pre-Cambrian basement as far as the western border of Togo. Here it forms an E-W band 50 km to 100 km wide between the basement and Post-Eocene continental deposits. This strip extends eastward to the River Niger and then takes a south-easterly direction to intersect the coast near the Cameroon border.

The continental Post-Eocene borders the coast to 120 km west of Togo where the Lower Pre-Cambrian rocks intersect the coastline. These sands, clays and gravels underlie the bulge of the Nile Delta and extend in a narrow belt eastwards to Cameroon.

The Imo Shales and Post-Eocene sediments dip gently seawards.

All ~~folded~~ flood plains of the major rivers are underlain by Quaternary alluvium which also forms the superficial deposits of the Niger delta.

2.8 MINOR SEDIMENTARY BASINS

These include the Gondo Plain of the bend of the Niger, the Voltaian Basin of Ghana and inextensive basins along the south coast.

Gondo Plain:

This is a closed basin in southern Mali, south of the bend of the Niger. It is bound on the west by the Palaeozoic plateau of Bandiagara, and on the north, east and south by the crystalline basement. Shales, dolerites and sandstones of the Continental Terminal are the main sediments.

Voltaian Basin:

The Voltaian Basin occupies about 40% of the area of Ghana, where a downwarp of the basement is filled with thick continental and marine deposits of Devonian age. These shales, mudstones and consolidated sandstones are flat or gently dipping except at the eastern contact with the Pre-Cambrian where the lower part is gently folded.

Coastal Basins:

A belt of sediments extends from Fresco, in the west of Ivory Coast into western Ghana.

Seaward-dipping sandy limestones and fine sands of Maestrichtian age are overlain by (?) Eocene marls and Continental Terminal sands and clays. The Quaternary cover consists of lacustrine deposits of heterogeneous sands and coastal dunes.

In the Accra region of Ghana, Accraian and Sekondian Formations of Devonian age, and the Amisian Fromation of Jurassic age form a block-faulted province. The Accraian includes sandstones, grits and shales; the Sekondian consists mainly of sandstone and shale. The Amisian consists of poorly sorted, semi-consolidated sandstones and shales in down-faulted blocks outcropping near the mouth of the Ochi (Amisa) River. The coastal basin of south-east Ghana has been discussed in the section on the Benue-Niger valleys.

3. HYDROGEOLOGY

South of the Sahara traditional wells are up to 1 metre in diameter and rarely deeper than two metres below the water table. In dry years these wells are insufficient for pastoral needs and migration southwards increases pressure on grazing and water resources. Since the semi-arid savannah zone has a marginal vegetation and climate, it is most affected by climatic change. Hence the intensification of hydrogeological investigations since the most recent drought. Many of these investigations have been financed by foreign aid.

In the more humid south, surface water is sufficient in quantity for most needs but pollution (e.g. from mine drainage), a high silt content, and seasonal shortages during the dry season make groundwater preferable in many areas. The vast areas of basement outcrop, with their inherent difficulties in prospection for groundwater, have hindered development.

The availability of hydrological data (that is requisite for establishing a water balance) is discussed by Rodier (1963, a). Discharge data for many of the rivers is available in "Annuaire Hydrologique de la France d'Outre Mer" which is held in IGS library. Most of the hydrogeological literature contains the relevant climatic and hydrologic information used to calculate recharge to the aquifers.

A comparison of yields from various geological formations in different regions is shown in Table 1.

3.1 THE PRE-CAMBRIAN

3.1.1 Hydrogeology and Ground-Water Occurence

The crystalline rocks and metamorphosed sediments of the Pre-Cambrian may provide local aquifers where they have become sufficiently permeable, by fracturing or weathering, to yield water to wells. Fractured rocks usually provide higher yields than basins of alteration but the latter are more predictable. Plote (1968) discusses the availability of groundwater

in the Pre-Cambrian terrain of the Sahara, with particular reference to the weathering of different rock types in Mauritania. Biscaldi (e.g. 1968) discusses the same topic for those parts of West Africa with a more tropical climate.

It has been established that granites and, to a lesser extent, gneisses are the most deeply weathered due to the alteration of feldspars under warm humid conditions. This process can increase the porosity from 1% - 3% to as much as 35%, as in northern Nigeria (Asseez, 1972). The most permeable horizon is that of the shattered bed rock together with the overlying layer of sand-sized particles. Higher up the profile argillaceous material becomes more dominant but relict fractures and other structures may increase the permeability.

In arid areas such weathering was most effective during the warm, humid climate of the Tertiary period. Since then erosion has been intense and the altered zone has rarely survived to more than a few metres. In the more humid south this zone can be as much as 73 metres thick (Bannerman, 1975) but aquifers are usually localised and discontinuous with low transmissity values due to a high clay content.

Fine-grained rocks are generally more resistant to weathering than coarser-grained types. Rocks which were originally argillaceous such as schists weather to impermeable clays and rarely supply ground water except where they are well fissured. In general, joints are better developed in granites and quartzites than in the gneisses migmatites and schists. Rocks in valleys are usually more fractured and more deeply weathered. Shattered quartzite veins and weathered micaceous quartzites and basic dykes may act as conduits for groundwater and provide relatively high yields. An indication of the order of yields obtainable in different areas for differnet rock types is shown in Table 1C.

Yields are also dependent on the amount of recharge, and water supplies are less dependable in the north. In the Sahara the majority of wells are

seasonal, but recharge may occur in some years (in the order of 1 in 10) even where the average rainfall is 50 mm (e.g. Fort-Gourard, Mauritania; Roussell, 1968a). Recharge in arid and semi-arid regions is dependent on surface flow concentrated in the wadis. The most favourable conditions for storage of groundwater exist in fractured and altered granites underlying the confluence of different wadis.

Roussell (1968a) gives a fairly detailed account of the availability of groundwater in the basement rocks of the western Sahara (Mauritania). The region of Inchiri has been investigated in most detail: here the fissured alteration zone of greenstones provides the water supply for the copper-mining town of Akjoujt. Roussell quotes a transmissivity value of 600 $m^3/d/m$ and a porosity of 4% below the confluence of wadis, where the water-table is found at a minimum depth of 6 m.

Very little literature has been located on the hydrogeology of the basement complex in the west of the Sahara, but similar considerations as those for Mauritania can be applied in most areas.

Further south most detail is available for Ghana and Nigeria. The most densely populated parts of Ghana are underlain by Pre-Cambrian rocks and by granites. Gill (1969) compares the success rate and yields from boreholes and wells in the various rock types. He found that yields of up to 2×10^{-2} l/sec are available even from slates phyllites and schists of the Lower Birrimian where these are strongly foliated and jointed. In general the Middle Pre-Cambrian (Birrimian) granites and gneisses have the greatest potential for reliable water supplies. Gill concludes that small supplies (1.3×10^{-4} l/sec to 6.5×10^{-3} l/sec) are available in most areas from carefully sited boreholes. Despite Gill's optimistic approach, more recent publications (e.g. Bannerman, 1975; Aseez, 1972) have emphasised the difficulty of borehole siting without specialised personnel and the trend now seems to be towards development of surface water supplies.

In Nigeria, springs from the base of the weathered zone are frequent and their density and discharge indicate the amount of groundwater

available from these discontinuous pockets.

Due to the localised nature of the weathered mantle, recharge is also only local, and may be limited by the presence of hard pans (which have largely been eroded in the more arid north).

In Ivory Coast a small experimental catchment in Birrimian granites and migmatites has been relatively intensely studies (e.g. Forkasiewicz and Margat 1968). Guerin-Villeaubriel (1962) gives details of the water supply for 5 towns from the weathered zone of granites. Here it is estimated that some 900 mm of the annual precipitation of 1500 mm is lost by evapotranspiration leaving 600 mm for run-off and infiltration. Determination of the depth of alteration and the water-table is often carried out with surface geophysical techniques. Electrical resistivity methods are often limited due to highly resistive hard pans or laterite developments near the surface. In these cases shallow seismic refraction is of more value (Biscaldi, 1968c). The low success rate of boreholes in Nigeria has been attributed to the lack of personnel trained to use these techniques (Ayoade, 1975). George (1968) illustrates the different modes of occurence of hard pans in relation to the depth of alteration. He uses reconstructions of the palaeotopography to predict zones of deepest weathering and most reliable recharge. His examples are mainly taken from the Birrimian chain in Upper Volta (e.g. Figure 3).

Biscaldi (1967) has prepared a 'hydrogeological map of the crystalline rocks of much of the region at a scale of 1:2 million. He uses mean annual isohyets and geological boundaries to delineate hydrogeological provinces.

The thickness of alluvial deposits along river valleys generally increases with rainfall from north to south. In the zone where most rivers are seasonal there is almost always groundwater at or near the surface of river beds throughout the dry season in alluvial deposits and weathered bed rock (e.g. in north-central Nigeria, McCurry, 1973). Further north alluvium is thinner, recharge less, and only temporary aquifers exist in wadis and sand dunes. In the Sahara they are exploited by 'ogols'. In the Dorsale

Reguibat of Mauritania yields from ogols in sand dunes above the Pre-Cambrian are rarely more than .08 l/sec even just after rainfall (Roussel, 1968a).

3.1.2 Groundwater Chemistry and Quality

Dissolved solids are generally low (less than 400 mg/l) but increase with aridity: in the Sahara groundwater is only fresh for a few months after recharge. Most analyses are available from the weathered zone of granites, and dissolved silica usually accounts for half of dissolved solids, as in Bauchi, northern Nigeria (Schroeter, 1974). Bicarbonate is the other dominant ion in most samples. Iron and magnesium are often high: iron is often found in concentrations greater than .3 mg/l which creates problems of precipitation and staining. A hardness of over 100 mg/l is often found, but most of this is temporary hardness. The pH is usually acidic, becoming increasingly alkaline with depth: in the north part of Ivory Coast the average pH of water from wells is 5.5, while from boreholes it is 7.1 (Tardy, 1969).

3.2 THE CHAD BASIN

Gischler (1967) gives a summary of the involvement of various organisations in this area. Prior to 1964 O.R.S.T.O.M. covered the hydrological geophysical and pedological aspects of research, while B.R.G.M. dealt with the geology and ground water in Chad, Cameroon and Eastern Niger. In Nigeria most of the work was carried out by the Geological Survey of Nigeria.

In 1964 the Chad Basin Commission was set up and these organisations now work in conjunction with UNESCO. Since then UNESCO has been carrying out the more sophisticated projects of establishing an electrical analogue model and both stable and unstable isotope analysis. Since most of the surface drainage is perennial, regular water supplies must be taken from the ground. Superficial aquifers provide for most of the pastoral needs but the Chad Formation constitutes the most important aquifer of the basin.

Most of the literature in English is for north-eastern Nigeria, and therefore most detail is available for this area. Although UNESCO has

published the results of work for the whole basin (UNESCO, 1969) this is not available at present. Since then several articles have appeared in English on specialised aspects of the hydrogeology (e.g. Arad and Kafri, 1975) using the data provided by UNDP/FAO.

3.2.1 Hydrogeology and Groundwater Occurence

Sandstones of the Palaeozoic plateaux in the north of the basin give yields as high as 65 l/s from fissured zones. There is hydraulic continuity with the Kufra Basin of Libya and groundwater from these series may contribute little to the water balance of the Chad Basin (Schneider, 1966).

The Continental Intercalary is argillaceous over much of the basin and has therefore little potential as an aquifer. In the south the Cretaceous sediments of the Upper Benue valley extend into the Chad Basin. Their properties are discussed in section 3.6. This series only forms an important aquifer north and west of Goure (Niger) where the Chad Formation is very thin.

In the grits, sands and clays of the Eocene Kerri-Kerri Formation (in north eastern Nigeria), groundwater mainly occurs under water-table conditions. Occasional clay lenses may give rise to confined conditions in some areas, and confined water probably occurs under the Chad Formation. This aquifer is of low permeability due to the presence of interstitial clays, but in most areas the water-table is accessible to hand-dug wells (Du Preez and Barber, 1965). In many areas the water-table has risen considerably since the 1930's due to a decrease of transpiration and increased runoff and recharge from streams following deforestation.

The aquifers of the Chad Formation have been investigated over a small area of the basin: in the vicinity of Lake Chad and to the south-west in Nigeria. Much of the literature which discusses groundwater in the Chad Basin is limited to the Chad Formation (e.g. Miller et al, 1968). In north eastern Nigeria there are often three aquifers each confined or semi-confined by clayey horizons, and referred to as the Upper, Middle and Lower Pressure Zone aquifers. However, these aquifers are not discrete, nor necessarily continuous due to the heterogeneous nature of the deposits. The diagram in

Du Preez and Barber (1965, Fig 19) shows the lateral variation in facies, with the sandy horizons of the three 'zones' being indistinguishable nearer the western limit of deposition.

The Lower Zone aquifer has not been proven to extend far from the Maiduguri borehole where it was located. It may consist of a limited lens of sand with no recharge except by compaction of surrounding clays.

The Middle Zone aquifer is more extensive, with an artesian head of 30 m above surface at Lake Chad. It extends over at least 3,000 square miles, and is now being exploited in north western Nigeria to provide watering points every 12 km.

Artesian supplies are obtainable from permeable sands up to 600 m thick lying between 190 m (in the west) and 380 m (in the east) below surface, and yields range from .06 l/sec to 25 l/sec. The piezometric surface falls towards Lake Chad: any recharge is presumably from the south and west where there is hydraulic continuity with sand lenses higher up the succession.

The Upper Pressure aquifer is the most widely utilised: it contains a phreatic water-table and also semi-confined water under clay intercalations. It has been exploited for many years by hand-dug wells in surface depressions. Recharge is mainly from the south, from rivers flowing northward to Lake Chad. There is some evidence of recharge from the area of the Tibesti massif in the north (Arad and Kafri, 1975), but there is little information available north of the latitude of Lake Chad. Highest yields are obtained in the west where clean sands and gravels are common; in the east there may be no lenses sufficiently permeable to give borehole supplies.

Almost the entire surface of the basin is overlain by fixed dunes separated by hollows which contain up to 3 m of silts. Where the dunes are underlain by the less permeable deposits of the Chad Formation they may contain a saturated zone up to 10 m thick. North of Massakory, the Erg Kanem forms an important unconfined aquifer.

3.2.2 Groundwater Chemistry

The water in the Palaeozoic sandstones in the north of the basin has a TDS content of less than 250 mg/l, which with the high yields mentioned above indicates significant recharge in these upland areas. The dominant ions are HCO_3, Ca and Na.

Little is known about the quality of water in the Continental Intercalary, but in Niger the composition should be similar to that in the Iullemeden Basin (section 3.3.2), possibly with higher concentrations due to the more argillaceous facies. In northwestern Nigeria the water from the Benue sandstone underlying the Kerri-Kerri and Chad Formations probably has a similar composition to that in the Benue valley (section 3.6.2).

The Kerri-Kerri formation contains water of low salinity of the Na, Ca, HCO_3 type.

The quality of groundwater in the Chad Formation is everywhere good. In the phreatic aquifers, the southern and south western intake areas are characterised by fresh, calcium bicarbonate waters both from direct infiltration and from rivers. Down-dip the composition evolves to a sodium type, either $NaHCO_3$ or $NaSO_4$ and the pH becomes slightly acidic but concentrations are generally less than 250 mg/l, only reaching 3,000 mg/l in areas of evaporative discharge. The confined (Middle Zone) aquifer is characterised by a predominance of Na. Salinities in north western Nigeria are in the range of 190 to 1,060 mg/l. Free carbon dioxide is always present in wells due to pressure release and the waters are slightly acidic. Temperatures are high (Du Preez and Barber, 1965), and iron and manganese concentrations are often high.

Corrossion of well linings by slightly acidic waters and silting up of wells creates problems in maintaining yields. In Bornu Province, Nigeria, plastic linings are now being used in wells tapping the Middle Zone aquifer.

Waters from the superficial aquifers are good quality for a few months after the end of the rainy season, but then the quality deteriorates as evaporation progresses.

3.3 IULLEMEDEN BASIN

3.3.1 Hydrogeology and Groundwater Occurence

The Iullemeden Basin includes eastern Mali and western Niger. For this report the western boundary is Aaken as the southerly extension of Adrar des Iforas as in Saad (1969). Other authors (e.g. Anderson and Ogilbee, 1973) include a strip west of the Adrar. About one tenth of the basin lies in the north western Nigeria where it has been most fully investigated and is known as the Sokoto Basin.

There are three major aquifers: the Continental Intercalary, the Upper Cretaceous and Continental Terminal. All these consist of heterogeneous continental deposits with a variable clay content. The marine Tertiary deposits are impermeable except where limestones are well developed as in the Kalambaina Formation of north western Nigeria. The two major aquicludes are: Cenomanian - Turonian shales which overlie the Continental Intercalary, and clays above the Upper Cretaceous aquifer. Clay beds within the major aquifers may also give rise to confined conditions. The relationship of the various aquifers and aquicludes can be seen in Du Preez and Barber (1965, Fig 13).

The Continental Intercalary possibly provides the most important aquifer due to its extensive outcrop. East of longitude 6° 40' E the facies is more argillaceous and little groundwater is available. West of this longitude sandy facies are better developed and in hydraulic continuity with each other so that specific yields are always greater than 0.2 l/sec/m, ranging upward to 2 l/sec/m (e.g. east of Adrar des Iforas). Transmissivities in the Sokoto area range from 4.5 to 980 $m^3/d/m$. There is recharge at outcrop around the whole of the basin, greatest amounts being available from the south where rainfall is highest. In the north of the basin recharge only occurs during concentrated surface runoff. The piezometric head falls toward the centre of the basin and there are indications of some flow eastward into the Chad Basin (Saad, 1969).

Artesian pressures are probable in the valley floors of e.g. the Sokoto

River, but the aquifer has not been well explored towards the centre of the basin due to its greater depth and the presence of overlying aquifers.

Outcrops of continental Upper Cretaceous sediments are more limited in area than those of the Continental Intercalary, and the amount of recharge is therefore lower. Artesian conditions have been proved in the West of the basin in the Gulf of Gao, and an economically important aquifer exists in the Rima Group of north western Nigeria. Clay beds in the Rima Group practically disappear down dip from outcrop in Sokoto Province and the sandy beds become thicker and coarser grained. Artesian conditions are widespread along valley floors and the transmissivity has been estimated at about 670 $m^3/d/m$ (Anderson and Ogilbee, 1973).

Above 18 m of clay (Dange Formation) is a shallow perched aquifer in Eocene limestones (Kalambaina Formation). This sustains many springs and dug wells in outcrop in north western Nigeria and southern Niger, but is largely impervious down dip.

The overlying Continental Terminal deposits are relatively thin, and are limited to the south and south west of the basin. In the western part of the basin the continental Terminal is generally less than 100 m thick, of which only 40% is permeable (Saad, 1969). Specific yields are rarely greater than .2 l/sec/m. Further west, in Niger, specific yields reach 2 l/sec/m due to the greater development of permeable facies. The basal sands are under artesian pressure over much of north western Nigeria. Although this aquifer has long been exploited in eastern Mali, there are few well records and the hydrogeology is not well known (Saad, 1969).

The main source of recharge is from rainfall in the south. The Kalambaina Formation also contributes an unknown volume. There is hydraulic continuity with the River Niger but any recharge from this source is probably returned by base-flow downstream. There is also significant recharge from the south part of Adrar des Iforas to the Gulf of Gao region.

Quaternary aquifers consist of river alluvium and of fixed sand dunes of limited extent. There is considerable potential for development of unconfined

groundwater from the alluvium of the Rivers Niger and Sokoto and from other large river valleys.

3.3.2 Groundwater Chemistry

Water from the aquifer of the Continental Intercalary generally has a T.D.S. of less than 700 mg/l. The pH can be as low as 5.1 and this acidic water type is characterised by a dominance of SO_4. Concentrations in the Upper Cretaceous aquifer are more variable, from 44 mg/l in the Rima Group to 3,000 mg/l east of Adrar des Iforas. The pH range is from 6.0 to 8.1, and Ca, HCO_3 and SO_4 ions are generally dominant.

The Kalambaina Formation is characterised by hard, alkaline waters of Ca, HCO_3 type with a pH ranging from 7.2 to 8.3.

Water from the Continental Terminal deposits is more varied in composition, the most common being a Ca, Mg, HCO_3 type, and an Na, HCO_3 type at down dip. The pH varies from 6.6 to 7.7 and T.D.S. is generally less than 700 mg/l.

In all these formations the iron content tends to be high: the highest recorded values in north western Nigeria are 32 mg/l in water from the Continental Intercalaire, and 14 mg/l from the Upper Cretaceous. These waters are therefore often corrossive, particulary where a high iron content is combined with a low pH.

The river alluvium generally contains water with a T.D.S. less than 150 mg/l, which is soft except where it is adjacent to limestone.

Anderson and Ogilbee (1973) discuss the chemistry of ground water in the Sokoto area in more detail.

3.4 TAOUDENI BASIN

3.4.1 Hydrogeology and Groundwater Occurence

The Palaeozoic and Infra-Cambrian plateaux crop out widely in the north, west and south of the basin. They cover much greater areas than equivalent sediments in the other sedimentary basins and have therefore been more

thoroughly explored for groundwater than in other areas. By contrast, the more recent deposits of the centre of the basin have been relatively little explored except in the south, adjacent to the Niger River: to the north the Sahara desert inhibits settlement, water requirements, and hence investigation into water supply apart from that already in use by the desert nomads.

Roussel (1968a) discusses the hydrogeology of the Palaeozoic and Infra-Cambrian plateaux of Mauritania in some detail. Fissured zones in quartzitic sandstones and dolomite horizons provide the best yields especially where they are in contact with alluvial aquifers. These levels are well-developed and fairly continuous in the plateaux abutting against the Dorsale Reguibat and yields up to 1.4 l/sec are obtained. Further west and south, fissured zones and dolomite horizons are more localised but precipitation and recharge are greater, and alluvial deposits are more extensive. In Tagant springs from quartzitic Ordovician sandstones give yields of up to .5 l/sec in fissured synclinal zones. In the Aouker Hodh altered pelites give a phreatic aquifer which is only exploitable locally at low yields. Similar low yields are obtainable from dolerite intrusions in the south west. In the south east a plateau of Continental Intercalary sediments overlooks the Aouker. This series may contain several aquifers where it is thickest: in the Nara trench it reaches 400 m and contains two principle aquifers. This series has been little explored in the east where it is much thinner than its counterpart in the Iullemeden Basin. Although it is most likely that these sands, sandstones and clays are continuous beneath the basin, the changes of facies and therefore their potential as an aquifer(s) is unknown.

The Upper Cretaceous overlying the Continental Intercalary along Adrar des Iforas in the eastern part of the basin is only 100 m thick (compared to 400 m in the Iullemeden basin) but permeabilities have been estimated at about 30 $m^2/d/m$. Saad (1969) estimates recharge to this part of the aquifer at 38 mil m^3 per annum. The facies here consists almost wholly of limestones, marls, clays and shales. In the west of the basin this marine facies seems to be absent (i.e. it is not mentioned in the literature), and the Continental Terminal directly overlies the Continental Intercalary.

In the Aouker Hodh, sands of the Continental Terminal are thicker than 60 m, but the water-table is between 10 m and 40 m below surface. Basement highs divide this phreatic aquifer so that it is discontinous. Roussel (1968a) does not mention the Continental Terminal in the rest of the basin: presumably it is too thin to be of significance. This series is better known in the east of the basin where Saad (1969) estimates that recharge to the outcrop is in the order of 433×10^3 m^3 per annum.

The fossil delta of the Niger also consists of deposits of the Continental Terminal which are permeable throughout. Recharge from annual inumdation by the river is estimated at 7 mil m^3 per annum but yields near the river are disappointing (Balfour, 1973) and surface water is more often used.

Alluvial aquifers are important in wadis in the Palaeozoic and Infra-Cambrian plateaux. In the west, in the Adrar, alluvium is 10 m thick, with a water-table rarely greater than 3 m below surface and up to 3 m seasonal fluctuation. The wadi valleys usually form a series of unconnected basins. Further south in the Tagnat barrages have increased yields by 10-fold at the end of the dry season. Alluvium along the River Niger can be productive: yields of .7 l/sec are obtainable.

Lenses of fresh water may accumulate in sand-dunes where there is an impermeable base, but to these supplies are often temporary and become saline soon after the end of the wet season.

3.4.2 Groundwater Chemistry

In the north, groundwater from the Palaeozoic/Infra-Cambrian dolomite horizons has a T.D.S. of up to 7,000 mg/l. Further south, waters are much fresher due to increased recharge: in the Ordovician sandstones of Tagant the T.D.S. is usually less than 200 mg/l.

The Continental Intercalary aquifer contains fresh water wherever it is exploited. The T.D.S. content in the east of the basin is generally less than 700 mg/l. In the Dahr Nema, the ratio of $Cl:SO_4$ is .5 while that of Ca:Na is 1. The Cretaceous aquifer to the west of Adrar des Iforas contains

water with a T.D.S. content between 2,000 and 5,000 mg/l which limits its usefulness. Similar concentrations are found in the Continental Terminal of the eastern part of the basin, but the water becomes fresher to the south where there is greatest recharge from Adrar des Iforas and directly from rainfall. The dominant ions are SO_4, Ca and Na.

In the superficial aquifers the degree of mineralisation is largely dependent on the rate of evaporation: in sand dunes in the north, ground water may be potable for a short period only after rainfall. Salinities usually decrease with depth.

3.5 FERLO BASIN

3.5.1 Hydrogeology and Groundwater Occurence

The Jurassic-Cretaceous sandstones are only important as an aquifer (the Maestrichtian aquifer) south of the River Senegal. In this area the series is 250 m to 300 m thick and top lies between 100 m and 400 m below surface. The transmissivity ranges from 16 $m^3/d/m$ to 3,500 $m^3/d/m$ depending on the day content, but reliable yields in the order of 45 l/sec are usually obtainable (Audibert, 1966). Storage coefficient is in the order of 10^{-4} and there is artesian flow from boreholes in many areas. The hydraulic gradient varies between 1:10,000 and 1:25,000 , falling from south east to north west. Audibert considers that there is probably no recharge to this aquifer and that any movement of ground water is due to upward leakage.

The sandstones and limestones of Eocene age form good aquifers in some areas, and are often in hydraulic continuity with groundwater in the heterogeneous sandy clayey deposits of the Continental Terminal: In anticlines the regional water table is usually in Eocene strata, while in synclines it is in the Continental Terminal.

North of the River Senegal, the Continental Terminal is most widely used for water supply. From north to south, the areas of Tiresiaim, Bennichab and Trarza have been investigated, but the degree of hydraulic

continuity between the different regions has not yet been determined. South east of Trarze the Eocene limestones and sandstones become more important in the region of Brakna. South of the River Senegal the Eocene strata are utilised more than to the north.

The Eocene limestones are karstified, at least in the region of Sebikotane (Degallier, 1962), and yields are therefore even less predictable than in the Continental Terminal. Yields from the Continental Terminal are about 3 l/sec for a drawdown of 1 to 2 m in most areas (Elouard, 1962), but clogging with fines reduces yields with time. Also, yields decrease westward with increasing clay content. The limestones may be confined between thick marls, and semi-confined or confined conditions may be present in the Continental Terminal due to intercalated clays.

Degallier (1962) presents many well logs for the Continental Terminal and Eocene for the area between 15°N and the River Senegal. He also illustrates the piezometric surface which is basin-shaped, indicating evaporative discharge. Due to the shallow dip of sediments in the east the aquifers are dry adjacent to the basement outcrop in a band 20 km to 25 km wide. The water-table may be as low as 40 m below surface in parts of Mauritania, and although water-levels rise in the west near the coast, saline intrusion limits development.

The main sources of recharge are from rainfall in the south and south-east and from the River Senegal which forms a major divide in the water-table. In the north the only recharge possible is from concentrated flow in the wadis.

The Quaternary alluvium of the major rivers forms relatively poor aquifers which are recharged by the rivers during the wet season, and discharge water to the rivers during the dry season. The alluvium is usually in hydraulic continuity with the aquifers of the Continental Terminal and Eocene. River alluvium makes a significant contribution to the water supply of the Kaedi region in the Senegal Valley at the confluence of the Gorgol and Savalel.

Near the coast, fresh water is only available during the rainy season in shallow lenses above the saline water interface. Along the coast of Senegal,

semi-consolidated sand dunes and shelly beach deposits overlie marls and clays. Their transmissivities range from 12 $m^3/d/m$ to 73 $m^3/d/m$, with higher values for the shelly facies (Debuisson and Moussu, 1966).

The Quaternary sand dunes both at the coast and inland, are exploited by "ogols" during the rainy season.

Due to the difficulty in obtaining sufficient fresh water for the more densely populated coastal region, de-salination plants have been built at Nouakchott (the capital of Mauritania) to supplement supplies from the aquifers further inland. In the Sebikotane region of Senegal, water from the Maestrichtian aquifer is being artificially recharged to the Eocene limestones in order to control the position of the saline-water interface.

3.5.2 Groundwater Chemistry and Quality

The quality of groundwater in the Maestrichtian aquifer of Senegal is generally "satisfactroy" (Audibert, 1966), but the salinity increases northward into Mauritania. Audibert distinguishes two chemical groups of groundwater in the Maestrichtian: where T.D.S. is less than or equal to 1,000 mg/l, $CO_3 \gg Cl > SO_4$, $Ca \gg Na$; where T.D.S. is greater than 1,000 mg/l, $Cl > CO_3 > SO_4$, $Na \gg Ca$.

In the Eocene and Continental Terminal, T.D.S. is in the range 200 mg/l to 600 mg/l but tends to be higher in older wells, probably due to the compaction of clays. In the south, recharge from rivers and rainfall results in lower concentrations, around 50 mg/l to 150 mg/l, which increase northward and away from the rivers. Degallier (1962) distinguishes groundwater recharged by rainfall from that from rivers by the ratio of SO_4 to Cl. Recharge from rainfall is characterised by $SO_4 < Cl$, while for river recharge, $SO_4 > Cl$. Where there is direct recharge to Eocene limestones (as in the Linguere region where the annual rainfall is 518 mm) $Na < Cl$ whereas where the groundwater in the limestones is from the Continental Terminal $Na > Cl$. The major components of the T.D.S. are usually Ca and HCO_3 ions.

In the north where evaporation from the water table is most effective, concentrations may reach 1,000 mg/l at the surface as in the region of Idini.

Here semi-confined water lower down in the Continental Terminal is of better quality (300 mg/l). The major ions in the water are Na and Cl probably due to previous marine invasions (Depagne, 1967).

Near the coast, development of these aquifers is limited by saline water at depth since there is hydraulic continuity with the Quaternary deposits.

In the Quaternary of the coast, the water tapped by ogols and shallow wells reaches concentrations greater than 3,000 mg/l by the end of March and so becomes unpotable. Similarly water held in wadi alluvium and sand dunes in the interior rapidly becomes saline with evaporation and in the direction of flow.

3.6 NIGER-BENUE VALLEY

3.6.1 Hydrogeology and Groundwater Occurence

The major reference located for the northern part of this area is by Du Preez and Barber (1965). In the upper Benue (east of longitude 9°E) and the basal Bima Sandstone is everywhere an important aquifer, but its permeability is often low due to interstitial clays derived from decomposed feldspars. Yields are in the range of 3 l/sec to 6 l/sec under confined conditions, which may be due to infra-formational or overlying shales and clays.

The overlying formations are more variable in lithology, but tend to be more arenaceous to the north and east. They may form several aquifers each separated by shales and clays which result in confinement down-dip from outcrop, so that sub-artesian conditions are common. The main source of recharge for these aquifers is by infiltration of precipitation at outcrop, and they are all effluent to the rivers.

West of longitude 9°E the sediments become rapidly more shaly and only negligible yields have so far been obtained except in the Idah-Ankpa Plateau where the Falsebedded Sandstone forms a good aquifer. Here the depth of the piezometric surface varies from 60 to 170 m below surface. Numerous springs mark the junction of the sandstones with the Lower Coal Measures on the escarpment bordering the plateau. There are also springs within the Lower

Coal Measures at the top of coal seams. Discharges may exceed 760 l/sec.

In the Niger valley the Nupe Sandstone is very fine grained and therefore of low permeability. Average yields to wells are somewhat lower than in the Upper Benue, being around 2 l/sec. In the west, coastal region, yields averaging 4 l/sec are obtained from the continental deposits, limestones in the Eocene and Palaeocene and from the underlying Cretaceous sands. These diposits are too thin on the coast of Ghana and Togo to be intensely developed. Erdelyi (1965) suggests that deep drilling to these aquifers may solve the problem of water supply to the sand bars off the Volta Delta, where they would be thicker. The UN has been studying groundwater resources of Togo, but it is not known whether the results have been published.

The main aquifer of the coast in the Continental Terminal, which has variable specific capacities (2 - 4 l/sec/m). In the Niger Delta the water table may be as much as 20 m below surface, with a fluctuation of only 2 m, being highest from December to March (Ward, Ashcroft and Parkman, 1974).

No literature has been located on the importance of groundwater in river alluvium.

3.6.2 Groundwater Chemistry and Quality

Most of the information presented below is from Du Preez and Barber (1965). Groundwater in the sandstone formations of the upper Benue valley generally has a T.D.S. in the range 184 mg/l to 496 mg/l. The waters are donimantly of Ca HCO_3 type with little or no sulphate. The pH varies between 6.1 and 7.2. Iron concentrations may be high but otherwise these are good quality drinking waters. Industrial use is limited by high hardness, alkalinity and iron concentrations. Further downstream in the more argillaceous deposits concentrations of ions, particularly of SO_4 are higher. In this region there are locally saline (Na Cl) waters with T.D.S. of 9,000 ppm whose origin is not understood. The shale formations of the upper Benue yield water with HCO_3 and SO_4 as the major anions while Ca and Na are the dominant cations. The SO_4 content is due to the presence of gypsum, but T.D.S. is generally less than 500 ppm.

The chemistry of groundwater from the Nupe Sandstone of the Niger valley is very similar to that from the Bilma Sandstone of the Benue valley. Waters from the False bedded Sandstone have low concentrations of dissolved solids, the dominant ion being HCO_3.

Little information has been located on the composition of groundwater from the Eocene limestones, but in the Continental Terminal of the coast and Niger Delta the pH is always low, generally less than 6.5 (Ward, Ashcroft and Parkman, 1974).

Saline intrusion along the coast is limited by the seaward dip of the sediments. Overlying clays tend to exclude saline water from the Continental Terminal aquifer, but connate water of high salinity is found in some regions. Saline intrusion into the Quaternary aquifers is a problem along the whole coastline, and at the end of the dry season the groundwater is too saline for human consumption up to 35 km from the sea.

3.7 MINOR SEDIMENTARY BASINS

The Gondo Basin

The wells of this area have been reviewed by UNDP, but it is not yet known whether the results have been published.

The Continental Terminal aquifer is recharged by runoff from the Bandiagara plateau and Pre-Cambrian outcrops which surround the basement, and to a lesser extent by direct infiltration. The water-table falls from the edge of the basin to a depth of 30 m to 50 m below surface in the centre (Balfour, 1973). Yields are variable due to the heterogeneous nature of the deposits, and are often disappointing.

Voltaian Basin

The Palaeozoic sediments of this basin are generally well consolidated, and only permeable in the plains area near the Sene River and in a long belt between Kete-Krachi and Sang, where the sandstones, quartzites and arkoses are well-jointed and produce permeable weathering products.

The massive sandstones which crop out in the western and southern escarpments are massive with widely-spaced, open joints which result in many permanent springs. One of these, near Abudem, was reported to have a discharge of 4,500 l/day in 1916.

There is little available ground water from the central part of the basin due to the predominance of shales. No exploratory boring deep aquifers had been carried out at the time of Gill's (1969) investigation.

In the northern part of the basin the permeability is higher but salt beds result in a T.D.S. generally over 1,000 mg/l. Even if these arkosic sandstones extend under the shales in the centre of the basin the water is expected to be saline. Valley alluvium in the region held the greatest potential for obtaining groundwater supplies from induced recharges. Construction of the Volta dam has, however, resulted in flooding of large areas.

Coastal Basins

In the coastal basin of Ivory Coast and western Ghana boreholes are located in the upper 100 m of unconsolidate coarse sands of the Upper Cretaceous to Lower Tertiary age. Yields from 31 boreholes in Ghana are 3.5 l/sec on average. Gill (1969) considers these values low for the nature of the sediments, and that better borehole construction should substantially increase yields. However, the effect of increased abstraction on saline intrusion has not yet been investigated. At present (1969) chloride concentrations are in the range of 10 to 25 mg/l contributing to a low T.D.S. of 80 mg/l on average. The hydrogeology of that part of the basin lying in Ivory Coast is discussed in some detail by (Guerin-Villeaubriel, 1962). The Palaeozoic sediments of the Accra region have been little explored. They are generally well consolidated but reasonable yields can be expected where boreholes intersect major fissures. Considering the history of faulting, jointing should also be extensive. It seems however, that boreholes have not been located using structural guides. Yields from the Sekondian sandstones and shales are 1 l/sec in the region of Takoradi.

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ABBREVIATIONS USED:

Locations:

I.G.S.	Institute of Geological Sciences (most in main library)
I.G.S. bf	" " " " Box File for area.
O.D.M.	Ministry of Overseas Development Library.
S.R.L.	Science Reference Library
b	Bayswater branch
h	Holborn branch
U.C.L.	University College London Library.

Organisations:

B.R.G.M.	Bureau de Recherche Geologie et Minière.
B.U.R.G.E.A.P.	Bureau d'Etudes de Geologie Appliqué et d'Hydrologie Souterrain.
C.I.E.H.	Comité Inter-Africaine d'Etudes Hydrauliques.
C.G.G.	Comagnie Général de Géophysiques.
D.F.M.G.	Direction Fédérale Mines et Géologie.
D.M.G.	Direction Minière et Géologique.
F.A.O.	Food and Agricultural Organisation (of the United Nations)
S.G.P.M.	= D.F.M.G.
U.S.G.S.	United States Geological Survey
O.R.S.T.O.M.	Office de la Recherche Scientifique et Technique Outre Mer.
U.N.D.P.	United Nations Development Programme
U.N.E.S.C.O.	United Nations Education, Scientific and Cultural Organisation.

Publications:

A.I.H.	Association International d'Hydrogéolistes.
(A.I.H.S.	Association International d'Hydrologie.
	Scientifique).
I.A.S.H.	International Association of Scientific Hydrology.

Miscalleneous:

A.E.F.	Afrique Equatoriâle Française.
A.O.F.	Afrique Occidentale Française.
Arch.	Archives.
C.R.	Compte-Rendu.
Serv.	Service.

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TABLE 1. YIELD OF WELLS

1. AQUIFERS WITH INTERSTITIAL POROSITY

1.1 SANDS

COUNTRY		AQUIFER	YIELD per WELL (l/sec)	DRAWDOWN (m)	S	K (m^2/d/m)	T (m^2/d/m)
MAURITANIA	Plain of Kiffa	sand dunes	1.4 - 2.8	-	-	-	-
	Plain of Assaba	"	-	-	-	10	-
SENEGAL	Malika	Clayey sands	7.2	7.8	17		

2. ALLUVIA, DELTAS, QUATERNARY OF CHAD BASIN, COASTAL SEDIMENTARY BASINS

Alluvia

MAURITANIA	Wadi Seguelil	Gravelly Alluvia	2.8	-	-	10	-
GUINEA	Rio Nunez Estuary	Alluvia	5.6 - 14.0	-	-	-	-
IVORY Coast	Treichville Lagoon	Coarse Sands	57	-	3	-	-
TOGO	Coast	Clayey Sands	.8 - 1.4	-	-	-	-
CAMEROON	Chad Basin	Alluvial fill	2.8 - 22.4	-	-	-	-

Coastal Sedimentary Basins

BENIN-TOGO	Coast	Cretaceous Sands	up to 9.7 l/sec/m	-	-	-	-
IVORY COAST	Abidjan	Palaeo-Cretaceous Sands and Limestones	5.0	80	-	-	-
SENEGAL	Ferlo Basin	Maestrichtian Sandy sandstones	4.2 - 5.6	artesian	-	30 - 100	600 - 2,000

3. CONTINENTAL TERMINAL CONGLOMERATES AND SANDSTONES

MALI	Gondo	-	13.9 - 27.8	-	-	-	-
MAURITANIA	Trarza	Sandy interactions	.3 - 1.1	-	-	25	250
	Bennichab	"	8.3	23	-	-	-
	Neuakchott	"	4.2	8	1	-	-
SENEGAL	Casamance	Clayey Sandstones	1.7 l/sec/m	-		-	-

B. AQUIFERS WITH FISSURE POROSITY

MAURITANIA	Atar	Dolomitic limestones	19.4	4	-	-	-
	Trarza	Eocene limestones	0.03 - .3	-	-	-	-
SENEGAL	Pout-N'Diasso	Palaeocene limestones	up to 1.2	100 - 200	.1 - .5	.5 - .7	-
UPPER VOLTA	Tin Hrassan	Dolomitic limestones	1.1	10	.002	-	43

C. AREAS WITH LOW OR ONLY LOCAL POROSITY DUE TO WEATHERING OR FISSURES

BENIN	Parakou	Fractured granites in tectonic depressions	1.9	-	-	-	-
CHAD	Ouaddai	Granite sands	up to .5 exceptionally	Cartesian	-	-	-
BENIN-TOGO	-	Birrimian schists	.8 1.9	-	-	-	-
GHANA	-	Voltaian schists	very low	-	-	-	-
	-	Granites and granodiorites	up to .2	-	-	-	-
GUINEA	-	schists	very low	-	-	-	-
IVORY COAST	Yamoussokro	Fractured granites	1.7	-	-	-	-
	-	Micaschists	less than .01	-	-	-	-
		Granito-gneiss	.3 - 1.1	10 - 20	-	-	.5 - 1.0
MALI	Nara	Cambrian schists	very low	-	-	-	-
MAURITANIA	Aioun Atrous	Infracambrian sandstones	.06 - .08	-	5	5	-
	Atar	Schists below alluvia	5.6	2	-	-	-
	Hodh	Cambrian sandstones	up to .1	-	-	3	-
		Braser sandstones	up to .6	-	-	7 - 40	-
	Fort-Gourard	Micaschists and gneiss	.2	-	-	-	-
	South-West	Diorites	.1	-	-	-	-

	Ajkoujt	Basic rocks	.8	13	-	-	-
	Konadry	Basic rocks	.4 - 1.6	20 - 50	-	-	-
	Kongolikan	Fractured greenstones	.1	-	-	-	-

[illegible]	Sandy Sandstones	1.4 - 11.1 l/sec/m	-	-	20 - 40	-
Lobo-Diebiasso	-	25.0	-	-	-	-

CONTINENTAL INTERCALARY

Lokoto	Consolidated	High	-	3	150	1,500

FIG.1 LOCATION AND PRECIPITATION

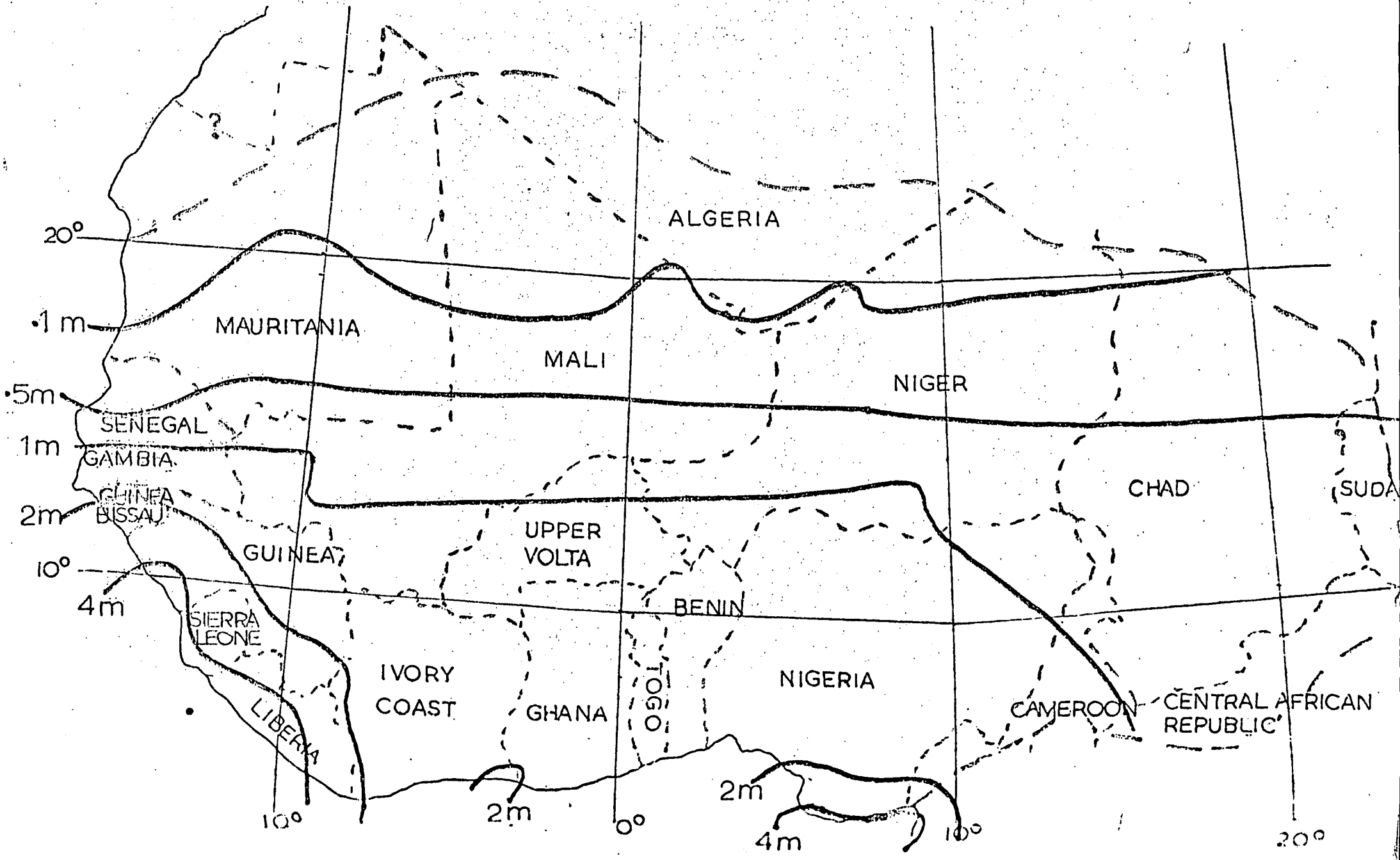
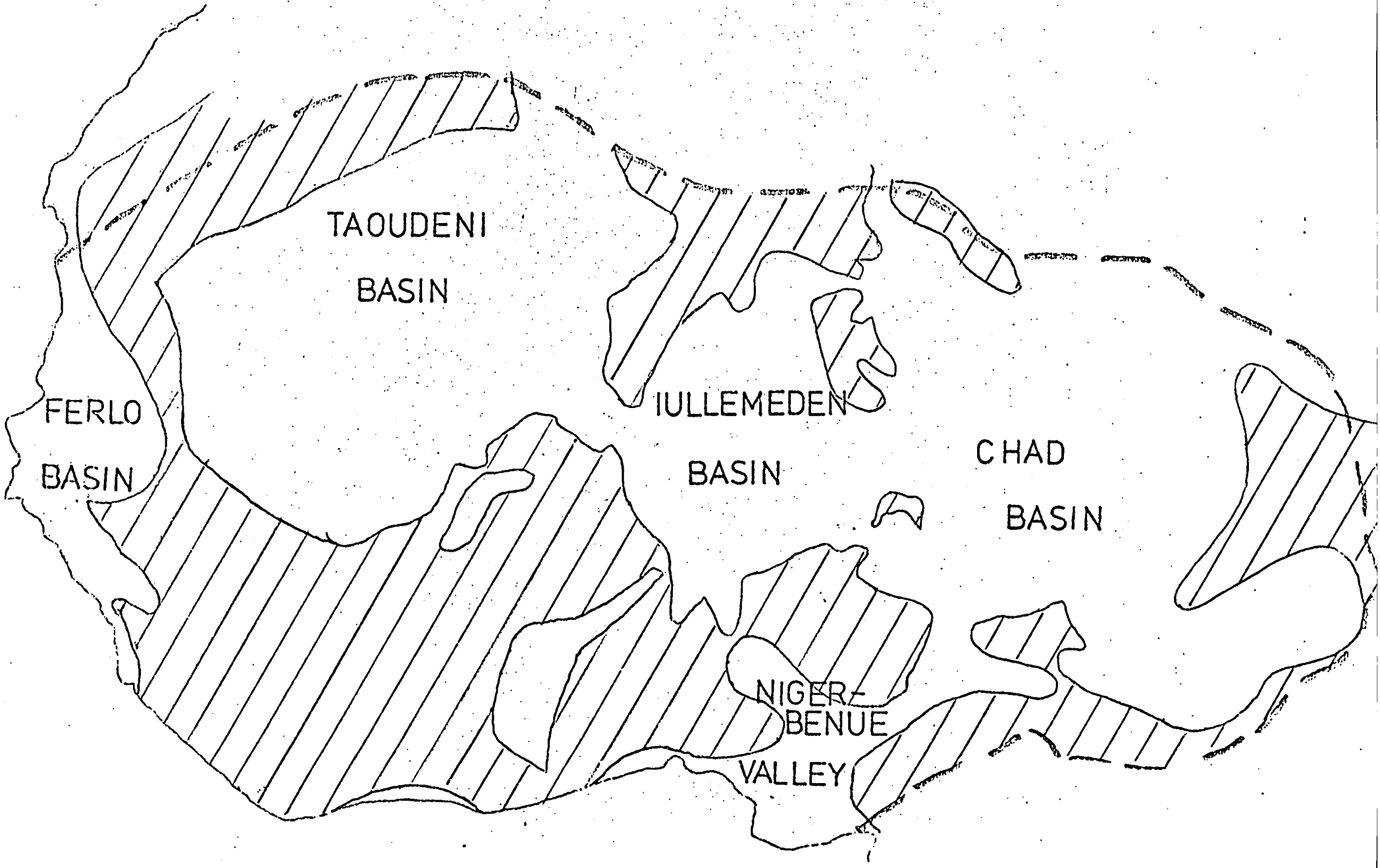
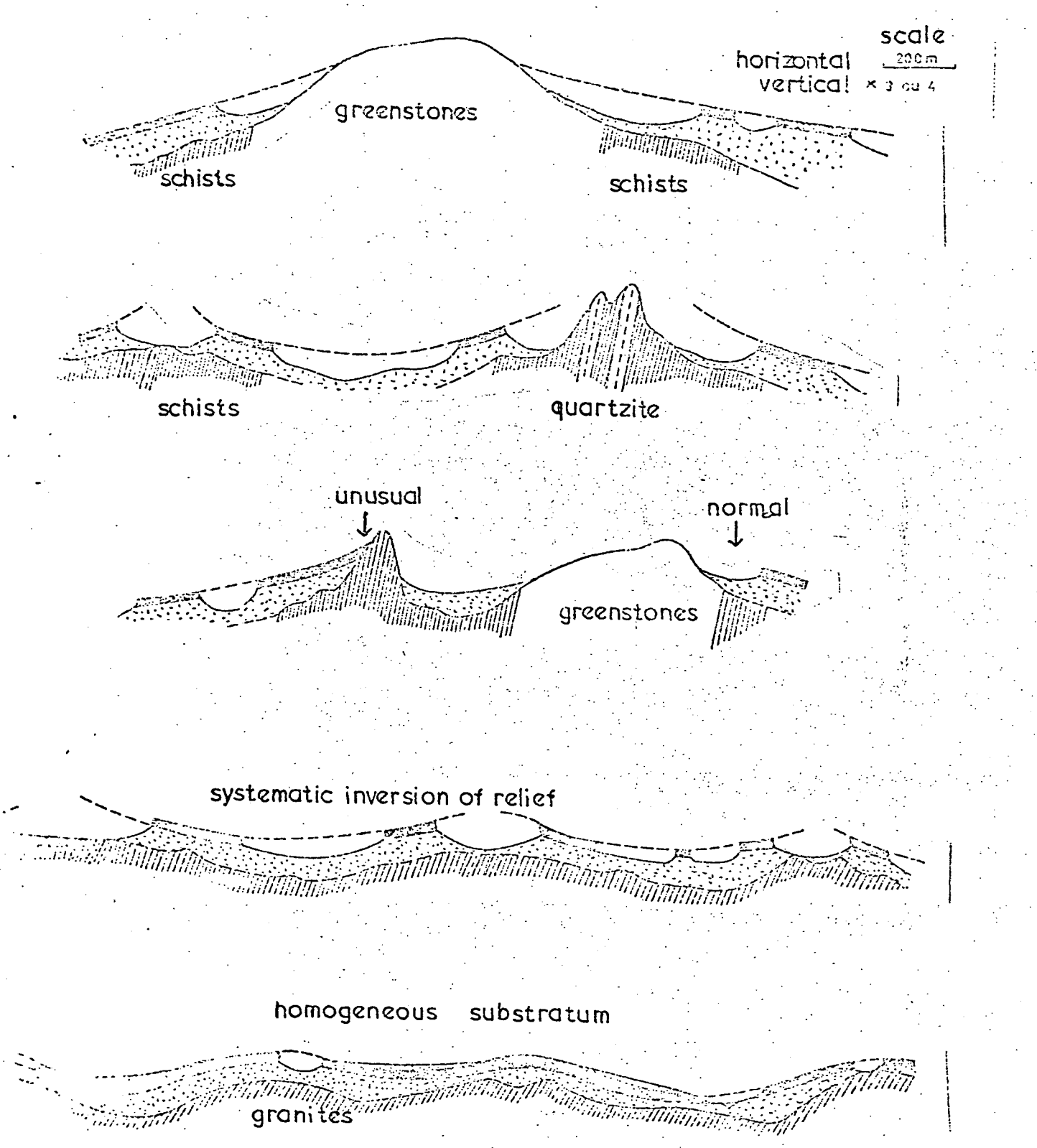


FIG.2 MAJOR SEDIMENTARY BASINS



from UNESCO (1968) and UN (1971)

FIG. 3 RELIEF AND OCCURRENCE OF THE WEATHERED ZONE IN IVORY COAST



from George (1968)