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SEDIMENTARY ROCKS OF THE COAST OF LIBERIA

by

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ABSTRACT

Two basins containing sedimentary rocks of probable Cretaceous age have been recognized near the coast of Liberia in the area between Monrovia and Buchanan; geophysical evidence suggests that similar though larger basins may exist on the adjacent continental shelf.

The oldest sedimentary unit recognized, the Paynesville Sandstone of possible early to middle Paleozoic age, is intruded by dikes and sills of diabase of early Jurassic age and lies unconformably on crystalline rocks of late Precambrian age. Dips in the Paynesville Sandstone define a structural basin centered south of Roberts International Airport (formerly called Roberts Field) about 25 miles east of Monrovia. Wackes and conglomerates of Cretaceous age, herein named the Farmington River Formation, unconformably overlie the Paynesville Sandstone and constitute the sedimentary fill in the Roberts basin.

The Bassa basin lies to the southeast of the Roberts basin and is separated from it by an upwarp of crystalline rocks. The basin is occupied by wackes and conglomerates of the Farmington River Formation, which apparently lie directly on the crystalline basement. Both basins are bounded on the northeast by northwest-trending dip-slip faults.

The best potential for petroleum deposits that exists in Liberia is beneath the adjacent continental shelf and slope. Geophysical exploration and drilling will be required to evaluate this potential.

INTRODUCTION

It has been known for some time that sedimentary rocks crop out near the coast of Liberia in the region between Monrovia and Buchanan (pl. 1). However, little information about these rocks has been published (Newhouse and others, 1945; Offerberg and Tremaine, 1961; Leo and White, 1967; Jones, 1968), and much of this is not widely available. Recent mapping has shown that these rocks occupy two basins along the coast, called the Roberts and Bassa basins, the limits of which have been fixed by post-depositional faulting and erosion. Moreover an airborne magnetometer survey of Liberia including the continental shelf has indicated possible substantial thicknesses of sediments on parts of the shelf (Behrendt and Wotorson, 1969a), and has attracted considerable interest from several petroleum companies. This paper, describing the sedimentary basins on shore, is presented as an aid to offshore exploration.

Some preliminary mapping of the sedimentary rocks (unpublished) was done near Monrovia in 1955 by geologists employed by what was then the Liberian Bureau of Mines and Geology. More extensive work near Monrovia done in 1963 by a team of consultants from the Battelle Institute, Germany, is described in an unpublished report to the government of Liberia.

The area near Little Bassa and Buchanan was investigated by geologists employed by the Liberian American-Swedish Minerals Company (Offerberg and Tremaine, 1961), and by B. R. Cooper (unpublished, 1963) of the Liberian Geological Survey. Offerberg and Tremaine correctly distinguished two sedimentary facies which in this paper are given formation status as the Paynesville Sandstone and the Farmington River Formation, but they neither mapped these units separately nor determined relative age between them. All outcrops indicated on their map were re-examined during the present study.

The geologic mapping on which this paper is based was conducted intermittently from 1967 to 1969. Mapping was done on 1:40,000-scale topographic maps or on aerial photographs; although some information was gained from road cuts, borrow pits, and dug water wells, for the most part mapping was restricted to surface exposures. However, exposures are extremely poor in the coastal area because of thick lateritic weathering and widespread deposits of unconsolidated sediments.

Most of the area of outcrop of sedimentary rock is less than 20 meters above sea level, the higher points within the area being on diabase dikes or sills. Land near all-weather roads is used for residences and businesses, rubber plantations, or farms; more remote areas are inhabited by tribal Liberians who practice shifting or swidden cultivation and who also maintain small rubber plantations. Much of the land in remote areas is sandy savanna, swamp, or fallow ground with second-growth bush; only isolated patches of virgin tropical rainforest remain in the coastal area. Routes of access into remote parts of the area are limited to footpaths, rivers, and a few dry-weather roads. Access is difficult in the rainy season (June to October) owing to high water conditions, but is no great problem at other times.

This study was undertaken as part of a joint program of regional mapping and mineral exploration being conducted by the Liberian Geological Survey and the U.S. Geological Survey under the sponsorship of the Government of Liberia and the U.S. Agency for International Development.

STRATIGRAPHY

The stratigraphic succession in the sedimentary rocks on shore is shown in Table 1. The formation names used in Table 1 and defined below are introduced here for the first time. Because of the paucity of exposures in the coastal area, definitions of the respective formations are based on reconstruction of partial sections from widely scattered outcrops rather than on typical sections. The formations are not exposed well enough for any one section to qualify as a type section.

Crystalline basement

The crystalline basement underlying the sedimentary basins is made up of granitic rock, quartzo-feldspathic gneiss, granulite, schist, amphibolite, quartzite, and iron formation; subdivision of the basement is beyond the scope of this paper. Outcrops of the crystalline rocks are sparse, but nevertheless are more numerous than those of the sedimentary rocks. Mafic rocks form more resistant outcrops than felsic rocks, which may be weathered to depths as great as 30 meters.

Foliation in the crystalline basement strikes generally northwest near the shore, in contrast to northeast to east-trending foliation away from the shore (see fig. 1). Preliminary radiometric age determinations in Sierra Leone (Allen and others, 1967, p.19; Hurley and others, 1967, p.23) and in Liberia (Hurley and others, 1967, p. 5; 1968, p. 87; Leo and White, 1967, p. 23) suggest that a northwest-trending zone extending along the coast of Sierra Leone and of central and western Liberia may represent a late Precambrian (Pan African, 500-700 m.y.) tectonic zone. In Liberia this tectonism evidently involved reheating and redeformation of

Table 1.--Generalized geologic column in coastal Liberia between Monrovia and Buchanan

Age	Unit	Thickness (meters)	Character and distribution
Quaternary(?)	Unconsolidated sediments	1-20	Sand, sandy clay, clay, and peat; widespread.
	Disconformity		
Tertiary(?)	Edina Sandstone	2-20(?)	Coarse-grained, well-sorted sandstone; widespread isolated remnants.
	Disconformity		
Cretaceous	Farmington River Formation	1,000(?)	Wacke and polymict conglomerate; sparse plant fragments and invertebrates; occupies center of Roberts and Bassa basins.
	Unconformity		
Early Jurassic	Monrovia Diabase	-	Dikes and sills of tholeiitic diabase intruding Paynesville Sandstone; widespread; localized extrusive basalt may be correlative
	Intrusive Contact		
Early Paleozoic(?)	Paynesville Sandstone	1,000(?)	Fine-grained, well-sorted sandstone; no fossils known; widespread.
	Unconformity		
Late Precambrian	Crystalline basement	-	Granitic rock, quartzofeldspathic gneiss, granulite, schist, amphibolite, quartzite, and iron formation; intruded by dikes of diabase; underlies sedimentary sequence and forms a northwest-trending belt along the coast of Liberia.

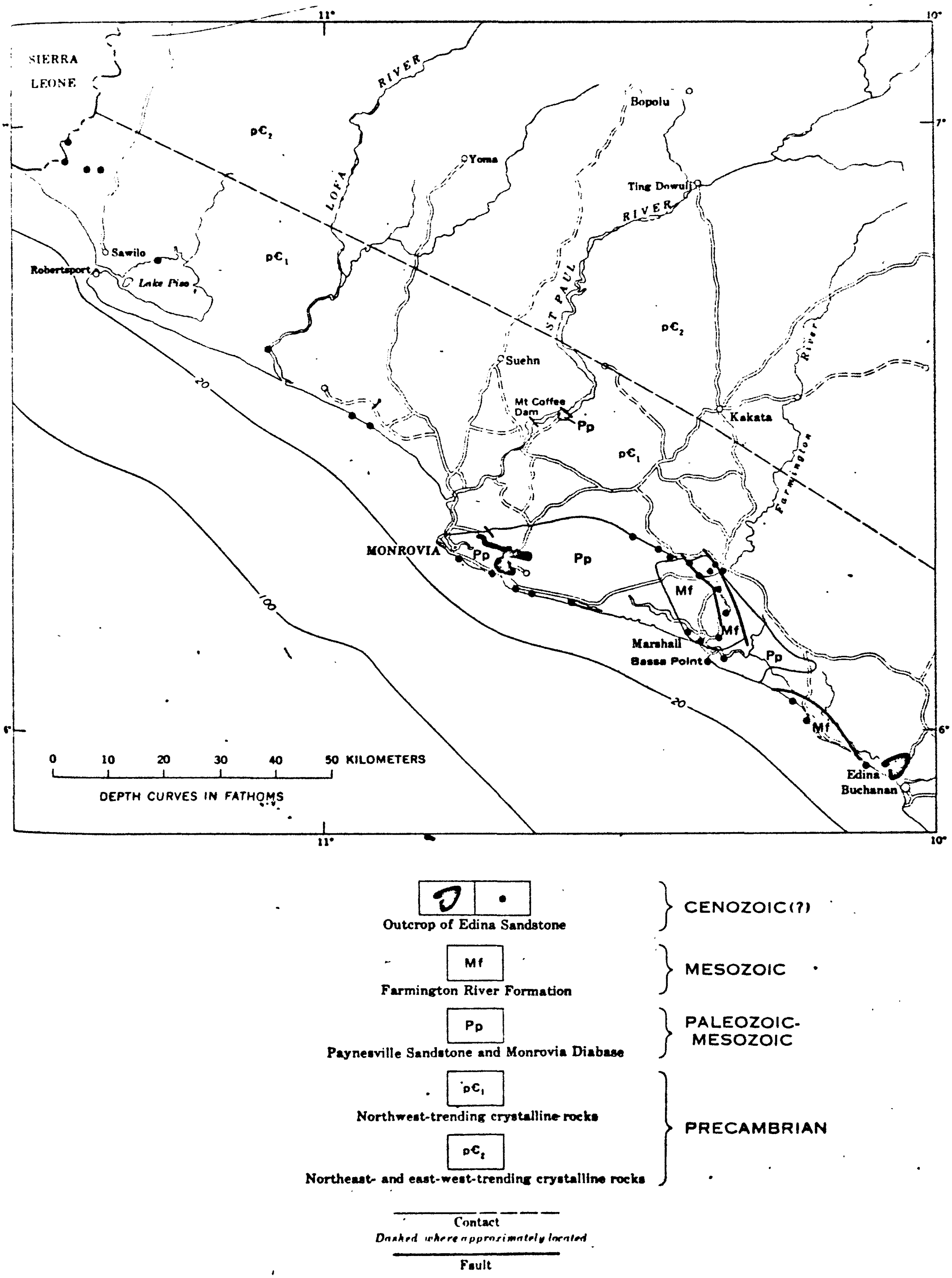


Figure 1.– Map showing outcrops of Edina Sandstone and relationship to older rock units

older crystalline rocks. Kennedy (1966, p. 10) has noted the association of Mesozoic and younger coastal sedimentary basins with tectonic zones of this age elsewhere in Africa.

Paynesville Sandstone

The Paynesville Sandstone, which is named and described herein, is the oldest unmetamorphosed sedimentary rock unit known in Liberia. The name is taken from Paynesville township near Monrovia (pl. 1) where the formation is fairly widely exposed. The several outcrops along a north-south line passing through Sugar Beach are typical of the formation. Other good exposures are found in the area of the Liberia Refining Company (fig. 2) near Monrovia, east of Zarzu, and on Bassa Point. An outlier of Paynesville Sandstone, found by W. E. Stewart (oral communication, 1967) on the St. Paul River upstream from the Mount Coffee dam (fig. 1), indicates an original distribution more widespread than at present. This outcrop was permanently inundated by the Mount Coffee reservoir in 1966. All other known outcrops of the sandstone are restricted to the contiguous area around the Roberts basin (pl. 1).

Most natural exposures of this formation are found in low-lying savannas in which the soil consists of fine-grained white sand; a few outcrops are found along streams and on the seashore. Savannas with coarse sandy tan soil generally do not contain outcrops of Paynesville Sandstone. The exposure consists of smooth, rounded boulders or low, flat outcrops of white, tan, or red sandstone which may be coated with black lichens. In artificial exposures the rock commonly is weathered and extremely friable, and is red or brown.

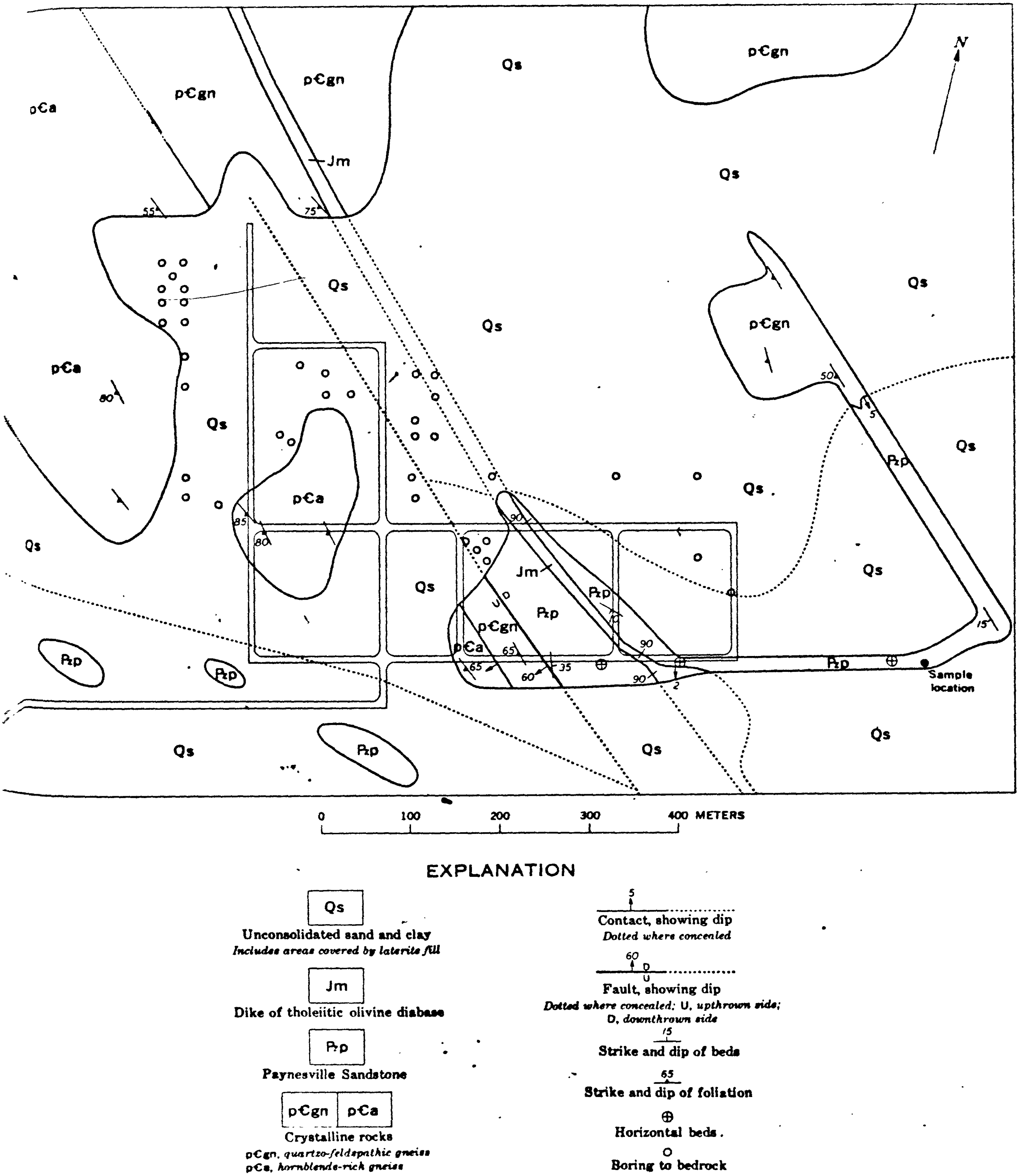


Figure 2.—Geologic sketch map of the site of Liberia Refining Company

The sandstone generally is weathered less deeply than the felsic crystalline rocks. A typical soil profile consists of a surficial zone rich in ferruginous pisolites, overlying a sandy clay soil which is a few meters thick. Weathered, friable sandstone is usually encountered at depths no greater than 2 to 5 meters, and coherent, though weathered, rock at slightly greater depth.

The Paynesville Sandstone is fine-grained (0.05 to 0.4 millimeters), well-sorted, mature quartz arenite throughout. The quartz grains are well rounded and are cemented by quartz overgrowths (pl. 2-1, -2). Five to ten percent of detrital feldspar is typical; small amounts of detrital muscovite, tourmaline, and opaque minerals also have been detected.

Many outcrops of the formation exhibit crossbedding, with more or less tabular crossbedded units of thickness 50 centimeters or less. However, other outcrops appear quite massive so that bedding is difficult to recognize. Ripple marks have been recognized in only a single outcrop. Local thin interbeds (10 to 25 centimeters) of mudstone are known; these have been found only in artificial exposures and hence could be more widespread than natural outcrops would indicate.

The sandstone appears quite porous and friable in outcrop, but this apparently is due to weathering out of detrital feldspars; examination of thin sections suggests that the porosity of unweathered rock would be quite low. Widely spaced, northwest-trending vertical jointing is found in some outcrops, but it does not appear to be developed well enough to have much effect on the permeability of the rock.

Plate 2. -- Photomicrographs of sedimentary rocks

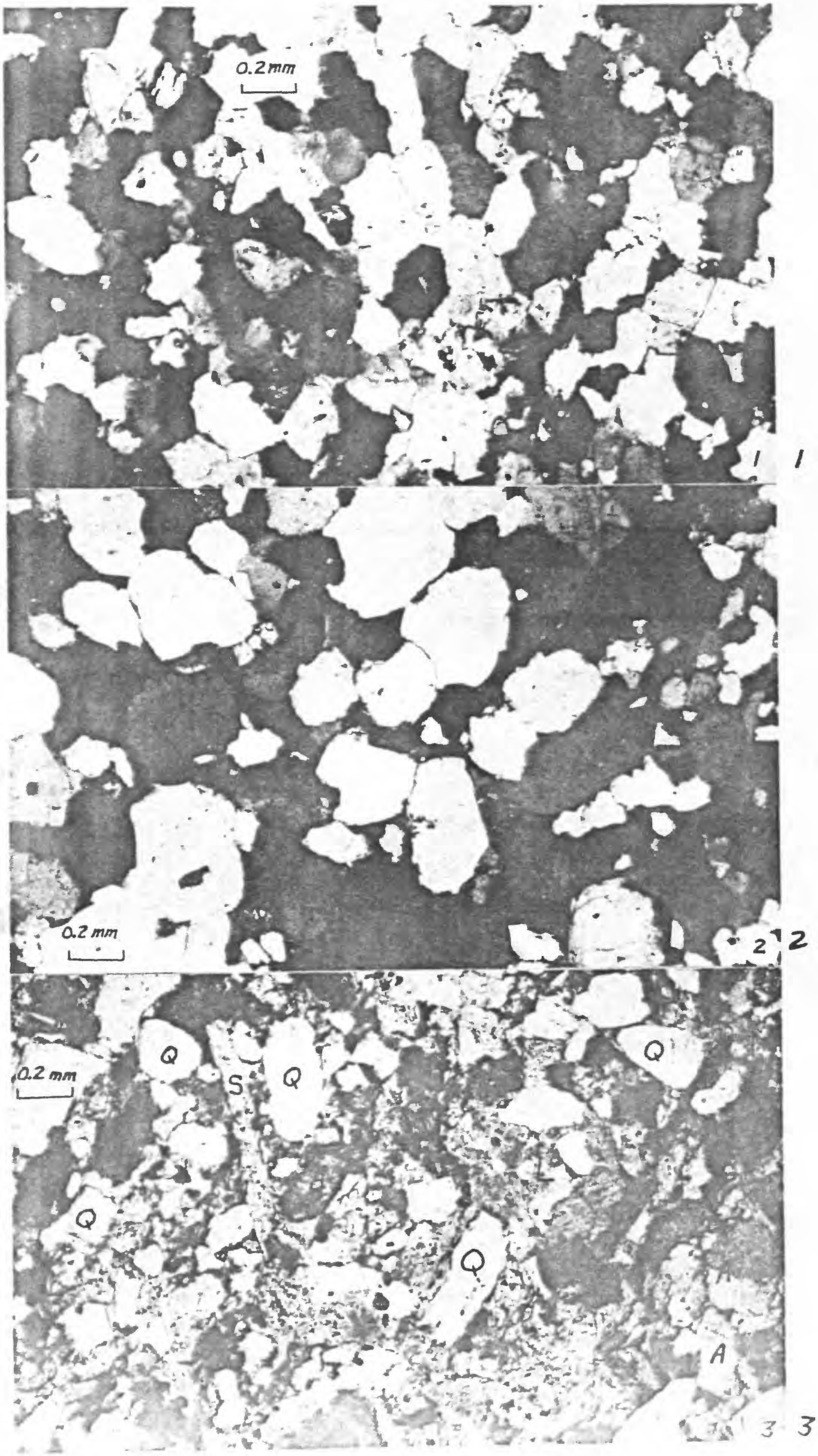
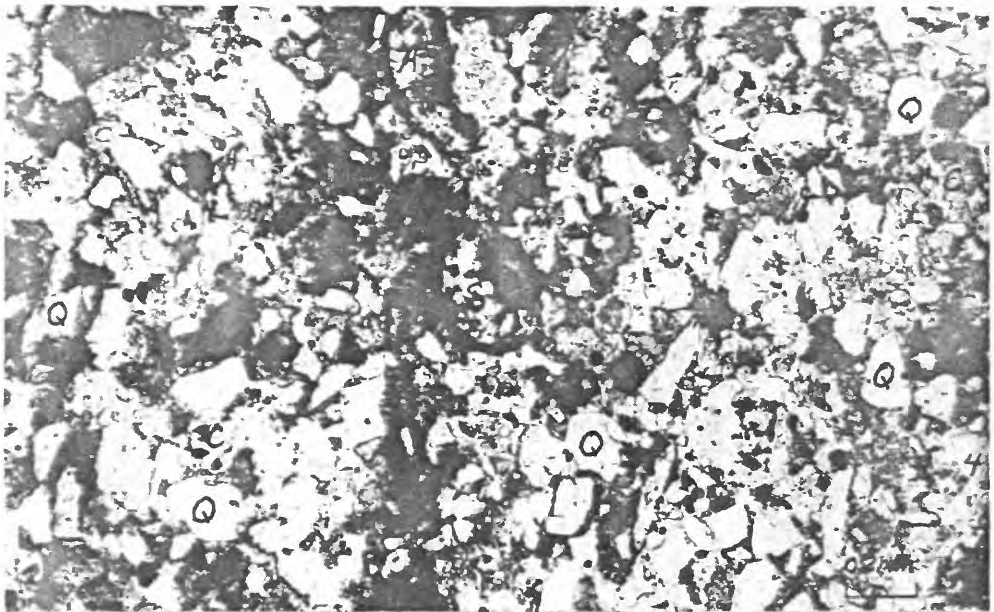


Plate 2 (continued)



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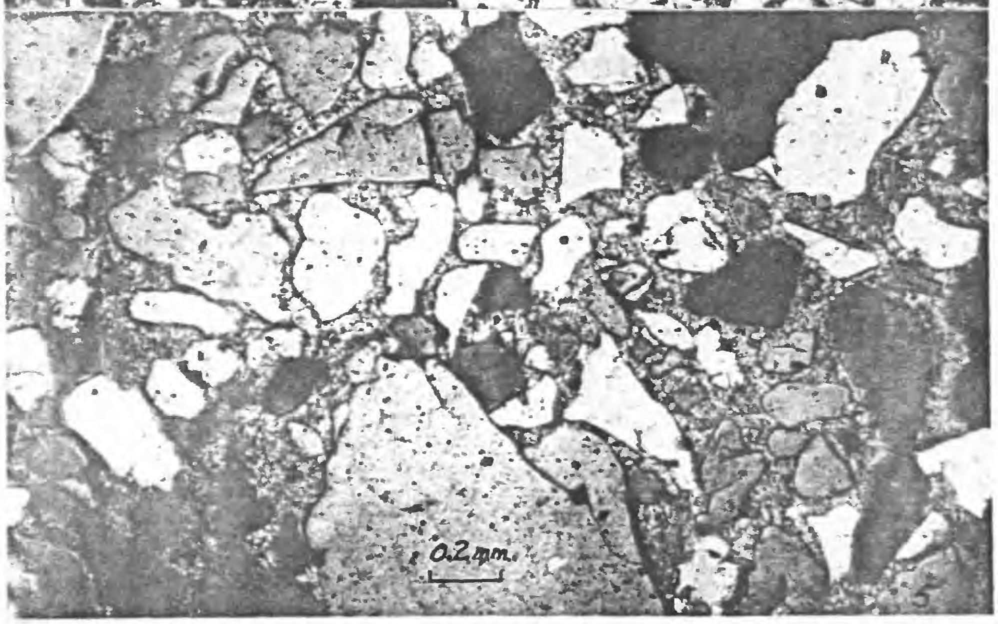

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1. Paynesville Sandstone, a few meters above base, on freeway near Liberia Refining Company (461B). Clastic quartz cemented by quartz overgrowths. Partially crossed polarizers.

2. Paynesville Sandstone, near top of section, on shore near Bassa Point (590A). Clastic quartz cemented by quartz overgrowths. Partially crossed polarizers.

3. Farmington River Formation, wacke, in creek near Farmington River, 0.8 mile south of terminal at Roberts Field (526A). Q, quartz and lesser feldspar; A, amphibole and other accessory minerals; S, shell fragment; L, lithic fragment. Plane polarized light.

4. Farmington River Formation, wacke, on shore 1.1 miles south of Little Bassa (597A-2). Q, quartz and lesser feldspar; A, accessory minerals; S, shell fragment; C, calcite cement. Plane polarized light.

5. Edina Sandstone, loose boulder on outcrop of Farmington River Formation, on shore 1.1 miles south of Little Bassa (597A-3). Clastic quartz in matrix of crystalline clay mineral. Partially crossed polarizers.

The Paynesville Sandstone lies unconformably on Precambrian crystalline rocks. A single exposure of the basal contact is known, in a ditch on the north side of the site of the Liberia Refining Company northeast of Monrovia (fig. 2). At the contact the sandstone is fine- to medium-grained with appreciable clay content; it encloses irregularly shaped concretions of chalcedony. Both the sandstone and the underlying quartzo-feldspathic gneiss are deeply weathered; the chalcedony and much of the clay may be products of weathering.

The top of the sandstone also is poorly exposed. It is overlain in various areas by amygdaloidal basalt, by the Farmington River Formation, by the Edina Sandstone, and by unconsolidated sands. The last three, and probably all four, of these rest unconformably on the Paynesville Sandstone.

The thickness of the Paynesville Sandstone can only be inferred, as outcrops are too sparse for good structural control, and no drillhole data are available. Projection of dips suggests a thickness of about 1,000 meters in the area of Sugar Beach. The thickness inferred in the same area from airborne magnetometer data and gravity data by Behrendt and Wotorson (oral communication, 1968) is of the same order of magnitude.

No fossils of any kind have been found in the Paynesville Sandstone. The sediments have the character of shallow-water deposits, but it is not known whether they were deposited under lacustrine or marine conditions.

The age of the Paynesville Sandstone is not known, but it is between the limits of about 500 million years (underlying crystalline rocks) and

192 million years (intrusive diabase), or between early Paleozoic and Triassic. According to the stratigraphic summaries for Africa of Haughton (1963) and of Reyre (1966), no sedimentary rocks deposited within the upper end of this range (late Paleozoic to Triassic) are known in west Africa south of the Sahara. The Karoo continental sediments of central and southern Africa were deposited within the upper end of this range and are intruded by diabase comparable in age and character to the Monrovia diabase. However, the absence of any fossils in the Paynesville Sandstone is in marked contrast to the rich fossil assemblages of the Karoo sediments; it seems unlikely that the two are correlative.

Sedimentary rocks of early to middle Paleozoic age are known at several places in west Africa south of the Sahara; those nearest to Liberia are in western Guinea and northwestern Sierra Leone. The Saionia Scarp Series of Sierra Leone (Dixey, 1925, p. 213) resembles the Paynesville Sandstone in that both consist of relatively flat-lying unfossiliferous sandstones that have been intruded by sills of tholeiitic diabase. The Saionia Scarp Series is continuous with the widespread Grès siliceux horizontaux of Guinea, which contain shale interbeds with graptolites of Silurian age (Sinclair, 1928, p. 477).

Although it cannot be regarded as firmly established, it seems more likely that the Paynesville Sandstone was deposited in early (or middle) Paleozoic time than in the late Paleozoic or Triassic.

Monrovia Diabase

The Paynesville Sandstone is intruded by northwest-trending vertical dikes and broad sills of diabase for which the name Monrovia Diabase is proposed. The dikes cut both the underlying crystalline basement and the Paynesville Sandstone, but the sills are found only within the sandstone or at the unconformity at its base. The Monrovia Diabase as here defined includes those dikes and sills which intrude the Paynesville Sandstone, as well as localized flows of amygdaloidal basalt which lie on the sandstone. The diabase dikes intruding the adjacent crystalline rocks are largely if not wholly of comparable age, hence they are provisionally included in the formation at this time. However, additional radiometric age determinations may require subdivision of some of the diabases within the crystalline basement.

The best exposed body of diabase is one that crops out in downtown Monrovia and on Mamba Point, with almost continuous exposures from sea level to an altitude of about 70 meters. Natural exposures of the contacts between diabase and sandstone are not known, but the contacts of dikes are revealed in artificial exposures at several places, and the basal contacts of diabase sills overlying gently dipping Paynesville Sandstone are exposed in borrow pits near Paynesville and Schieffelin.

Some dikes pass laterally into sills. A well-exposed example is seen on the site of the Liberia Refining Company (fig. 2), where a vertical dike 20 meters thick passes laterally (and stratigraphically upward) from gneiss into Paynesville Sandstone, thinning upward. About 5 meters above the base of the sandstone, one edge of the dike deflects parallel to the subhorizontal bedding, whereas the other continues vertically.

Diabase is more resistant to weathering than any other type of rock in the coastal area, and consequently it tends to form ridges. A thin lateritic soil with ferruginous capping is preserved on some diabase bodies, but it usually is possible to find completely unweathered diabase as boulders at the surface even where the underlying diabase is weathered. Where it is exposed to the atmosphere the diabase seems to weather only by dissolution, with the development of lapies or rainwash flutings. Beneath a soil cover, the diabase weathers spheroidally away from joints, and spheroidal cores of unweathered diabase are preserved within shells which grade rapidly through weathered diabase to orange-brown clay-rich soil.

The Monrovia Diabase is a tholeiitic diabase consisting mostly of labradorite, augite, and accessory magnetite. Local pigeonite and the widespread distribution of accessory quartz in graphic intergrowths with alkali feldspar confirm its tholeiitic character. Sparse olivine is found in some dikes, and phenocrysts of bronzite are locally fairly abundant in the high levels of some sills. Otherwise dikes and sills are petrographically indistinguishable. Deuteric alteration has been noted only locally in the sill which crops out at Schieffelin.

The sills are characterized by uniform fine (to medium) grain sizes, by widely spaced jointing, and by the absence of vesicles or amygdules. Gently dipping flow-layering is present only locally, and columnar jointing is poorly developed except in the sill on Bassa Point; otherwise the direction of the dip of the sills usually can be inferred only from the asymmetry of landforms. Dips so inferred generally are conformable with adjacent Paynesville Sandstone. The fine grain size and the absence of marked magnetic anomalies over many of the sills indicates that they must be relatively thin sheets (10 to 50 (?) meters). In contrast, vertical dikes commonly yield prominent linear magnetic anomalies; similar linear anomalies associated with some gently dipping sills probably represent underlying feeders (Behrendt and Wotorson, oral communication, 1969).

The age of the Monrovia Diabase is known from two potassium-argon age determinations of plagioclase separates by G. B. Dalrymple of the U.S. Geological Survey. The results are 176 ± 5 m.y. for a specimen from Bernard's Beach at Sinkor, and 192 ± 6 m.y. for a specimen from the lighthouse on Mamba Point, Monrovia. These dates correspond to early Jurassic. These two separate bodies of diabase both appear to be sills, although associated magnetic anomalies suggest underlying feeders of some width (Behrendt and Wotorson, oral communication, 1969). Unfortunately no contacts of these particular bodies with Paynesville Sandstone are exposed, but by their structural positions they are unlikely to be older than the sandstone.

Amygdaloidal basalt member of Monrovia Diabase

The Paynesville Sandstone is overlain by amygdaloidal basalt east of Sugar Beach near Monrovia and at Bassa Point (pl. 1). No beds of Paynesvil Sandstone stratigraphically higher than the basalt can be confirmed in either area, hence it is assumed that the basalt is younger than, rather than interbedded with, the sandstone.

Although exposures in both areas of basalt outcrop are poor, it seems likely that each represents a single flow. The flow on Bassa Point is amygdaloidal only in the northwestern-most outcrops; this is in the direction of the top of the flow if the flow is conformable with the underlying Paynesville Sandstone. The amygdules consist of differing proportions of chalcedony, quartz, calcite, zeolites, and chlorite.

Three lines of evidence suggest that the basalt is the extrusive equivalent of the Monrovia Diabase: (1) The basalt is at at the stratigraphic position one would expect for an extrusive; i.e., post-Paynesville Sandstone and pre-Farmington River Formation; (2) the basalt is petrographically similar to the diabase; (3) both areas of basalt are situated at the seaward end of broad northeast-trending magnetic anomalies, the landward portions of the anomalies being located over areas of abundant sills and dikes of diabase.

Farmington River Formation

The center of the Roberts basin and most of the Bassa basin are occupied by wacke and polymict conglomerate which are here grouped together as the Farmington River Formation. The name is taken from the Farmington River which crosses the eastern portion of the Roberts basin, and along which the formation is fairly well exposed at low tide (pl. 1). Other good exposures are found on Long Reef Point; these also are best examined at low tide. The two facies are interbedded in part, but conglomerate is most abundant near the base of the formation and becomes less abundant upward and toward the sea, with concomitant decrease in grain size of the wackes and increase in proportion of thin shale interbeds.

It may be desirable with additional work to subdivide the formation into two separate members or even into separate formations.

The wacke is a poorly sorted, coarse-grained rock containing a diversity of clastic grains in a matrix of chlorite, sericite, and calcite (pl. 2-3, -4). The clastic grains consist dominantly of rounded to angular quartz, with lesser amounts of altered and unaltered plagioclase and microcline. Accessory minerals include amphiboles, muscovite, biotite, epidote, pyroxene, garnet, opaque minerals, tourmaline, zircon, and sphene. Lithic fragments such as graphic quartz-microcline intergrowths, granitic rock, amphibolite, diabase, fine-grained sandstone, siltstone, shale, and chert, and fragments of gastropod and pelecypod shells and of carbonized plant detritus also are common. The wacke is similar in both basins, except that amphiboles, epidote, and pyroxene are more abundant and calcite cement, garnet, and biotite are less abundant in the Roberts basin than in the Bassa basin. This probably is a reflection of the differing source areas, as the crystalline rocks adjacent to the Roberts basin include abundant mafic granulites and gneisses, whereas those adjacent to the Bassa basin are predominantly quartzo-feldspathic gneisses rich in biotite and garnet.

Newhouse and others (1945, p. 31) have reported that tuffs underlie Roberts Field and crop out on the Farmington River adjacent to the airfield. Petrographic examination of these rocks indicates that they are wackes like those described above: they contain abundant evidence of derivation from metamorphic and sedimentary terranes, and contain no evidence of volcanic constituents such as ash or lapilli. Hence the designation of these rocks as tuffs must be rejected.

The conglomerates contain abundant well-rounded cobbles and boulders of various rocks in a matrix of wacke. The largest fragment observed was an angular block of altered diabase, 1 by 3 meters; however, most of the boulders do not exceed half a meter, and the most common size of clastic fragment is 15 centimeters or less. Counts of about 100 cobbles at each of two locations indicate the following proportions of various rock types:

Rock type	Du River (Roberts basin)	East of Long Reef Point (Bassa basin)
Paynesville Sandstone	62 %	19 %
Granitic rock, gneiss, and granulite	19	28
Diabase	8	26
Quartzite and vein quartz	4	7
Chert	5	-
Amphibolite	2	20

The most notable aspect of these data is the far lesser proportion of cobbles of fine-grained, well-sorted sandstone of the Paynesville type in the Bassa basin. This is consistent with the outcrop of that unit in the two basins. No outcrops of the Paynesville Sandstone are known in the Bassa basin; although it may have been deposited in that area, its extent and thickness must have been less than in the Roberts basin.

The wacke is quite massive, and bedding is difficult to recognize except where distinctive horizons such as shale beds or beds or laminae rich in plant fragments or pebbles are present. The weathering pattern of the wacke is spheroidal, similar to that of diabase, with unweathered rock preserved in the cores of some of the spheroids. This weathering pattern indicates relatively low permeability.

Neither the top nor the base of the formation is exposed. Cobbles and boulders of Paynesville Sandstone and of diabase are found in conglomerate beds in the formation, hence it is assumed that the basal contact is an unconformity. Other than a few outcrops of overlying Edina Sandstone (see fig. 1), the Farmington River Formation is overlain only by unconsolidated sediments.

Insufficient structural data are available to permit inference of the thickness of the Farmington River Formation, and drillhole data are lacking. The characteristics of the formation (poorly sorted wacke and conglomerate) indicates rapid deposition, hence the thickness could be appreciable. Behrendt and Wotorson (oral communication, 1969) suggest that a thickness of 1 kilometer is consistent with their gravity data.

The age of the Farmington River Formation is not precisely known. R. A. Scott of the U.S. Geological Survey (written communication, 1969) examined the pollen and spores in a specimen of carbonaceous wacke from west of Roberts International Airport and determined that the age probably is Albian, although it may be as old as Aptian or as young as Cenomanian. Poorly preserved molluscs have been found at several locations (see pl. 1), but as yet no age determination based on these has been possible.

The lithology of the Farmington River Formation is similar to parts of the lower and middle Cretaceous of Ivory Coast (Spengler and Delteil, 1966, p. 104-106), in that the latter includes feldspathic sandstones and conglomerates and contains plant remains. Invertebrate marine fossils in the Ivory Coast Cretaceous sequence confirm marine deposition, but it is not known whether the Farmington River Formation was deposited under marine or lacustrine conditions.

Edina Sandstone

The formation which is here named the Edina Sandstone consists of a few small contiguous areas and numerous isolated remnants of a flat-lying coarse-grained quartz arenite. The best known outcrops are exposed at low tide as islands in the lower St. John River at Edina, from whence the name originates. Edina, however, is located on unconsolidated sand overlying weathered crystalline rocks, which illustrates the typical thin and discontinuous character of the formation.

Remnants of Edina Sandstone are widespread both within and outside the older sedimentary basins (fig. 1). The best development typically is in or near the mouths of some of the larger rivers. The largest known remnants, at Edina and on the Mesurado River near Monrovia, are about 10 square kilometers in area; many remnants consist of single outcrops surrounded by older rock or even of loose slabs and boulders lying on older rock.

The sandstone is coarse-grained throughout, containing well-rounded and generally well-sorted quartz grains (pl. 2-5). Well-rounded quartz granules are present locally, and this granule sandstone may grade into quartz conglomerate with well-rounded quartz pebbles one to three centimeters in diameter. Concentrations of black sands are found locally in the granule sandstones. Crossbedding is common but not ubiquitous in the sandstone. Inclined bedding in crossbedded sections dips as steeply as 30 degrees, but the true bedding is more nearly horizontal. The characteristics of the sandstone suggests that it represents a continental or littoral deposit rather than a marine deposit.

The degree and type of cementation of the sandstone varies from one lamina to another, resulting in a typical knobby or cavernous weathering surface. Laminae or beds cemented by a white clay mineral are quite firm and break across the grains, whereas those cemented by limonitic clay are rather friable. The porosity of both varieties is high. A third variety of sandstone, with hematite cement, is less common. The hematite-rich sandstone apparently represents a fossil soil; it tends to be best developed over iron-rich rocks such as diabase.

A thickness of 8 meters of Edina Sandstone has been measured on the north bank of the Mechlin River 2 kilometers upstream from Edina. Lesser thicknesses are suggested at many outcrops, but vertical relief generally is not sufficient to accurately determine the thickness. It seems unlikely that the maximum thickness exceeds a few tens of meters.

The Edina Sandstone unconformably or disconformably overlaps all rock units described above. It is overlain by unconsolidated sediments, predominantly sands. The sandstone has been subjected to lateritic weathering but the overlying sands have not, hence the top of the formation must represent a disconformity.

The rocks underlying the Edina Sandstone generally are deeply weathered as well. For example, all gneiss outcrops in the lower St. John River are deeply weathered beneath as much as eight meters of apparently less weathered Edina Sandstone. It is possible that the gneiss has been weathered through the porous sandstone cover, or that the apparent greater degree of weathering is a result of the more feldspathic composition of the gneiss, but it seems likely that some of the lateritic weathering predates the Edina Sandstone.

The age of the Edina Sandstone cannot be stated with certainty. It is younger than the Farmington River Formation and therefore is post-Albian; its character and distribution would suggest a young age. The only fossils that have been found in the formation are an angular fragment of silicified wood weathered out of quartz conglomerate west of Sugar Beach, and a wood fragment replaced by hematite, in the hematite-rich part of the sandstone near Paynesville.

The distribution and characteristics of the Edina Sandstone are similar to that of part of the Bullom series of Sierra Leone (Dixey, 1922, p. 44; Pollett, 1951, p. 12), with which it is more or less continuous. The Bullom series, however, includes both consolidated and unconsolidated materials, and consists of sandstones similar to the Edina Sandstone, interbedded clays, and overlying unconsolidated sediments. The Bullom series has been said to be of Pleistocene to Recent age (Pollett, 1951, p. 12), but more recent work (*in* Reyre, 1966) indicates that some units within it may be as old as Eocene.

The Edina Sandstone also has similar distribution and character to the *Tertiaire Continental* of Ivory Coast (Spengler and Delteil, 1966, p. 108), which is inferred by its stratigraphic position to be of Pliocene age. By analogy with the *Tertiaire Continental* and the Bullom series, it would seem likely that the Edina Sandstone also is of Tertiary age.

Unconsolidated sediments

Much of the coastal area of Liberia is overlain by unconsolidated sediments which include sands, sandy clay, clay, and peat. These sediments are more extensive than indicated on the geologic map (pl. 1). The boundaries indicated on the map are drawn to enclose only those areas where the unconsolidated sediments are thick enough to completely obscure the underlying bedrock over large areas. Where the sediments are thin and hence the bedrock is sporadically exposed only the bedrock is mapped.

The most widespread facies of the unconsolidated sediments is a poorly sorted, massive, yellowish-tan coarse-grained sand. Another widespread facies, which overlies the yellowish-tan sand, is a well-sorted white quartz sand. Clays and sandy clays are of more restricted distribution; they generally are found beneath swamps and along river courses, such as the lower parts of the Du, Farmington, Mechlin, St. John, and St. Paul Rivers. Blade (written communication, 1969) has described the stratigraphy of such a clay unit near monrovia. Gravels are found only locally, as on the lower Farmington River.

The surface of the unconsolidated sediments forms a fairly well-defined littoral terrace which is 7 to 10 meters above sea level near the present shore, where it is best preserved. Former beaches, which are more or less parallel to the present strand line, can be recognized on aerial photographs of the undissected terrace. Away from the shore the terrace is dissected and can be recognized only by accordant drainage divides on coarse tan sand. These divides are about 15 meters above sea level in the Paynesville area, 4 kilometers from shore.

The thickness of the unconsolidated sediments is not well known, but it has been shown by drilling to exceed 15 meters on Bushrod Island near Monrovia, in the Lake Piso area northwest of Monrovia, and on the Junk

River near Schieffelin. Soil profiles are only weakly developed on the unconsolidated sediments, but they lie on lateritic soils which have been developed on all of the consolidated rocks.

Alluvial clay soils, containing tree stumps and roots in situ, are found as much as 14 meters below sea level in the harbors of Monrovia and Buchanan, hence the unconsolidated sediments must extend offshore. Further southeast in Liberia, the coastal strip of uncolsolidated sediments is narrower and apparently thinner than that in the Monrovia-Buchanan area, and may be less extensive offshore. Lateritic soil, which is older than the unconsolidated sediments, is found offshore at depths as great as 15 meters in the harbors of Greenville and Harper, with no sedimentary cover.

The unconsolidated sediments are presumed to be of Quaternary age. The only age determination which is available is a radiocarbon age of a soil buried by sand. The buried soil, which is developed on Paynesville Sandstone, is exposed in a ditch on the east side of the site of the Liberia Refining Company near Monrovia (fig. 2). Tree stumps in situ in the soil are truncated at the base of a younger layer of well-sorted white quartz sand. The sand is about 1.5 meters thick and probably represents a littoral deposit, although its base is about 3.5 meters above present sea level. The radiocarbon age of a specimen of rotted tree root collected about 1 meter below the soil level is 1,440 ± 250 years (M. Rubin, written communication, 1968). 1/

1/ Specimen W-2141, Radiocarbon Laboratory, U.S. Geological Survey

This date seems too young to be representative of the entire section of unconsolidated sediments. Furthermore, similar buried soils overlain by well-sorted white quartz sand are developed on the unconsolidated yellowish - tan sand ~~in the~~ Paynesville area. The white quartz sands are thin surficial deposits (S. Rosenblum, oral communication, 1968), hence it would appear that the bulk of the unconsolidated sediments is older than the 1,440 year age.

Beach cobbles

Loose pebbles and cobbles of a variety of types of sedimentary rock are found on certain beaches southeast of Monrovia. Some of the source rocks are not known in outcrop, but they apparently crop out on the seabottom only a short distance offshore.

Carbonaceous sandstone

Pebbles and small cobbles of fine- to medium-grained light-gray carbonaceous sandstone are the most widespread and abundant type of transported sedimentary rock found on the beaches. They contain sparse to abundant small fragments of carbonized plant detritus as well as sparse poorly preserved pelecypod shells. Such pebbles have been found on the shore between ELWA Beach and Cole's Beach (pl. 1), where the sedimentary rock on shore is Paynesville Sandstone, as well as northwest of Little Bassa (pl. 1), where the sedimentary rock on shore is the Farmington River Formation. The rock resembles the wacke of the Farmington River Formation, but typically is better sorted and finer grained than the wacke.

R. A. Scott (written communication, 1968) has examined pollen and spores from a collection of such pebbles from Cole's Beach and has determined that they are of Albian age.

Bituminous shale

Slabs and flakes of bituminous black shale are found with the carbonaceous sandstone pebbles on the shore between ELWA Beach and Cole's Beach. These are as large as 10 x 35 x 45 centimeters and weigh as much as 9 kilograms, hence the outcroping cannot be very far offshore. The rock is fissile and contains abundant carbonized plant fragments and bituminous material; it will burn unaided for a few seconds, and gives off a bituminous odor like that of burning petroleum.

R. A. Scott (written communication, 1968) examined a collection of flakes of the shale from Cole's Beach, but unfortunately did not find enough species of pollen and spores to establish the age more closely than the range Jurassic through early Cretaceous. A few specimens show interlaminations of bituminous shale with carbonaceous sandstone similar to that described above, hence the two types of rock may be of comparable age.

Limestone

Rare flakes of limestone are found on the shore between ELWA Beach and Cole's Beach. These include shell-rich, massive, laminated, and crystalline types; most contain shells or shell fragments which are poorly preserved. The flakes commonly do not exceed a centimeter in thickness; in conjunction with their variety and paucity, this suggests that they represent thin laminae in other rocks such as shales rather than fragments from extensive sections of carbonate rocks.

J. E. Hazel of the U.S. Geological Survey (written communication, 1969) examined two specimens of the limestone and found that they contain abundant ostracods of several species undescribed in the literature, probably of lacustrine origin. Based on the genera of the ostracods, a Late Jurassic to Early Cretaceous age is possible. The limestone flakes suggest an analogy with the basal unit in the sedimentary sequence of the Ivory Coast. That unit, which is of continental origin, contains abundant lacustrine ostracods (and molluscs) of probable Late Jurassic to Early Cretaceous age; it is succeeded by marine sediments of Aptian or Albian age (Spengler and Delteil, 1966, p. 104).

Tar

Tar-like material washes up on the beaches throughout Liberia at intermittent times, particularly in the rainy season when the sea is rough. Analysis of this material in laboratories of the U.S. Geological Survey (I. May, written communication, 1966) indicates that it is a natural petroleum-like material rather than a refined product. It seems likely that the material is transported from afar, although the possibility that it comes from nearby offshore seeps cannot be totally discounted.

STRUCTURE

Because of the paucity of outcrops in the coastal area, relatively few structural observations have been made on the sedimentary rocks and a good deal of inference was necessary in preparing the geologic map (pl. 1). Nevertheless, with the aid of airborne magnetometer and radiometric data as well as the gravity data of Behrendt and Wotorson (1969b), it was possible to project contacts and faults through areas which are covered by unconsolidated sediments or which were not traversed.

The Paynesville Sandstone crops out around the perimeter of a structural basin centered south of Roberts Field (now Roberts International Airport), and dips generally toward the center of the basin. Average structural dips of the sandstone are of the order of 5° to 15° and locally are as steep as 25°, but dips of more than 40° are found on the north edge of the basin near Roberts Field. The Farmington River Formation constitutes the principle sedimentary fill within this basin, for which the name "Roberts basin" is proposed. A closed structural basin is not evident in the dips of the Farmington River Formation in the Roberts basin. Dips steeper than 15 degrees have not been observed, and the beds do not dip toward a center. However, the gravity data of Behrendt and Wotorson (1969 b) suggest a considerable thickness for the Farmington River Formation, and indicate that the greatest thickness is toward the north edge of the basin. This is consistent with the structural asymmetry of the underlying Paynesville Sandstone and with known faulting (see below).

The Farmington River Formation also crops out on and near the shore southeast of Little Bassa, in an area separated from the Roberts basin by an upwarp of crytalline rocks. The name "Bassa basin" is proposed to designate this second area of outcrop of the Farmington River Formation. The Paynesville Sandstone is not known in this basin except as cobbles in conglomerates of the Farmington River Formation. As in the Roberts basin, no closed structural basin is evident in the dips of the bedding.

The Farmington River Formation is bounded on the northeast side by dip-slip faults in both basins. Despite the poor exposure, stratigraphic and structural breaks provide good geologic evidence for the existence and position of the faults. Additional evidence of faulting is seen in the gravity data of Behrendt and Wotorson (1969 b); the faults shown on the geologic map (pl. 1) have been drawn so as to be consistent with both geologic and gravity data. Other minor faults, as yet unrecognized, no doubt cut the sedimentary rocks elsewhere in the Monrovia-Buchanan area. However, the gravity data of Behrendt and Wotorson suggest that the faults which have already been recognized are those which have the greatest displacement.

These faults trend northwest, parallel to the strike of the foliation of adjacent crystalline rocks. Elsewhere in Liberia it has been observed that faulting in crystalline rocks tends to be parallel to the foliation. Consequently, it seems likely that since the foliation of the adjacent crystalline rocks dips consistently southwest, the faults cutting the crystalline rocks and the overlying sedimentary rocks do also. In other words, the faults are normal or gravity faults downthrown on the seaward (basin) side.

The faults bounding the northeast edges of the Farmington River Formation in the two basins are more or less in alignment. Interpretation of airborne magnetometer data (Behrendt and Wotorson, 1969 a) suggests that this same alignment continues offshore to the southeast and bounds the northeast edge of an offshore basin which may contain as much as 5 kilometers of sediments. It is of interest to note that the single known outlier of Paynesville Sandstone, in the Mount Coffee reservoir (fig. 2), is also on this same northwest-southeast alignment; it may be preserved there due to down-faulting.

One reverse fault which is upthrown on the seaward side is known. This minor fault, well-exposed at the Liberia Refining Company (fig. 2), cuts the Paynesville Sandstone and the underlying gneiss; the fault is in the plane of the foliation of the gneiss. Interpretation of airborne magnetometer data (Behrendt and Wotorson, oral communication, 1969) suggests that other faults which are upthrown on the seaward side may be present offshore.

The precise age of the faulting is not known, but the character and thickness of the Farmington River Formation suggest that fault movements accompanied its deposition and were responsible for the basin in which it was deposited. By analogy, the offshore basin mentioned above probably is filled with sedimentary rocks equivalent to or younger than the Farmington River Formation rather than with older rocks such as the Paynesville Sandstone. The Paynesville Sandstone dips generally seaward in the Monrovia area, but if it is of Paleozoic age it probably predates the existing continental margin, hence there is no reason to suspect that it thickens to seaward.

PETROLEUM POTENTIAL

In West Africa petroleum currently is being produced from marine sedimentary rocks in coastal basins of Cretaceous age in Dahomey and of Cretaceous and Tertiary age in Nigeria. (Littlefield, 1968). Sierra Leone and Ivory Coast, bordering Liberia on either side, have no production of petroleum either on shore or off shore. A seismic survey across the continental shelf of Sierra Leone has been interpreted (Sheridan et al, 1969) as showing a thickness of more than two kilometers of Cretaceous rocks on the continental shelf. In Ivory Coast, oil seeps exist on shore, oil and gas shows have been found in test wells, and a fairly complete marine sequence from Albian to Miocene age is known through geophysical exploration and drilling, but no production of petroleum has yet been achieved (Spengler and Delteil, 1966). The present intensive activity in oil exploration along the coast of West Africa indicates that the region is regarded as potentially favorable for oil production.

The on shore petroleum potential within the Republic of Liberia appears to be small, whereas that of the adjacent continental shelf is larger though unevaluated at present. The sedimentary rocks seen in outcrop do not seem to be sufficiently porous and permeable to provide good reservoir material, unless fractured, and none of them have a proven marine origin. Because of its affinity with the lower and middle Cretaceous of Ivory Coast, in which shows of oil and gas have been found (Spengler and Delteil, 1966, p. 106), the potential of the Farmington River Formation would appear to be greater than that of the Paynesville Sandstone. The Edina Sandstone has no potential as a petroleum producer.

Interpretation of airborne magnetometer data suggests the presence of thick accumulations of sediments on parts of the continental shelf and slope adjacent to Liberia (Behrendt and Wotorson, 1969 a). For reasons presented above, these sediments are thought to be equivalent to or younger than the Farmington River Formation, or in other words of Cretaceous to Tertiary age. Pebbles of carbonaceous sandstone and of bituminous shale, of probable Albian age, that have been transported to the beaches from offshore outcrops lend support to this interpretation. Hence the potential for petroleum deposits beneath the continental shelf of Liberia seems real. Additional geophysical exploration and drilling will be required to evaluate this potential.

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