Progressive Metamorphism of Iron-Formation and Associated Rocks in the Wologizi Range, Liberia

GEOLOGICAL SURVEY BULLETIN 1302

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PROGRESSIVE METAMORPHISM OF IRON-FORMATION AND ASSOCIATED ROCKS IN THE WOLOGIZI RANGE, LIBERIA

By Richard W. White

ABSTRACT

The Wologizi group comprises a sequence of metamorphosed sedimentary rocks. In the lower part of the group these are pelitic and psammitic schists and subordinate mafic volcanic rocks and silicate iron-formations; in the upper part oxide and silicate iron-formation predominate. The group overlies and is folded into an older basement of granitic gneisses, and it forms an elongate synclinorium surrounded by the gneisses.

The upper part of the group has been weakly metamorphosed and corresponds to the biotite zone. The metamorphic grade increases progressively toward the gneissic rocks which surround the group, and concentric garnet, staurolite, and sillimanite zones occur in pelitic and ferruginous rocks. Metamorphism of the Wologizi group and the granitic gneisses coincided with incipient anatexis of the gneisses, which generated at least one small body of synkinematic alkalic granite in the area adjacent to the sillimanite zone of the Wologizi group. Minor muscovite pegmatites cut the group in the sillimanite zone.

In the iron-formations a lower silicate facies grades upward into a more abundant oxide facies, and downward and laterally into pelitic rock. Magnetite, quartz, and iron-silicate minerals are present in both facies of iron-formation at all observed metamorphic grades. The two facies are distinguished by different proportions of these minerals, as well as by the more common presence of accessory pyrite in the silicate facies. Chemical differences between the two facies reflect these mineralogical differences. Carbonate is sparse in the iron-formations, and primary or metamorphic hematite is lacking. Sedimentary lamination is preserved throughout.

Chlorite and very minor amounts of biotite are the only silicate minerals found in iron-formations in the biotite zone. Chlorite persists with grunerite and garnet in small amounts throughout the garnet zone and is abundant in quartz-poor chlorite-garnet laminae in that zone. Grunerite and garnet appear at about the same level at the garnet isograd, but garnet is sparse or lacking in the oxide facies at any grade. Textural evidence shows that grunerite forms by reaction of either chlorite or carbonate with quartz. The paucity of carbonate minerals throughout the iron-formations, and the other members of the Wologizi group as well, suggests that most iron-silicate minerals in the iron-formations have formed from an iron-silicate precursor, rather than by metamorphic reaction between iron carbonate and quartz.

Chlorite in the iron-formations disappears at or before the staurolite isograd, and blue-green hornblende forms at about the same level. Ferrosalite is found in a silicate iron-formation from the sillimanite zone, but hypersthene is not known within the area of the Wologizi Range. The grain size of the iron-formation increases progressively with metamorphic grade.

Staurolite coexists with andalusite, or with sillimanite, or with both minerals in high-grade pelitic rocks. Overlap of the stability fields of staurolite and sillimanite is an indication of the relative pressure-temperature gradient under which metamorphism took place. This overlap, in conjunction with the presence of garnet, rather than cordierite, and the presence of minor amounts of chloritoid in low-grade rocks, shows that the metamorphism took place under an intermediate pressure-temperature gradient close to that of the classical Barrovian-type facies series. The temperature level at which muscovite breaks down was not reached within the Wologizi group.

The Wologizi group has been subjected to prolonged lateritic weathering that has affected the economic potential of the iron-formations. Calculations based on surface mapping show an inferred 37 billion tons of unenriched magnetite iron-formation to a depth of 500 meters or less, of which about 3 billion tons, to a depth of 50 meters, may be weathered and more readily milled. However, the iron content of the primary iron-formation is only 33 percent, and more than 70 percent of this potential low-grade ore is within the biotite zone, where the grain size of the magnetite is exceedingly fine (estimated median 0.02 mm). Areas wherein the grain size is likely to be coarsest can be predicted from the measured grain sizes in the various metamorphic zones and the position of the metamorphic isograds.

Several small bodies of hard surficial hematite ore have been developed from the primary iron-formations by lateritic weathering. These include cappings on iron-formation on high ridges and spurs, broader sheets of canga on bedrock and colluvium of iron-formation on lower spurs and slopes, and a crust on the Tertiary(?) conglomerate of iron-formation detritus which forms a piedmont alluvial plain west of the range. The observed thickness of the hard high-grade ores does not exceed 9 meters, and it commonly is less than 5 meters; the crust on the conglomerate averages less than 2 meters in thickness. The ore potential of the mapped sheets of hard ore, excluding the conglomerate, aggregates 18 million tons per meter of depth, of which half is in the three largest bodies. The grade is 54 to 61 percent iron, with high alumina (3.1 to 10.4 percent), phosphorus (0.16 to 0.24 percent), and combined water (4.3 to 7.2 percent). The hard ores derived from conglomerate and from silicate iron-formation have lower iron and higher aluminum contents.

INTRODUCTION

Examination of the Wologizi Range was begun as part of a larger project of systematic reconnaissance geologic mapping of western Liberia. Eight weeks of fieldwork were done in the range and environs during the dry season of early 1967. (Precipitation in the area of the Wologizi Range falls mostly during the rainy season of June to October; the total probably exceeds 250 cm (centimeters) per year (Stanley Engineering Co., written commun., 1960).) Mapping was done in more detail than would be done routinely because exposures in the area, though not good, are better than those elsewhere in western Liberia and because iron deposits in the range are of possible economic importance. Greater emphasis was put on geologic mapping than on evaluation of the iron deposits; the evaluation is not considered complete in this work. This paper is concerned mainly with the general geology and metamorphic petrology of the iron-formation and its associated rocks and with the effect of the metamorphism and of weathering on the economic potential of the iron deposits.

The Wologizi Range is in northern Liberia, about 200 km (kilometers) from the coast (fig. 1). All-weather laterite roads pass within 25 km of the range, and well-maintained foot trails connect all towns in the area. Subsequent to the fieldwork, an access road, passable in dry weather by four-wheel-drive vehicle, and an airstrip were constructed on the west side of the range. The area surrounding the range is sparsely inhabited by tribal

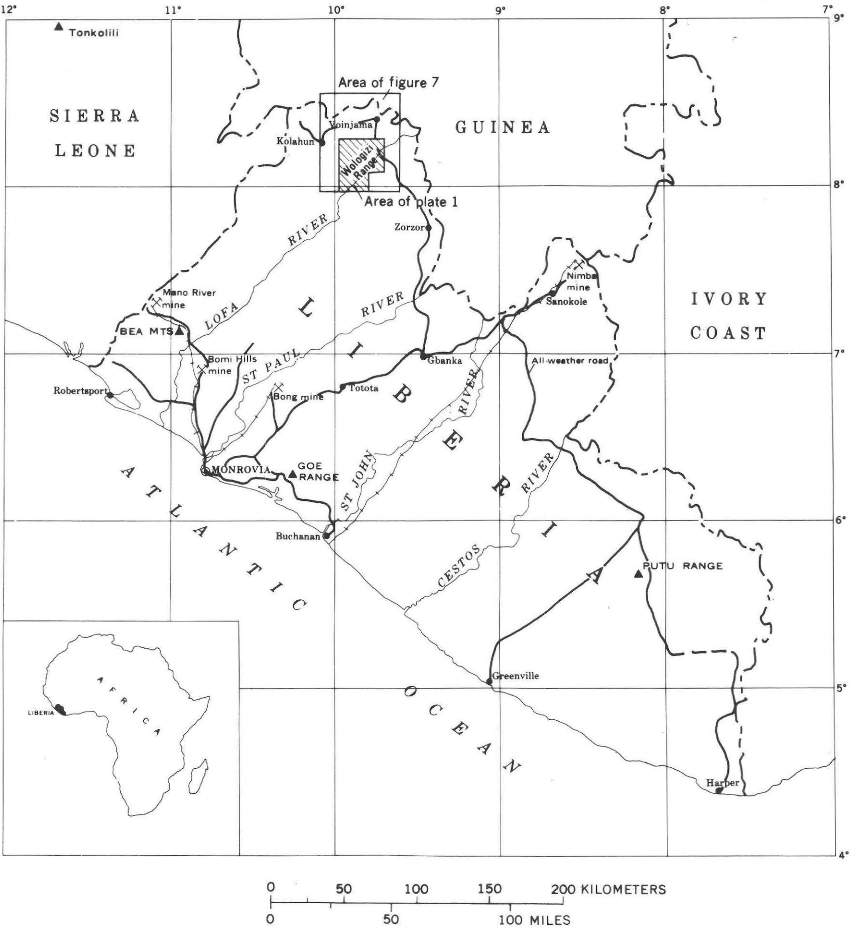

FIGURE 1. — Index map of Liberia, showing area of plate 1 and figure 7.

Liberians, who practice shifting cultivation in the vicinity of the towns and trails. Large areas to the east, south, and west of the range are uninhabited and are under second-growth or primary forest; the mountainous area is mostly under primary tropical rain forest.

The Wologizi Range is near the north edge of the tropical rain-forest belt of West Africa. At lower elevations in the range, the primary forest consists predominantly of tall trees with a relatively open understory. Access on foot is relatively easy, although visibility is limited to a maximum of about 30 m (meters). At higher elevations, the trees are shorter, and the underbrush is correspondingly more dense; the steep upper slopes can be traversed, if at all, only after considerable cutting of brush. Elephant trails along the spurs and ridge crests offer the only practical access to the higher areas.

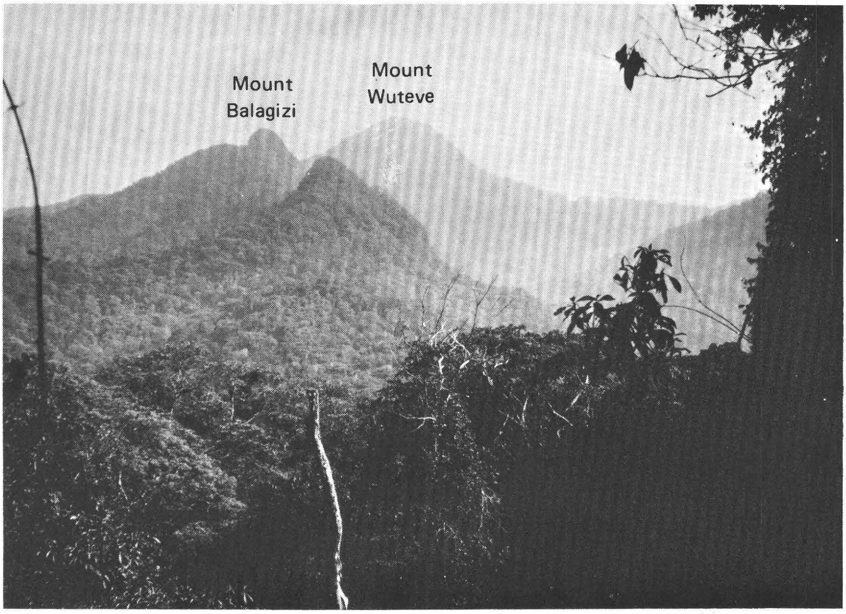

FIGURE 2. — The rugged topography of the Wologizi Range, as viewed northward along the crest from the vicinity of station 143A. Note the steep slopes and dense forest cover.

The mountain range is rugged, with about 800 m of relief (fig. 2). Valleys, spurs, and ridges are steep-sided, and waterfalls are plentiful. The range has recognizable topographic limits and is bounded by rolling mature topography on which relief generally is less than 150 m. Mount Wuteve has an elevation of 1,442 m and is the highest summit in Liberia.

When this study was made, few well-maintained trails existed within the area of the mountain range, and no good base map was available. Mapping was done by pace-and-compass traverses along streams, ridges, spurs, and existing trails, the data being plotted on a preliminary form-line base map made from aerial photographs at 1:40,000 scale. Because of the strong effect of the iron-formation on the magnetic compass, the most satisfactory method was to pace along topographic features, such as streams or ridges, that are recognizable on aerial photographs and on the form-line base. In the relatively flat areas around the base of the range, where the tall forest obscures the topography, aerial photographs were of little use, and mapping was entirely by pace and compass. Subsequent to the fieldwork, a better form-line base map, prepared by J. T. Heare of the U.S. Geological Survey, became available, and the traverse routes have been adjusted to fit that base.

Unweathered rock was found intermittently on most stream traverses; less information was gained on ridges, spurs, and trails, where the rock is

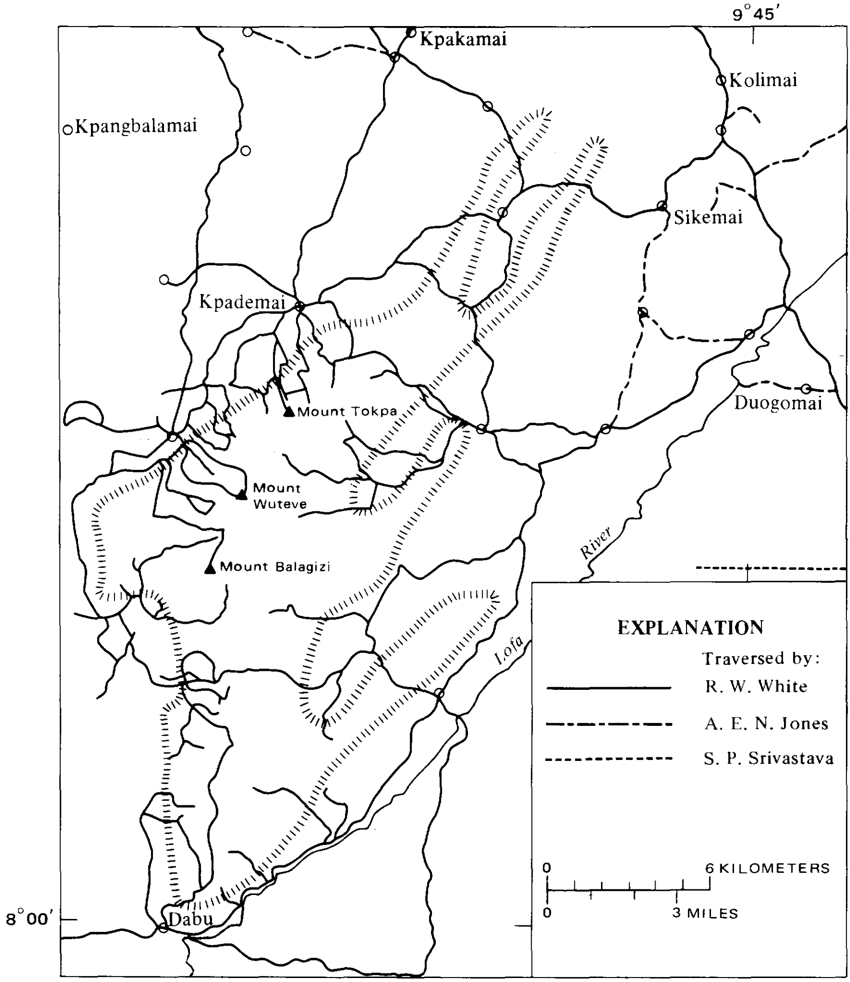

FIGURE 3. — Map showing routes of geologic traverses within the area of plate 1.

deeply weathered and covered with soil or lateritic iron ore. Waterfalls make most stream courses impassable below the ridge crest; therefore, steep slopes immediately below the crest of the main ridge were examined only on spurs, where exposures are poor, and must be considered as inadequately mapped. Observations throughout the area are based on study of available outcrop or float, as neither excavation nor drilling was done in the course of this work.

Traverse routes are shown in figure 3. The traverses were most closely spaced in areas of high relief, where exposures are best, such as north and west of Mount Wuteve. Where streams are more widely spaced and less deeply incised, as on much of the east side of the range, exposures are poor.

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More closely spaced traverses there would necessarily be in areas of increasingly poorer exposures and, so, would contribute little more detail to the geologic map (pl. 1).

PREVIOUS WORK

The iron deposits of the Wologizi Range have been the subject of several previous geologic investigations, most of which apparently were short examinations seeking high-grade iron ore, and little geologic literature resulted therefrom. The report by Newhouse, Thayer, and Butler (1945) is the only one readily available. The following tabulation lists known previous investigations:

Year	*Organization*	*Investigators*
1935	Holland Syndicate	P. F. de Groot, H. Terpstra, N. van Doorninck.
1944	U.S. Geological Survey	W. H. Newhouse, T. P. Thayer, A. P. Butler, A. Sherman.
1949	Liberian Bureau of Mines	G. K. Massaquoi.
1956	Liberia Mining Co	J. L. Patrick.
1959–60	Gewerkschaft Exploration	R. Thienhaus, H. Grüss.
1966	Armco Steel Corp	L. C. Armstrong, D. J. Enochs.
1966	U.S. Steel Corp	C. D. Reynolds, D. J. Enochs.

In May 1967, following the present study but resulting from the work by L. C. Armstrong, an exploration and exploitation concession on the Wologizi Range was granted to the Liberian Iron Ore and Steel Co. Exploration began in November 1967 and was continuing at this writing (1970).

An airborne magnetometer and radiometric survey of Liberia was flown for the Liberian Geological Survey in 1968. The geophysical data over northernmost Liberia, including the Wologizi Range, have been published (Behrendt and Wotorson, 1973a, b).

ACKNOWLEDGMENTS

This study was a part of a larger program of reconnaissance mapping and mineral exploration sponsored by the Government of Liberia and the U.S. Agency for International Development and conducted jointly by the Liberian Geological Survey and the U.S. Geological Survey.

I was accompanied during the course of this work by geologic aide George K. Massaquoi of the Liberian Geological Survey. His knowledge of the Wologizi Range and environs, which he gained through participation in four previous investigations, was extremely helpful. His assistance is gratefully acknowledged. I also appreciate assistance from the following persons: E. H. Brown, who ran some of the X-ray determinations; J. T. Heare, who prepared the form-line base map; A. E. N. Jones, who mapped the adjoining area to north and east; G. W. Leo, who did the initial petrographic study of specimens from the Wologizi Range; R. N. Spencer, who provided guidance about possible beneficiation of the low-grade iron ores; S. P. Srivastava, who examined all the heavy-mineral samples collected in this study; W. E. Stewart, who mapped the adjoining area to the west; and the chiefs of the various towns in the area of the Wologizi Range, who assisted in obtaining guides and laborers, accommodations, and food.

STRATIGRAPHY AND METAMORPHISM OF THE WOLOGIZI GROUP

The Wologizi Range is underlain by a tightly folded sequence of metamorphosed Precambrian sedimentary and volcanic rocks that is herein referred to as the Wologizi group. The group consists of metamorphosed shale, sandstone, graywacke, conglomerate, chert, oxide- and silicate-facies iron-formation, and mafic volcanic rocks. Although certain amphibolites are rather calcareous and may represent metamorphosed marls, no carbonate-rich rocks are known in the group, and accessory carbonate minerals are sparse. The group overlies and is folded into an older basement of granitic gneiss.

The stratigraphic succession in the Wologizi group is not well known. Rapid lateral and vertical facies changes, isoclinal folding, and gaps in the exposure make reconstruction of the succession difficult from surface mapping alone. Nevertheless, one can reconstruct the approximate succession in some areas on the basis of cumulative observations from several parallel traverses. The successions in two such areas on the better exposed west side of the range are listed in table 1. (See also pl. 1.)

TABLE 1. — *Stratigraphic succession on the west side of the Wologizi Range*

Northwest of Mount Wuteve		West of Maaso–Babo divide	
Unit	Approximate thickness (meters)	Unit	Approximate thickness (meters)
Canga and lateritic ironstone	2–20(?)	Canga and lateritic ironstone	2–20(?)
Itabirite	500 (+)	Itabirite	500 (+)
Silicate iron-formation with interbedded quartzite and pelitic phyllite	600	Pelitic phyllite (discontinuous)	0–150
Quartz-muscovite schist	50–250	Quartz-muscovite schist	700
Amphibole schist and amphibolite	200	Grunerite iron-formation	150
Quartz-muscovite schist	5		
Granitic gneiss	—	Granitic gneiss	—

Wologizi group

Intruded by ultramafic bodies

Except for the canga and ironstone, thicknesses reported in table 1 were estimated from mapped outcrop width and dip. Deformation probably has modified original stratigraphic thicknesses of most units, and no doubt the present outcrop width of the itabirite reflects repetition caused by folding. The figure cited for thickness of the itabirite is a minimum based on inferred geologic structure sections (pl. 1).

The east side of the range differs stratigraphically from the west, owing to facies changes. For example, amphibolites in the southern part of the range and quartz-biotite-garnet schists are more abundant on the east side than on the west, and quartz-muscovite schists are proportionally less abundant.

The upper part of the Wologizi group has been only weakly metamorphosed and corresponds to the biotite (or chlorite) zone. The metamorphic grade increases progressively toward the gneissic rocks which underlie the group, and concentric garnet, staurolite, and sillimanite zones of metamorphism surround the biotite zone. Metamorphic isograds indicating the initial appearance of each of three index minerals are used to delimit four zones on the geologic map (pl. 1). The isograds are approximately parallel to lithologic boundaries in the Wologizi group; thus, the biotite and garnet zones have been defined chiefly in ferruginous rocks, whereas the staurolite and sillimanite zones contain more abundant pelitic, psammitic, and mafic rocks. Small amounts of pelitic rock in the biotite zone and somewhat larger amounts in the garnet zone, as well as silicate iron-formations in the staurolite and sillimanite zones, contain mineral assemblages which confirm that the mapped metamorphic zones are analogous to those mapped wholly in pelitic rocks elsewhere.

IRON-FORMATIONS

The iron-formations in the Wologizi group consist of the metamorphosed equivalents of both the oxide and silicate sedimentary facies, as well as all gradations between them. Quartz and magnetite are present throughout both facies. The oxide facies also contains an iron-silicate mineral as an accessory, and the iron silicates grunerite, garnet, and chlorite are dominant minerals in the metamorphosed silicate facies. Although earthy hematite or martite is the predominant iron oxide in weathered iron-formation, primary or metamorphic hematite has not been found, and there is no evidence of oxidation or reduction of iron with progressive metamorphism. Small amounts of pyrite and lesser amounts of carbonate mineral are found locally, but no outcrops of the sulfide or carbonate facies of iron-formation are known.

The metamorphosed oxide facies corresponds closely to itabirite, as defined by Dorr and Barbosa (1963, p. 18), and the term "itabirite" is used throughout this paper as a synonym for oxide-facies iron-formation. Itabirite in the Wologizi group is a thin-bedded rock made up of alternating quartz-rich, magnetite-rich, or quartz-magnetite (-iron silicate) laminae (fig. 4). (See also Newhouse and others (1945, p. 96) for a description of the

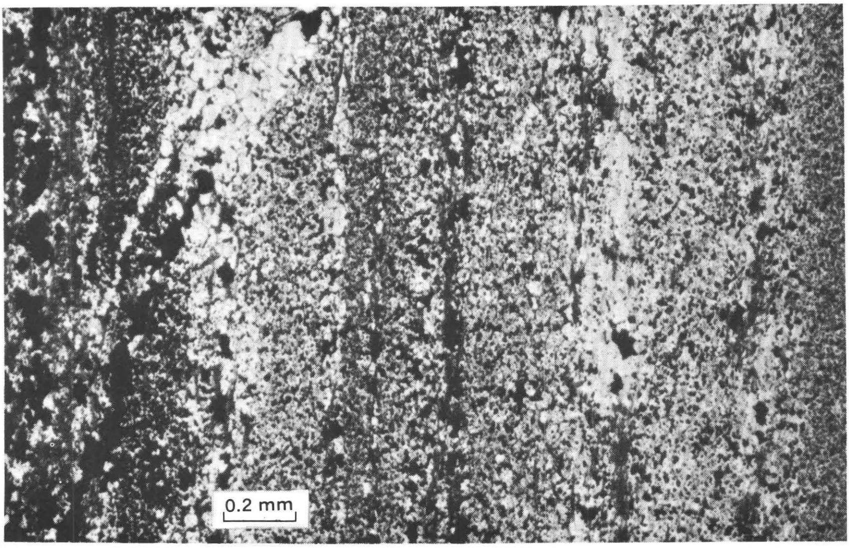

FIGURE 4. — Photomicrograph of grunerite-bearing itabirite, sample 144D. Magnetite is black, quartz is white, and fine-grained grunerite-quartz (-chlorite) aggregates are gray. Note the crosscutting quartz-magnetite veinlet. (See table 2, No. 4.)

iron-formation.) The laminae may be sharply bounded or may have boundaries marked by gradation in proportions or in grain size of quartz and magnetite. Laminae of uniform mode generally are 0.1 to 1 mm (millimeter) thick but may be as thin as 0.03 mm or as thick as 10 mm. The quartz-rich laminae are thicker than the magnetite-rich laminae, and the volume of quartz is about twice that of the magnetite. Some thin beds contain more magnetite than quartz, and a hand specimen from such a bed would not be representative of the typical iron-formation. Likewise, some beds are richer in quartz than the average, but these are readily recognized in sampling by their lighter color and weaker magnetism.

The quartz in itabirite is finely crystalline and granoblastic and represents recrystallized chert. It varies in grain size from one lamina to another, with the coarsest quartz generally found in the quartz-rich laminae. The grain size of the quartz increases with metamorphic grade and is 0.1 to 1 mm in the sillimanite zone. Most of the itabirite is found within the biotite and garnet zones, where the typical range in grain size of quartz is 0.01 to 0.05 mm. These ranges of grain size are similar to those reported by James (1955, p. 1462) for progressively metamorphosed oxide-facies iron-formation at comparable grades in a comparable metamorphic facies series.

The magnetite forms octahedra or equant anhedral grains with a wide range of grain sizes. The total observed range is 0.002 to 0.2 mm in the biotite zone and 0.01 to 1 mm in areas of higher metamorphic grade. Median values of the grain size are approximately 0.02 and 0.05 mm, respectively.

Accessory chlorite or grunerite occurs in both the quartz-rich and the magnetite-rich laminae in itabirite or may be concentrated in one or the other. Only one of 35 specimens of iron-formation examined in thin section did not contain an iron-silicate mineral, but the outcrop from which that specimen was collected contains thin silicate-rich beds. Plates of chlorite and prisms of grunerite are generally alined parallel to the sedimentary laminae. Some rocks show a set of uniformly spaced fractures or slip planes oriented at a low angle to the sedimentary laminae; these may be filled with thin veinlets of quartz and magnetite (fig. 4), but the silicate minerals are not oriented parallel to these structures.

Itabirite grades through silicate-rich itabirite into silicate iron-formation. Intermediate rocks contain laminae rich in quartz, magnetite, or iron silicate, as well as mixtures of two or all three phases. Silicate iron-formations display considerable variety depending upon the silicate mineralogy, the proportions of quartz or magnetite, and the metamorphic grade. Calculations of approximate volume from mapped outcrop area (pl. 1) indicate that the ratio of itabirite to silicate iron-formation in the Wologizi group is about 7:3.

Accessory pyrite is considerably more common in silicate iron-formations in the Wologizi group than in itabirites. A few silicate iron-formations contain as much as 5 percent pyrite and may represent a transition toward the sulfide facies of iron-formation. Pyrite is most common in an area extending along both sides of the range for about 4 km northeast from Mount Wuteve. Accessory pyrite also is common in schists and quartzites there, probably reflecting depositional conditions in that part of the basin.

BIOTITE ZONE

Itabirites and phyllites are the predominant rocks in the biotite zone; micaceous quartzite and metagraywacke (with relict clastic texture) occure in lesser amounts. Biotite is abundant in pelitic rocks, but it is present, in small amounts, in only a few iron-formations.

The phyllites include both silicate iron-formations and pelitic rocks. Phyllitic silicate iron-formation grades into itabirite, as well as into pelitic phyllite. Some phyllitic silicate iron-formations consist of even-bedded silicate-rich strata 2 to 3 cm thick alternating with quartz-rich iron-oxide-silicate-sulfide strata of similar thickness. Detrital quartz grains are preserved in the silicate-rich strata; such rocks may be cyclic clastic-chemical sediments.

Typical mineral assemblages in ferruginous and pelitic rocks in the biotite zone include the following (constituent minerals shown in estimated order of decreasing abundance, accessory minerals in parentheses):

Itabirite	Quartz-magnetite (-chlorite).
Silicate iron-formation	Chlorite-quartz-magnetite.
Pelitic phyllite	Biotite-quartz-oligoclase-chlorite.
Do	Chlorite-muscovite-biotite-quartz.

Stilpnomelane has not been found in the Wologizi Group. A yellow-brown sheet silicate previously was identified as stilpnomelane (White and Leo, 1969, p. 8), but further work disclosed that it is found only in the weathered parts of chlorite-bearing rocks and that it probably is an oxidized chlorite of the type described by Chatterjee (1966).

A small area of chlorite-zone metamorphism may exist within the biotite zone. As judged by the grain size of quartz-rich laminae in itabirite, the lowest metamorphic grade in the Wologizi Range was attained within an area of a few square kilometers, immediately southwest of Mount Wuteve. The mineral assemblage in iron-formation there is quartz-magnetite-chlorite, and biotite is lacking. The lack of biotite may be due to rock composition rather than to metamorphic grade; therefore, the existence of a biotite isograd surrounding that area is uncertain.

GARNET ZONE

Itabirites and phyllites are the predominant rocks in the garnet zone, as in the biotite zone. Many ferruginous and pelitic phyllites in this zone contain garnet, generally in the form of small euhedral porphyroblasts that are evident in megascopic examination (fig. 5). Garnet is sparse or absent in quartz-rich silicate iron-formations and in itabirite; grunerite is the predominant iron silicate in such rocks. Sparse chlorite persists with grunerite or with grunerite plus garnet, especially near the garnet isograd, whereas chlorite-garnet assemblages (without grunerite and with very little quartz) are found throughout the garnet zone.

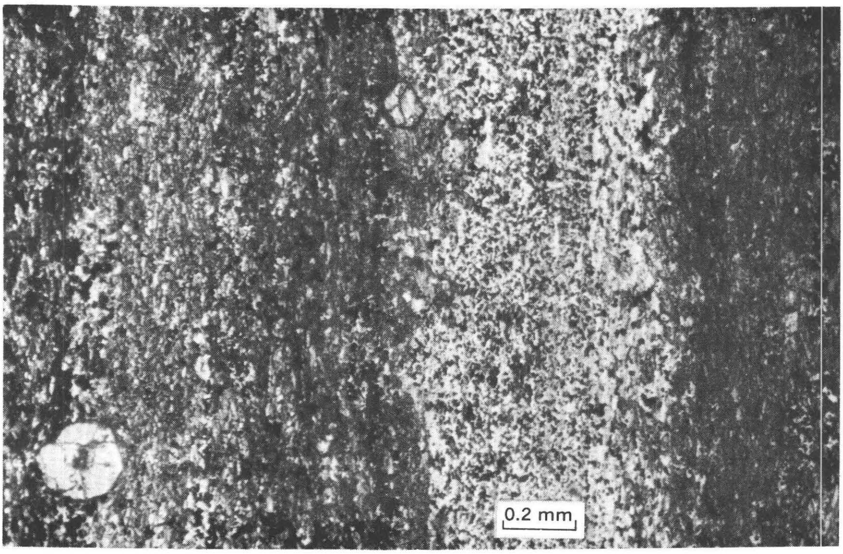

FIGURE 5. — Photomicrograph of phyllitic grunerite iron-formation, sample 235C. Magnetite is black, quartz is white, grunerite is gray, and garnet forms euhedral porphyroblasts. (See table 2, No. 7.)

Typical mineral assemblages in iron-formations in the garnet zone include (minerals in order of decreasing abundance):

Quartz-magnetite-grunerite (-chlorite).
Chlorite-garnet (-quartz-magnetite or pyrite).
Grunerite-garnet (-magnetite-quartz-chlorite).

Some impure metacherts from the garnet zone are finely laminated, with adjacent laminae differing markedly in bulk composition. These laminated rocks are useful in that they show, unequivocally, the mineral assemblages in different rock compositions at a given metamorphic grade. One of the more interesting examples contains the following assemblages in adjacent laminae within a thin section:

Quartz-biotite-garnet-muscovite (-chloritoid-opaque mineral).
Quartz-garnet (-opaque-amphibole).
Grunerite-garnet-quartz (-opaque).
Chlorite-garnet (-quartz-opaque).
Quartz-garnet (-opaque-amphibole).
Grunerite-garnet-quartz (-opaque).
Quartz (-grunerite).
Grunerite-garnet-quartz (-opaque).
Quartz-grunerite (-garnet-opaque).

The garnet isograd is not considered to be accurately mapped in the Wologizi Range. The isograd was drawn on the basis of presence or absence of garnet in ferruginous and pelitic phyllites. However, it is parallel to the lithologic boundaries, and the direction of increasing grade is also the direction of increasing proportion of pelitic interbeds and of decreasing proportion of quartz in iron-formations. In view of this compositional gradation toward rocks more favorable for garnet, the possibility cannot be excluded that the mapped position of the garnet isograd is controlled by rock composition as well as by metamorphic grade.[1] Any adjustment in the position of the isograd would increase the width of the garnet zone at the expense of the biotite zone. Systematic decrease in grain size of the itabirites within the biotite zone shows a gradation toward a low-grade node within that zone (p. 11); so, the biotite zone cannot be reduced to zero in favor of the garnet zone.

FORMATION OF GRUNERITE

The available data suggest that grunerite appears at a slightly lower grade than garnet. James (1955, p. 1477) reported a similar level of appearance of grunerite in metamorphosed iron-formations (in a comparable facies series) in northern Michigan. Consequently, the first appearance of grunerite in progressive metamorphism is at a lower grade than that of cummingtonite (Winkler, 1967, p. 119), with which it, nevertheless, forms a solid-solution

[1] The manganese content of the garnet is not known, but there is little reason to suspect that the garnet is particularly rich in the spessartine component. Indeed, the few lateritic concentrations of manganese oxide found in the Wologizi Range are from the biotite zone, which suggests that the absence of garnet there is not due to a deficiency in manganese. However, in view of the fact that the analyzed rocks show variable amounts of manganese (table 2), and that the rocks richest in manganese also carry garnet, some compositional control by manganese also is conceivable.

series. The dependence of the cummingtonite-grunerite series on rock composition thereby reduces its value as an indicator of metamorphic grade.

Iron-formations in the Wologizi group are notable for their low carbonate contents. Carbonate minerals were detected optically in only two of 35 specimens, and CO_2 is uniformly low in the analyzed specimens (table 2). The paucity of carbonate in both low- and high-grade rocks suggests that formation of grunerite by reaction between iron carbonate and quartz was not significant in the Wologizi group; this reaction is inferred to have been important in the metamorphism of iron-formation elsewhere (James, 1955, p. 1474).

One of the two carbonate-bearing specimens was collected very close to the grunerite isograd and preserves textural evidence of the mode of formation of grunerite (fig. 6). In one part of the section (fig. 6*B*), patches of fine-grained chlorite enclosed predominantly in quartz are wholly rimmed by grunerite prisms projecting into the quartz. Obviously, the grunerite has formed by reaction between chlorite and quartz. A large grain of iron carbonate in the same sedimentary lamina and a second large grain in an adjacent lamina show no sign of reaction with quartz. In another part of the same section where chlorite is absent (fig. 6*C*, in a lamina 2 mm from field shown in fig. 6*B*), iron carbonate (confirmed by immersion) enclosed in quartz is rimmed by radiating grunerite prisms in the same manner as the chlorite just described.

These textures indicate that grunerite can form by reaction of quartz with either chlorite or iron carbonate during prograde metamorphism of iron-formation. Temperature or CO_2-pressure gradients are unlikely across a distance of 2 mm during metamorphism; therefore, local variations in the composition of the iron carbonate must have governed the first formation of grunerite in this specimen. In view of the widespread occurrence of chlorite and the more restricted occurrence of iron carbonate in the lower grade rocks and the demonstrated ability of grunerite to form from chlorite and quartz, much of the grunerite (and the other iron-silicate minerals, as well) in the higher grade rocks of the Wologizi group must have formed from previous iron-silicate mineral (that is, chlorite or its precursor), rather than from iron carbonate and quartz. As recognized by J. W. Berge (written commun., 1970), carbonate-bearing iron-formation is more susceptible to lateritic weathering than is carbonate-free iron-formation; carbonate minerals may, therefore, be more abundant in the Wologizi group than the study of outcrops would indicate. If so, a greater proportion of the grunerite may have formed from iron carbonate and quartz than the available evidence would indicate.

STAUROLITE AND SILLIMANITE ZONES

Silicate iron-formations are found in the staurolite and sillimanite zones, but itabirite is uncommon. The silicate iron-formations are coarser and more schistose than in the lower grade zones. Sedimentary laminae are

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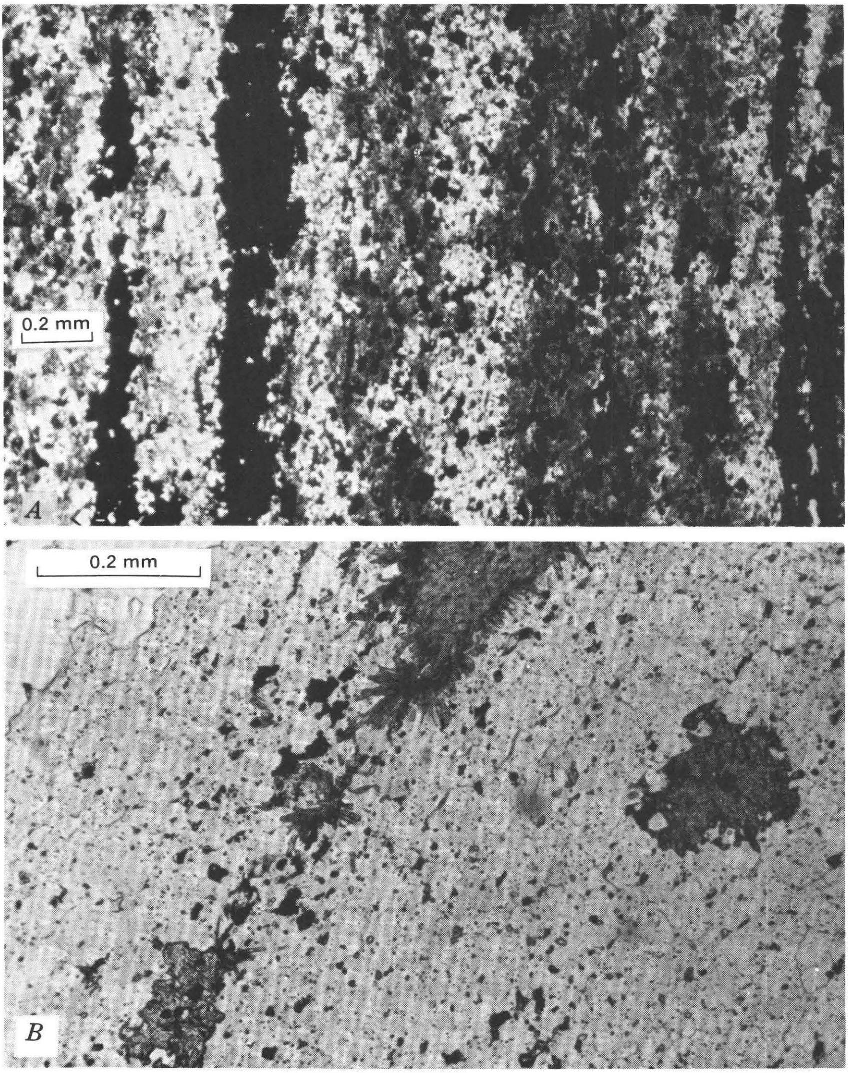

preserved, but the average thickness of the laminae is greater than that in the lower grade zones, implying that the finer laminae were destroyed by metamorphic recrystallization.

Grunerite, garnet, and sparse hornblende are the characteristic silicate minerals in silicate iron-formation metamorphosed in the staurolite and sillimanite zones. Optical measurements indicate that the grunerite generally contains 75 percent or more of the iron amphibole end member. Trace amounts of biotite (one to five small crystals per thin section) occur locally in both zones, and ferrosalite (with quartz-grunerite-magnetite-hornblende) was identified in one specimen from the sillimanite zone.

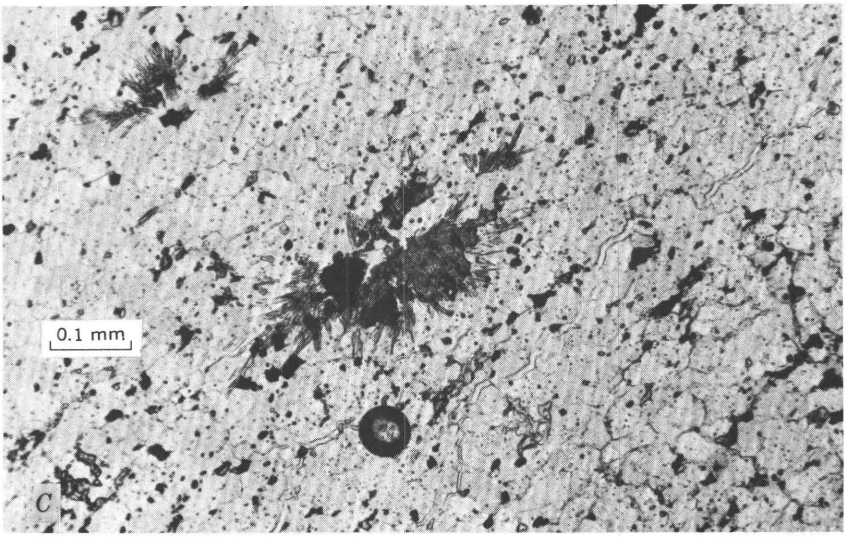

FIGURE 6. — Photomicrographs of grunerite-bearing itabirite, sample 84F. (See table 2, No. 3.) *A*, Laminated itabirite with grunerite-bearing (gray) and magnetite-bearing (black) laminae. *B*, Quartz-rich lamina adjacent to field of *A*, showing patches of chlorite rimmed by radiating prisms of grunerite. Nearby grains of iron carbonate show no grunerite rim. Black grains are magnetite. *C*, Quartz-rich lamina 2 mm from field of *B*, showing iron-carbonate grains rimmed by radiating prisms of grunerite. Black grains are magnetite.

Typical mineral assemblages are:

Quartz-grunerite-magnetite-hornblende.
Grunerite-quartz-garnet-magnetite.
Grunerite-garnet (-magnetite-quartz).

These rocks differ from those of similar composition in the garnet zone by the absence of chlorite, the greater abundance of hornblende, and the coarser grain size.

Hornblende (or actinolite) occurs in the silicate iron-formation of the garnet zone as sharply bounded rims on grunerite crystals, but it forms discrete crystals in such rocks only in the staurolite and sillimanite zones. Yet, James (1955, p. 1477) reported similar amphibole, in part retrograde, as very common in the garnet zone of northern Michigan. In the staurolite and sillimanite zones, this amphibole is pleochroic in bluish green (*Z*), olive green (*Y*), and buff (*X*) and has a small to moderate negative optic axial angle, but it cannot be definitely distinguished from actinolite by optical methods alone. This amphibole is presumed to be a variety of hornblende on the basis of the composition of a rock containing 16 volume-percent of blue-green amphibole, which shows 1.5 percent Al_2O_3 and higher CaO and Na_2O than other specimens of iron-formation (table 2, No. 8). Although other analyses listed in table 2 show higher aluminum contents, each of such rocks has appreciable chlorite or garnet as an aluminum-bearing phase. Attempts to calculate the compositions of the constituent minerals from these parameters indicate that the blue-green amphibole must contain more Al_2O_3 than is generally found in actinolite.

PELITIC AND PSAMMITIC SCHISTS

BIOTITE AND GARNET ZONES

Pelitic rocks within the biotite zone have already been described (p. 10). The psammitic rocks contain similar mineral assemblages but with a predominance of detrital quartz grains. The assemblage quartz-muscovite-andalusite (-chloritoid-tourmaline) — with no textural evidence of disequilibrium — characterizes a micaceous quartzite from well within the biotite zone. The coexistence of chloritoid and andalusite (both confirmed by determination of optical parameters with universal stage) — minerals once thought of as characteristic "stress" and "antistress" minerals, respectively — is worth noting. Several examples of this association are now known. (See Winkler, 1967, p. 92.)

Plagioclase has been recognized in very few specimens from the biotite zone. In a specimen in which the plagioclase is coarse enough to be determined with the universal stage, the composition is An_{15}; and in a second, finer-grained specimen, the composition is An_{20} by both immersion and X-ray diffraction techniques.[2] The mineral assemblage in both is quartz-biotite-chlorite-oligoclase (-muscovite); the coarser specimen also contains actinolite but no epidote-group mineral. Both specimens lack garnet although the rock composition is appropriate, and they lie below the smoothly curving garnet isograd.

James (1955, p. 1477) reported that the garnet isograd in ferruginous rocks in northern Michigan appeared at the same metamorphic grade as that in pelitic rocks. No contradictory evidence was discovered in the Wologizi group. However, because the actual isograd is located mostly in ferruginous rocks displaying apparent compositional control, no confirmatory evidence can be offered, either.

Chloritoid is present in small amounts in three specimens from the garnet zone, including the impure metacherts described earlier. All three are unsheared rocks exhibiting preserved clastic textures or sedimentary laminae. Examination with the universal stage of the chloritoid in two specimens, one of them from the biotite zone, indicates that it is the triclinic rather than the monoclinic polymorph. Chloritoid and biotite are generally thought to be mutually incompatible (Turner and Verhoogen, 1960, p. 539; Winkler, 1967, p. 100), but they coexist, without textural evidence of disequilibrium, in two specimens from the garnet zone.

Chlorite, where coexisting with quartz, muscovite, or garnet, is generally acknowledged to be destroyed during prograde metamorphism when the conditions of the amphibolite facies are reached. By this criterion the

[2]All other plagioclase compositions reported herein were determined by universal-stage techniques.

metamorphic conditions of the garnet zone in the Wologizi group correspond to those of the albite-epidote-amphibolite facies.Except in ultramafic rocks, only small amounts of retrograde chlorite are found above the staurolite isograd; that isograd approximates the upper limit of the facies. Chloritoid, likewise, is limited to areas below the staurolite isograd.

Definition of the lower limit of this facies — if a lower limit does exist within the Wologizi group — is more difficult. The biotite zone might correspond to the greenschist facies, but the presence of oligoclase in some rocks therein would seem to rule out this possibility. If the greenschist facies exists it is to be found in a small area southwest of Mount Wuteve, where only iron-formations, lacking stilpnomelane, crop out.

STAUROLITE ZONE

The staurolite and sillimanite zones are characterized by a wider variety of pelitic and psammitic rocks than is found in the biotite and garnet zones, as well as by amphibolites and silicate iron-formations. Schists consisting predominantly of quartz-biotite-garnet or of quartz-muscovite are the most abundant rocks within these zones. Relict clastic texture in a quartz-biotite-garnet-staurolite schist in the staurolite zone indicates it to be a metagraywacke; probably, many other rocks of similar composition are metashales. Clastic textures more commonly are preserved in the quartz-muscovite schists in the staurolite zone, confirming that they are metasandstones and metaconglomerates. The quartz-muscovite schists grade along or across strike into muscovite-bearing quartzites that have relict clastic textures. Some even-bedded quartz-rich rocks, however, resemble metacherts.

Mineral assemblages diagnostic of the staurolite zone are found in amphibolites and silicate iron-formations, as well as in pelitic and psammitic rocks. Staurolite is uncommon along the west side of the Wologizi Range, presumably because of unfavorable rock composition. The staurolite isograd there has been mapped on the basis of mineral assemblages in amphibolites and silicate iron-formations. Small amounts of detrital staurolite found in streams draining that area confirm the existence of the zone but are of little help in locating the isograd.

Andalusite first appears in the biotite zone in the Wologizi group, but it persists to the sillimanite isograd. In the lower grade rocks it forms small, anhedral, extremely poikiloblastic grains, whereas the crystals within the staurolite zone are euhedral porphyroblasts that are less markedly poikiloblastic. The best developed crystals are pink prisms with a chiastolite cross, as much as 6 cm in length. Some typical andalusite-bearing assemblages in the staurolite zone are as follows:

Quartz-biotite-andalusite-staurolite-garnet (-muscovite-plagioclase-opaque-tourmaline).
Quartz-biotite-andalusite-garnet (-plagioclase-muscovite-clinozoisite-opaque).
Muscovite-quartz-biotite-staurolite-andalusite (-garnet-opaque-tourmaline).
Quartz-muscovite-andalusite (-rutile).

SILLIMANITE ZONE

The sillimanite zone was recognized chiefly through the presence of sillimanite in pelitic and psammitic rocks. Mineral assemblages in amphibolites and iron-formations in this zone do not differ markedly from those in the staurolite zone. The iron-formations are coarser grained than in the staurolite zone, but the difference is not established well enough to be used in locating the sillimanite isograd.

The position of the sillimanite isograd is not well established, owing to the wide spacing of diagnostic sample localities. Exposures are poor in the sillimanite zone, and many of the outcrops are weathered and do not yield specimens suitable for petrographic study. Substantiating evidence about the distribution of the sillimanite zone was gained from alluvial concentrations of heavy minerals collected from streams draining the Wologizi group. The alluvial samples, examined by S. P. Srivastava of the Liberian Geological Survey, show that sillimanite evidently is present in the Wologizi group along the entire east side of the Wologizi Range and that it is generally lacking along the west side of the range, except at the north end. On this basis, the sillimanite isograd has been extended northward to include an area in which unweathered pelitic rocks were not found.

The isolated infolds of metasedimentary rocks in the northeastern part of the mapped area (pl. 1) were not studied, owing to the paucity of outcrops of unweathered rocks. Detrital sillimanite in that area implies that the rocks are in the sillimanite zone, but detrital andalusite is known there, too. Farther north and northeast, outside the mapped area, sillimanite is well developed in infolds of schist and quartzite, and orthopyroxene occurs with grunerite-garnet (-quartz-magnetite-hornblende) in a silicate iron-formation.

The sillimanite zone cannot be recognized in the granitic gneisses, owing to lack of suitable index minerals. However, pegmatites (feldspar-quartz-muscovite) seem to be more abundant in the gneisses adjacent to the sillimanite zone of the Wologizi group than elsewhere. Sparse muscovite pegmatites that cut the Wologizi group are restricted to the sillimanite zone.

Three mineral assemblages have been recorded in the sillimanite-bearing rocks:

Quartz-muscovite-plagioclase (-sillimanite-garnet).

Quartz-biotite-garnet-andesine-sillimanite (-andalusite-staurolite-muscovite-tourmaline-opaque).

Quartz-andesine-biotite-garnet-staurolite (-sillimanite-tourmaline-opaque).

Sillimanite shows two different habits in the one specimen in which it coexists with andalusite. One consists of pods of fine fibrous sillimanite intergrown with biotite that is finer grained than the abundant biotite elsewhere in the rock, whereas the other consists of coarser euhedral prisms as oriented inclusions (optical $X_s = Y_a$, $Y_s = Z_a$, $Z_s = X_a$) in andalusite porphyroblasts. Elsewhere in the specimen, oriented groups of similar coarse sillimanite lack the surrounding andalusite. The specimen obviously preserves an incomplete polymorphic transition from andalusite to sillimanite. The fibrous sillimanite-biotite aggregates surely did not originate by inversion from andalusite, but their precursors are unknown. (Harker (1950, figs. 170B, 172B) illustrated the identical two-sillimanite-andalusite texture in hornfels, a feature he attributed to polymetamorphism. But there is no evidence for more than a single prograde metamorphic event in the Wologizi Range.) The precursors must be stable within the staurolite zone where sillimanite is lacking; this seems to rule out chlorite-potassic feldspar and chlorite-muscovite as possible precursors. The stability field of chloritoid might extend to this grade, but chloritoid is unlikely to have been present in sufficient abundance in these biotite-rich rocks to produce the existing volume of sillimanite. Staurolite is a possible precursor because it, among all the minerals in this rock, is nowhere found in contact with the fibrous sillimanite, but crystals of staurolite elsewhere in the rock display no textural evidence of disequilibrium. Furthermore, staurolite persists in a second sillimanite-bearing assemblage (listed above) that contains no vestige of andalusite; breakdown of staurolite spanning such a range of conditions as is implied by these two assemblages seems unlikely.

The staurolite and sillimanite zones are considered to reflect the metamorphic conditions of the amphibolite facies. The so-called second sillimanite isograd, at which muscovite breaks down to form sillimanite and potassic feldspar, has not been reached in the Wologizi group.

AMPHIBOLITES

Amphibolites are found at many places in the lower part of the metasedimentary sequence and above the staurolite isograd, but they are most abundant in the southeastern part of the range. Many of the amphibolites form layers, as much as several tens of meters thick, interbedded with metasedimentary rocks; a few form larger bodies. Crosscutting relations suggestive of intrusion were not observed.

A majority of the amphibolites contain minor epidote and quartz in addition to the dominant sodic plagioclase (An_{20-45}) and green hornblende; garnet generally is lacking. Apatite, biotite, pyrite, and sphene are typical accessory minerals. The amphibolite forming the lowermost layer northwest of Mount Wuteve locally is considerably more calcareous and siliceous than the average (quartz-bytownite-hornblende-epidote-biotite). In other respects, the composition of the amphibolites — as judged by the proportions of the various minerals and the composition of the plagioclase — is rather uniform.

The foliation of the amphibolites is defined by the planar orientation of hornblende prisms. Only locally does the orientation of hornblende also define a lineation plunging at various angles in the plane of the foliation. Segregation of hornblende and plagioclase into thin discontinuous laminae parallel to the foliation is developed in many amphibolites but is lacking in others. The foliation and lamination are subparallel to recognizable bedding in adjacent metasedimentary rocks, as well as to the axial planes of inferred large-scale isoclinal folds.

Structures and textures indicative of the premetamorphism state of the amphibolites generally are lacking. One layer, though, contains what appear to be relict plagioclase phenocrysts. These large subhedral crystals of labradorite (An_{54}) contain abundant blebs of secondary epidote and are zoned (to An_{40}). The large crystals are enclosed in a granoblastic hornblende-plagioclase (-quartz-sphene-apatite-pyrite) matrix in which the granoblastic plagioclase lacks epidote inclusions and is not zoned (An_{40-42}). The texture and mineralogy of this amphibolite suggest derivation from an igneous rock of basaltic composition, probably a lava flow or tuff bed rather than an intrusive body. The amphibolite in question forms a 100(?)-m-thick layer overlying and conformable with silicate iron-formation.

As mentioned above, the amphibolites have a relatively uniform composition. Because one of these has a relict igneous texture, probably the others of similar composition are metamorphosed igneous rocks, as well. Those which deviate markedly from this composition, such as the calcareous amphibolite northwest of Mount Wuteve, probably represent metamorphosed sediments.

Low-grade schists of basaltic or other igneous-rock composition have not been found in the biotite and garnet zones; apparently, then, the metaigneous rocks are restricted to the lower part of the sedimentary section. The significance of this observation is discussed on page 36.

CONDITIONS OF METAMORPHISM

Several critical minerals and mineral assemblages permit some inferences to be made regarding the relative pressure and temperature conditions that prevailed during metamorphism of the Wologizi group. Chloritoid and staurolite, which are found in the Wologizi group in rocks of appropriate composition, are typical minerals of the classical Barrovian-type metamorphic facies series. However, recent work (Winkler, 1967, p. 117–120) has shown that these minerals are stable, though uncommon, in lower pressure facies series as well. More important is the widespread occurrence of pink to red garnet rather than cordierite in pelitic rocks, which is a clear-cut factor linking the metamorphic paragenesis in the Wologizi group to Barrovian-type metamorphism. On the other hand, the presence of andalusite and sillimanite, rather than kyanite and sillimanite, is an obvious similarity between the metamorphic paragenesis in the Wologizi group and lower pressure facies series. Another similarity is the presence of oligoclase, rather than albite, in the biotite zone. Also, the paucity of garnet in the amphibolites is consistent with formation in a low-pressure facies series.

These observations indicate that the mineral paragenesis in the Wologizi group is intermediate between that of Barrovian-type metamorphism and a somewhat lower pressure facies series. Intermediate paragenesis in pelitic rocks may be distinguished by relations between the critical minerals staurolite, andalusite, kyanite, sillimanite, almandine, and cordierite. In the Wologizi group, staurolite coexists with andalusite, with sillimanite, or with both, indicating that andalusite breaks down, or sillimanite is formed, at a lower temperature than that at which staurolite breaks down. This observation, plus the presence of garnet rather than cordierite, shows that the metamorphic paragenesis in the Wologizi group formed under a pressure-temperature gradient only slightly steeper than that for Barrovian-type metamorphism. It also shows that, although andalusite and sillimanite are the prevailing aluminosilicate polymorphs, the metamorphic conditions must have been close to those of the stability field of kyanite. Kyanite has not been identified in situ, but it was found in small amounts in a few of the alluvial samples from streams draining the Wologizi group (S. P. Srivastava, written commun., 1967), apparently confirming the designation of facies series.

METAMORPHISM IN OTHER AREAS OF LIBERIA

The structural and metamorphic pattern in the Nimba Range in Liberia is similar to that in the Wologizi Range, but the metamorphic zones there have been truncated at the east by faulting and so only half of the pattern is preserved (J. W. Berge, written commun., 1971). In other respects the grades and widths of the metamorphic zones in both regions are comparable. Berge described a quartzofeldspathic gneiss from the Nimba region containing garnet, sillimanite, and cordierite, which suggests that the metamorphic facies series there may be a relatively low pressure type, as well. Metamorphic zonation consisting of low-grade zones in the cores of synclines surrounded by higher grade zones near bounding granitic rocks is characteristic of the greenstone belts of early Precambrian terranes elsewhere (Anhaeusser and others, 1969), and the metamorphic facies series in such terranes in southern Africa typically is that of relatively low pressure (Saggerson and Owen, 1969). But the high-grade zones commonly are narrower, and the low-grade zone much larger, than those in the Wologizi and Nimba Ranges. Other important differences include the predominance of sedimentary rocks over probable volcanic rocks, the evidence of a basal unconformity, and the lack of evidence of intrusion by the bounding granitic rocks in Liberia.

The metamorphism has been studied in detail in only a few other areas of Liberia. Much of the terrane has been metamorphosed to the amphibolite facies, and lower grade zones are preserved only in some of the largest of the infolded belts, such as the Wologizi and Nimba Ranges. One of the best studied areas is the Bong Range, where Stobernack (1968) described a low to intermediate-pressure facies series in which pelitic rocks are characterized by sillimanite dominant over andalusite and staurolite, and garnet dominant over cordierite. The inferred pressure conditions are slightly lower than those developed in the Wologizi group, but the

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temperature reached the level of breakdown of muscovite, and evidence of anatexis is much better developed than in the Wologizi Range.

In contrast, the mineral assemblages described by Berge (1966a) in the Goe Range near the coast of Liberia clearly place the metamorphism of that region within the Barrovian-type facies series. White and Leo (1969, p. 9; 1970, p. 97, 100) noted that other areas near the coast of Liberia are characterized by similar parageneses, whereas metapelitic rocks in interior areas of western Liberia, such as the Bong and Wologizi Ranges, show a predominance of sillimanite and a scarcity of kyanite. This observation has been corroborated by more recent mapping in the respective areas, as well as through examination of numerous detrital heavy-mineral samples by S. P. Srivastava (written commun., 1970).

The two areas of contrasting metamorphic facies series in Liberia also correspond to areas of contrasting age, lithology, and structural trend (White and Leo, 1970). The coastal area was designated as the Pan-African age province (about 550 m.y.) by Hurley, Leo, White, and Fairbairn (1971) and is much younger than the Liberian age province (about 2,700 m.y.) that occupies the interior of western and central Liberia.

Miyashiro (1961, p. 303) pointed out that metamorphism in Precambrian shield terranes is characterized more commonly by relatively low pressure type facies series than by the Barrovian-type facies series. Saggerson and Owen (1969) refined this observation for southern Africa by recognizing that relatively low pressure type facies series are best developed in ancient cratonic areas there, whereas metamorphic belts of Pan-African age are characterized by typical Barrovian-type paragenesis. The Liberian and Pan-African age provinces in Liberia also illustrate that association.

RETROGRESSIVE METAMORPHISM

The metasedimentary rocks in the Wologizi group display but little evidence of retrogressive metamorphism. The chief effects seen in the staurolite and sillimanite zones are the formation of minor amounts of secondary chlorite after garnet and biotite, and of sericite after andalusite, staurolite, and plagioclase. The effects seen in schists, amphibolites, and iron-formations are comparable, and the primary textures and mineralogy are recognizable throughout.

Low-grade metamorphism (p. 25) has affected the posttectonic diabase dikes in the area. This metamorphism did not vary in intensity corresponding to the zoning in the Wologizi group; it is therefore thought to be an unrelated, younger feature. The incipient formation of sericite and epidote in plagioclase and of chlorite in biotite is widespread in the granitic rocks throughout the area of alteration of the dikes. It may be an effect of the younger, low-grade metamorphism, rather than a retrogressive feature associated with the high-grade deformation and metamorphism of the granitic rocks. Slight evidence of this younger metamorphism is seen in the metasedimentary rocks of the Wologizi group, unless the presumed retrogressive features just described are to be attributed to it. Possibly some of the ambiguous textures seen in the ultramafic rocks are the result of the younger metamorphism, although similar textures are common in serpentinized ultramafic rocks, where no younger metamorphism has occurred.

ROCKS OLDER AND YOUNGER THAN THE WOLOGIZI GROUP

GRANITIC ROCKS

Much of northern Liberia is underlain by gneissic rocks of granitic composition, which contain scattered northeast-trending belts of infolded metasedimentary rocks; the Wologizi Range is formed on one of the largest of such infolded belts in the country. Subdivision and mapping of the granitic rocks are difficult because of limited exposures and complex lithologic variations.

Two types of granitic rock in the area of the Wologizi Range were distinguished and mapped (pl. 1), according to the presence or absence of foliation: (1) Granitic gneiss as used herein refers to a coarse-grained rock with foliation developed well enough to be recognized in hand specimen. (2) Massive granitic rock has similar composition and grain size to the granitic gneiss, but has only a weakly or locally developed foliation, and in hand specimen it appears massive. This subdivision of granitic rocks has proved workable in the area of the Wologizi Range, but elsewhere in Liberia other structural types of granitic rocks can be distinguished and mapped. (See White, 1970.)

The granitic gneiss locally contains thin biotite-rich layers, pegmatite and aplite dikes, and lenses of amphibolite or massive granitic rock, but, for the most part, it is homogeneous though foliated. However, the composition is not uniform throughout, as scattered specimens range from quartz monzonite to quartz diorite or trondhjemite. The most common composition is that of granodiorite, with oligoclase (An_{18-25}, in part antiperthite), microcline microperthite, quartz, accessory biotite, and minor muscovite and epidote.

The granitic gneisses typically are xenomorphic granular, with a weak segregation into feldspar-, biotite-, or quartz-rich laminae. The texture is that of a metamorphic rock. Widespread incipient alteration of plagioclase to sericite and epidote and partial replacement of biotite by chlorite are evidence of retrogressive metamorphism of the gneisses. Epidote is especially prevalent near the shear zone in the bed of the Lofa River.

The massive granitic rocks exhibit a compositional range similar to that of the granitic gneisses; biotite is the predominant characterizing accessory mineral. The small body of massive rock mapped (pl. 1) as the Babo granite, an exception, contains albite (An_{2-12}), rather than oligoclase, and muscovite in addition to biotite. This alkalic two-mica granite is rather distinct from the other massive granitic rocks and is probably younger.

The texture of the massive rocks, including the Babo granite, is xenomorphic to hypidiomorphic granular. These rocks are more equigranular than the gneisses and generally lack pronounced laminar or linear mineralogic segregations. Nevertheless, they seem to have undergone a plastic-state recrystallization that has obscured the primary igneous texture. The massive rocks contain textural evidence of a late, lower grade metamorphism similar to that of the gneisses, including partial alteration of plagioclase to sericite and epidote and of biotite to chlorite.

Weak foliation observed locally in the massive granitic rocks is defined by orientation of biotite and the larger feldspar crystals; it generally is more sinuous than the planar foliation of the gneisses. Locally, rounded to angular blocks of foliated amphibolite, resembling xenoliths, are enclosed in the massive granitic rocks. Small dikes of pegmatite are found in some places. The general impression gained in the field is that of synkinematic granite.

Panned concentrates from 10 weathered friable granitic rocks indicate generally similar heavy-mineral suites in both massive and gneissic rocks. Zircon and either ilmenite or magnetite predominate, followed in abundance by monazite and rutile; xenotime is found in some samples (S. P. Srivastava, written commun., 1967). Apatite, pyrite, and chalcopyrite have been noted in petrographic studies of unweathered rocks.

ULTRAMAFIC INTRUSIONS

Small bodies of ultramafic rock are common throughout the lower part of the Wologizi group, particularly on the west side and toward the south end of the range. Most are pods or lenses intruded approximately parallel to the foliation of the enclosing schists; only those few bodies that were large enough to be mapped are indicated on plate 1. The largest body, an elongate mass 1,300 by 5,000 m, is discordant and cuts at a low angle across the contact between metasedimentary rocks and the bounding granitic gneiss.

The mineralogy and texture of the primary ultramafic rock are preserved in the core of the largest body and, locally, within some of the smaller bodies. The primary rock is dunite, consisting of forsteritic olivine (Fo_{90}) with minor disseminated chromite and a trace of pyrrhotite. Bastite pseudomorphs preserved locally in some small serpentinites suggest that those bodies may have been harzburgite rather than dunite. The olivine in the dunite of the largest body forms a closely packed aggregate of alined euhedral to subhedral crystals, outlined by marginal serpentinization; the accessory chromite also tends to be euhedral. Most olivine euhedra are less than 5 mm in diameter. Locally, secondary chlorite and amphibole poikilitically enclose the euhedral olivine, in a manner that suggests that they are pseudomorphs after a poikilitic pyroxene. The texture of this rock is more suggestive of the dunites found in stratiform bodies than of alpine dunite. Yet, other features of the ultramafic bodies, including mode of occurrence, composition, lack of lithologic layering, and a lack of apparent contact metamorphism, are characteristic of alpine intrusions (Thayer, 1960, p. 248). Possibly the dunite body represents a part of a disrupted stratiform body that was emplaced by alpine-type tectonics.

Metamorphic cummingtonite, chlorite, and carbonate are found locally in the dunite, and both the primary olivine and the secondary amphibole are partially serpentinized. Serpentinization is virtually complete near the margins of the largest ultramafic body and throughout most of the smaller bodies; a talc-rich border zone is locally developed. Some of the smaller bodies consist wholly of talc-rich schist with serpentine, chlorite, or carbonate. Sparse thin veinlets of fibrous chrysotile were found in a few blocks of float near the south end of the largest ultramafic body.

Serpentinization is less well developed in the southern part of the Wologizi Range, in an area where the metamorphic grade of the enclosing schists is relatively high. One dunite body within the sillimanite zone contains secondary cummingtonite, tremolite, and chlorite and has a border zone of dark-green nematoblastic schist consisting of tremolite and cummingtonite with accessory chlorite and magnetite. Other small bodies of metaperidotite consist wholly of similar amphibole-rich schist, or have a core of amphibole-rich schist and a surrounding zone of talc-rich schist. These mineral assemblages reflect metamorphism of the primary dunite under higher grade conditions than those characteristic of serpentinization, and indicate that emplacement probably occurred prior to the peak of metamorphism of the Wologizi group.

DIABASE DIKES

East-trending vertical posttectonic dikes of tholeiitic diabase are scattered throughout the granitic terrane surrounding the Wologizi Range. Only three dikes cutting the Wologizi group were mapped in situ, but stream boulders of diabase were observed at several places within the area of metasedimentary rocks. Such boulders are especially abundant in the tributary streams draining into the north fork of Maaso Creek (near sample loc. 115L) from the north. This locality is on strike with a mapped dike east of the range.

Most of the dikes within the area (pl. 1) are less than 1 km in length and do not exceed 30 m in thickness. The long dike in the northwest corner of the mapped area, however, can be traced on aerial photographs for more than 15 km. Similar dikes as much as 20 km long, trending roughly east, are common a short distance east and northeast of the mapped area (fig. 7); most of them are less than 50 m thick.

The dike rock is typical tholeiitic diabase. Sparse phenocrysts of olivine are found in some dikes, but most rocks are more saturated and contain accessory quartz in graphic intergrowths with alkalic feldspar. Although some diabases are completely unaltered, partial uralitization of the primary augite is common. In some rocks the augite has been wholly replaced by patchy green amphibole, with little apparent effect on the texture or composition of the coexisting plagioclase (An_{60-80}); in others the primary plagioclase has been altered to epidote, sericite, and albite. Dikes of similar uralitized diabase crop out on the road between Zorzor and Voinjama, east of the Wologizi Range. South of Zorzor, crosscutting dikes that trend east consist of foliated albite-epidote-amphibolite in which the foliation is oblique to the walls of the dike. Berge (written commun., 1971) has discovered a crosscutting dike of similar character approximately on trend near the Nimba Range. In contrast, the diabase in two broad zones of northwest-trending dikes farther south in Liberia typically is unaltered, except by weathering.

CONGLOMERATE PLAIN

The western foot of the Wologizi Range is mantled by a piedmont alluvial plain of indurated conglomerate, the surface of which slopes gently toward the southwest. This feature is best developed adjacent to the highest part of the range, and it extends southwest as much as 5 km from the foot of the range. Broad stream valleys within the range, such as those of the Maaso and the Windia, are floored with conglomerate, but steep, narrow valleys, such as those of the Ziaki and the Mavava, contain only isolated relics. Three major stream valleys on the east side of the range contain similar conglomerate fans, but the volume of material on the east side is much less than on the west.

The conglomerate plain is being dissected by modern streams, and, obviously, the conglomerate was deposited under a stream regimen very different from the present one. Some streams have cut through to the underlying bedrock, exposing a maximum thickness of about 15 m of conglomerate. The thickness may be greater over buried stream valleys, especially near the steepest western front (Ziaki and Mavava Creeks), but the maximum thickness of conglomerate is probably a few tens of meters.

The conglomerate consists predominantly of well-rounded cobbles and small boulders of iron-formation and lesser amounts of schist, quartzite, and other rocks. The size of the fragments decreases away from the range, and in the southwest corner of the mapped area, the alluvium consists predominantly of coarse-grained quartz sand with hematite cement.

Prolonged lateritic weathering and enrichment of the conglomerate caused the development of a surficial hematite-rich crust, or canga. The forest on the conglomerate is neither as dense nor as tall as that developed on granitic rock or schist elsewhere in the area. Several large savannas are found on the conglomerate plain, particularly on areas of hematite enrichment, but the hematite-rich crust is not restricted to the savanna areas. The savannas may have been initiated by repeated annual burning of fields following cultivation. However, except in regions of sterile soil, such as the canga-covered areas and beach-sand deposits near the coast, such savannas do not occur elsewhere in Liberia where the climate is similar and the same cultivation practices are followed. These findings are contrary to Beyer's (1959, p. 87) suggestion that the savanna areas control where hematite-rich lateritic crust can develop. Instead, the existence of hematite-rich crust or of other sterile soil controls where savanna may develop within the rain forest.

The age of the conglomerate can only be inferred, no fossils having been found. The form, position, and character of the deposit indicate that it is not particularly ancient, whereas arguments concerning the age of the lateritic crust suggest a probable Tertiary age.

STRUCTURE

FOLDING

The metasedimentary rocks which constitute the Wologizi group have been deformed into tight folds, most of which are isoclinal and overturned toward the west. Small-scale isoclinal folds are common throughout the section, but owing to parallelism of the fold limbs and to paucity of extensive well-exposed stratigraphic markers and of unequivocal primary structures indicative of stratigraphic tops, most large-scale folds could not be mapped directly. Some of the axial traces shown on the geologic map (pl. 1) were mapped by standard techniques of dip reversal and repetition of section, but the positions of many were inferred from minimal data. The resulting geologic-structure sections (pl. 1) make structural sense but are based on considerable inference; they could require revision if drill-hole data become available. The most likely revision would be the recognition of east-dipping high-angle faults subparallel to the axial planes of the folds.

All indications are that deformation of the metasedimentary rocks took place before the rocks had been appreciably metamorphosed and that little additional deformation accompanied or followed the peak of metamorphism. Clastic textures are preserved in some rocks in the staurolite zone, with no appreciable deformation of the clastic grains and pebbles. Sedimentary laminae of contrasting composition are well preserved in the low-grade area and are recognizable locally throughout the higher grade area; large-scale bedding also is well preserved, though deformed. Evidence is generally lacking for any deformation accompanying or postdating the metamorphism, such as helicitic structures in garnet or staurolite, deformed crystals, cataclastic structures, quartz rodding, crinkles in the foliation of phyllites and schists, or second lineations or foliations. Shearing was evident only locally near the Wologizi group—granitic gneiss contact and adjacent to some bodies of ultramafic rock.

Metamorphic foliation defined by orientation of phyllosilicates parallels the axial planes of small-scale folds, and the foliation cuts across the bedding in the hinge areas of these folds. The limbs of many folds are approximately parallel to their axial planes; consequently, bedding and metamorphic foliation are parallel over much of the area.

FAULTING

Little evidence of faulting has been recognized within the Wologizi group, mainly because of poor stratigraphic control and exposure. The style of deformation indicates that plastic flow probably was dominant over brittle failure or shearing; therefore, the indicated faults may be postmetamorphic structures.

The faults indicated on the geologic map (pl. 1) were first recognized on aerial photographs. The most significant may be the northwest-trending lineament in Zohnwo Creek, which can be traced discontinuously for about 20 km (fig. 7). Offset is apparently slight, and because the lineament generally follows alluvium-filled valleys, the actual trace was not inspected. A similar lineament trends northeast in the bed of the Lofa River, following a shear zone conformable with the foliation of the granitic gneiss.

BASAL UNCONFORMITY

The contact between the base of the Wologizi group and the underlying granitic gneiss was observed in streams at six places along the flanks of the range and was located within a few meters in several other places. Commonly, the contact is at or above the break in slope at the foot of the mountain. The contact is sharp and does not cut across the bedding of the metasedimentary rocks. The lowest metasedimentary rock is a 5-m-thick quartz-muscovite (-microcline-epidote) schist, which locally contains quartz augen suggestive of sheared pebbles; it resembles the sheared quartz-muscovite metaconglomerate found at the base of the metasedimentary sequence in the Nimba Range (Berge, 1968, p. 33). Clastic textures are well preserved in rocks of similar composition higher in the section, but the basal contact is generally so sheared that recognition of a basal conglomerate in the Wologizi Range is uncertain. Nevertheless, all other evidence indicates that the basal contact is a deformed nonconformity.

The basal quartz-muscovite schist is generally overlain by amphibolite, amphibole-quartz schist, or grunerite-rich iron-formation. In some places the basal quartz-muscovite schist is missing, and the amphibole-rich rock lies directly on the granitic gneiss.

Gneiss near the contact is fairly homogeneous, though foliated. Muscovite is more abundant than usual in the gneiss in an irregular zone as much as 100 m wide near the contact, a result, perhaps, of weathering of the gneiss prior to deposition of the Wologizi group. The gneiss lacks the character of an undeformed igneous rock, and no evidence of intrusion of gneiss into the Wologizi group was seen.

Foliation in the gneiss is generally subparallel to the contact between the Wologizi group and the gneiss along the flanks of the range, and, therefore, an angular unconformity is not apparent. At the south end of the range, the metasedimentary rocks are folded into several tight north-plunging folds, and the contact trends generally east around the fold hinges. There, the gneissic foliation maintains its general northeast trend with steep dip, and an angular discordance is apparent. Unfortunately, the actual contact is nowhere exposed in the critical areas where the gneissic foliation strikes into the contact.

The apparent parallelism between the gneissic foliation and the Wologizi

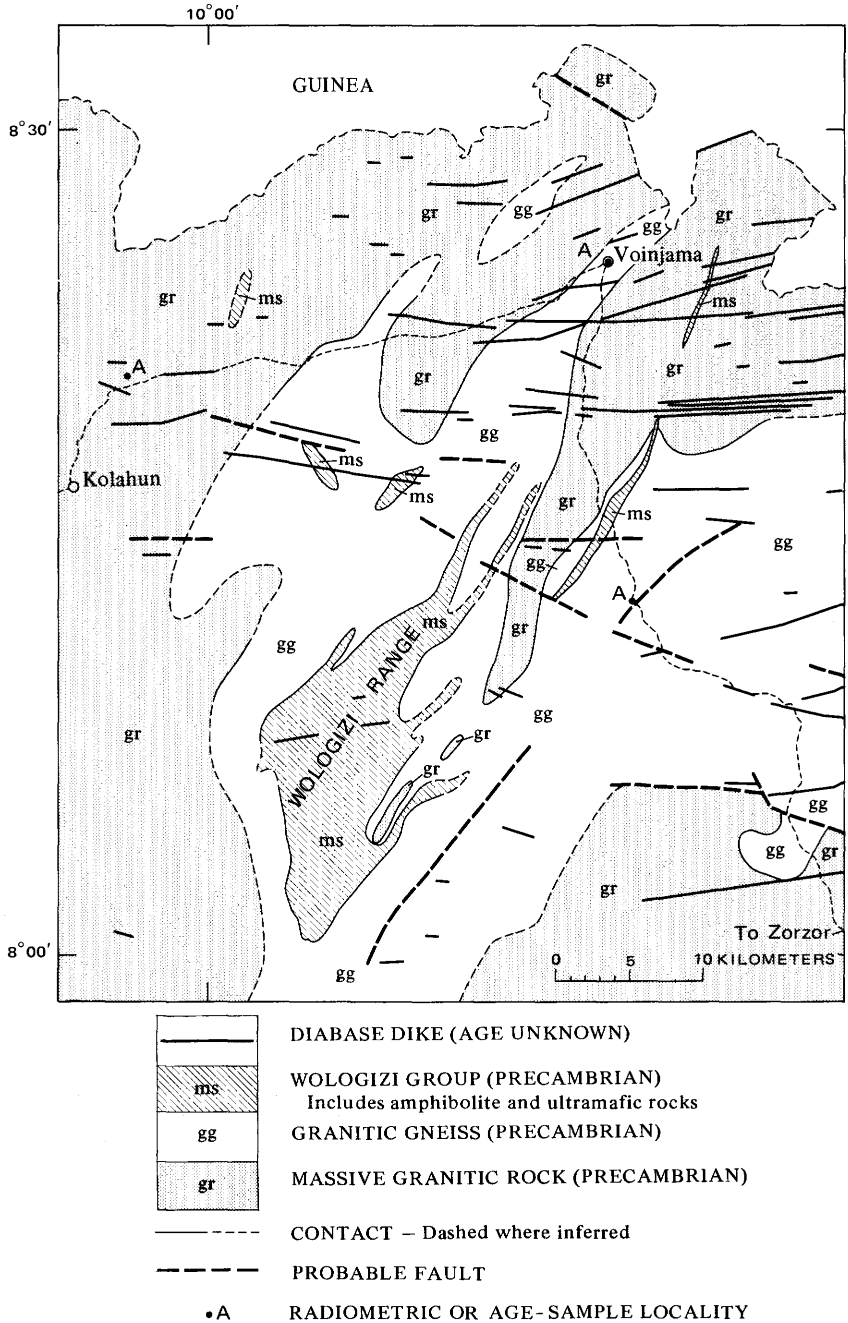

FIGURE 7. — Generalized geologic map of the Wologizi Range and surrounding area. Modified from J. F. Seitz, 1973.

group—granitic gneiss contact along the flanks of the range probably is not fortuitous; a similar situation exists at many other places in Liberia where metasedimentary rocks are folded into the gneissic basement. (See Offerberg and Tremaine, 1961, p. 21.) The gneissic rocks could not have escaped intense deformation at the time that the metasedimentary rocks were folded. The gneissic foliation has a general northeast trend and steep dip which is subparallel to the axial planes of folds in the metasedimentary rocks. The gneissic foliation could be chiefly a superimposed feature, produced during the folding of the metasedimentary rocks.

RELATIONSHIP BETWEEN MASSIVE AND FOLIATED GRANITIC ROCKS

The general arrangement of structural units in the area of the Wologizi Range consists of an infolded belt of metasedimentary rocks surrounded by an envelope of granitic gneisses, which, in turn, is surrounded by massive granitic rocks (fig. 7). According to one possible interpretation, the gneisses became foliated when they were deformed together with the Wologizi group, whereas the massive rocks farther from the axis of folding were deformed less intensely or in a different manner and, thus, remained massive. The only problem with this interpretation is the fact that in the area southeast of Voinjama (fig. 7; outside the area of pl. 1), one of the infolded belts of metasedimentary rocks projects northeast beyond the envelope of gneiss and is enclosed directly in massive granitic rock. In the absence of evidence that the massive unit is intrusive into the metasedimentary rocks in that area, the described relations are considered to be evidence that the distribution of the gneissic and massive structures predates deposition of the Wologizi group.

The origin of the contrasting gneissic and massive structures is still uncertain. Study of the contact between gneissic and massive granitic rocks would be the best method of resolving the uncertainty, but the contact is nowhere known to be exposed. It seems to be a smoothly curving surface without apparent apophyses of massive rock into the granitic gneiss, and without crosscutting relationships. Commonly, the foliation in the contiguous granitic gneiss is parallel to the contact. The contact appears sharp within the limits of available exposure, but it could be gradational over a thickness of 100 m or more.

Two possible interpretations of the origin of the contrasting structures are presented; probably both processes have played a part. Rock exposures in Liberia are so poor that this genetic uncertainty may never be unequivocally resolved.

1. The sedimentary trough followed an older axis of deformation, along which the gneiss previously had been deformed and foliated. The subsequent deformation has reoriented the gneissic foliation in such a manner that it now is subparallel to axial planes of the younger folds.

Doubtless, this younger deformation also has modified the granitic gneiss—massive rock contact, making the mutual relations of these rocks more difficult to interpret.

2. Textural and structural features observed in massive granitic rocks in the Kolahun area (White and Leo, 1969, p. 5), about 30 km northwest of the Wologizi Range, suggest that the massive rocks are the result of partial melting (anatexis) of gneissic rocks. As mentioned, the structural position of the granitic gneisses corresponds generally with the downfolds of metasedimentary rocks. In a similar manner, the position of the major lens of massive granitic rock east of the Wologizi Range corresponds with the projected trace of a major anticline in the infolded metasedimentary sequence. These observations imply that the massive rocks underlie the gneisses; anatexis presumably was more effective at deep levels.

BABO GRANITE

The small body of alkalic two-mica granite on Babo Creek, herein referred to as the Babo granite, is compositionally distinct from the enclosing gneisses as well as from other massive granitic rocks in the Wologizi area. Evolution of these latter units is thought to be older than the deposition of the Wologizi group. No clear-cut evidence of relative age of the Babo granite can be gained because the granite is not in contact with the Wologizi group. However, the granite body is parallel and adjacent to an axis along which the highest metamorphic grade attained in the Wologizi group is found. Furthermore, sparse muscovite pegmatites cutting schists in the sillimanite zone prove that conditions suitable for melting of granitic rocks existed somewhere in the area during or after the metamorphism. These observations are considered to constitute evidence that the Babo granite is younger than the Wologizi group.

The contact between the Babo granite and the enclosing gneisses is not exposed, but its general character is synkinematic, or concordant, similar to that of the contact between the other massive granitic rocks and granitic gneiss elsewhere in the area. Therefore, the Babo granite must have been emplaced while the Wologizi group and the bounding gneisses were being deformed and metamorphosed.

The great width of the metamorphic zones as compared with the size of the Babo granite indicates that the granite could not have been the sole source of heat for the metamorphism. More likely, the granite is an effect rather than the cause of metamorphism, having been produced by anatexis in a region where the metamorphic grade was higher and the composition more appropriate for melting than in the sillimanite zone of the Wologizi group. No doubt other bodies of anatectic granite of comparable age exist in the area, especially along the trend of the Babo granite, but poor exposures have precluded identification.

GEOCHRONOLOGY

Radiometric age determinations on rocks and minerals from several localities in Liberia were recently published (Hurley and others, 1971). These include determinations on three massive granitic rocks from the Kolahun area northwest of the Wologizi Range, and on two granitic gneisses from northeast of the range. Three of the localities are shown in figure 7; the other two are west of the area of that map. Whole-rock rubidium-strontium data on 12 specimens from these five localities define a single isochron of 2,652 m.y., with no discernible difference in age between the massive and foliated rocks (Hurley and others, 1971, fig. 3). Inasmuch as the arrangement of the granitic rocks in the area of the Wologizi Range into massive and foliated types probably predates deposition of the Wologizi group, a first approximation of the age of deposition of the group would be younger than 2,652 m.y.

Nevertheless, age determinations and field relationships elsewhere in Liberia suggest this interpretation to be too simple. The geology of the area of the Bong, Mano River, and Nimba iron mines (fig. 1; Thienhaus and Stobernack, 1967; White and Baker, 1968; Berge, 1968 and unpub. data, 1971, respectively) is similar to that of the Wologizi Range — a sequence, including pelitic and psammitic sediments and possible mafic volcanic rocks in the lower part and iron-formations in the upper part, has been metamorphosed and folded into granitic gneisses. Isotope data on 12 samples of the underlying gneiss from four localities at the three mines are consistent with an age of about 2,700 m.y. (whole-rock rubidium-strontium; Hurley and others, 1971). All 12 samples were collected within 300 m of a metasedimentary rock–granitic gneiss contact; therefore, this preliminary age value probably represents the time of deformation and metamorphism to amphibolite facies of the gneiss and overlying sediments (White and Leo, 1969, p. 14). The data may indicate a minimum age of sedimentation of about 2,700 m.y., rather than a maximum age.

Detailed work at the Bong mine indicates a complex geologic situation there. Stobernack (1968, p. 47) reported age determinations by the potassium-argon method on muscovite from two gneisses, a schist, and a pegmatite that are in the range of 1,561 to 1,713 m.y. He interpreted this as a later, postdeformation metamorphism synchronous with partial anatexis, superimposed on the approximately 2,700-m.y. metamorphism. According to this interpretation, the older date represents the minimum age of sedimentation.

Lithologic correlation in Precambrian terranes is only tenuous. Lithologically, the metasedimentary sequence in the Wologizi Range seems to be correlative with those at the Bong, Mano River, and Nimba iron mines. Available age determinations are consistent with this correlation and indicate that deposition of the sequences may have occurrred more than 2,700 m.y. ago. If so, the iron-formations in the Wologizi Range and elsewhere in Liberia are among the oldest known in the world.

IRON DEPOSITS

CHEMICAL COMPOSITION OF THE IRON-FORMATIONS

Several chemical and spectrographic analyses of unweathered iron-formation are reported in tables 2 and 4, and selected analyses of iron-formation from elsewhere in Liberia are shown in table 3. The iron-formation in the Wologizi group is essentially an iron-silica rock with minor aluminum and magnesium. The content of other elements is remarkably low, both on an absolute basis and by comparison with other Precambrian magnetite and silicate iron-formation (James, 1966, p. 21–23). The significance of the uniformly low CO_2 content has already been discussed (p. 12–13).

TABLE 2. — *Chemical analyses, in percent, of unweathered iron-formation from the Wologizi group*

[Rapid-rock analyses by Paul Elmore, Lowell Artis, Gillison Chloe, H. Smith, S. D. Botts, J. L. Glenn, and J. M. Kelsey, U.S. Geological Survey. Sample localities are shown on pl. 1]

Analysis No. Sample	1 (102B)	2 (253F)	3 (84F)	4 (144D)	5 (115L)	6 (99C)	7 (235C)	8 (140F)	9 (253D)	10 (81F)	11 (129E)
SiO_2	71.0	67.0	43.2	53.7	46.5	43.6	55.0	54.0	39.7	41.9	55.4
Al_2O_3	.42	1.3	.52	.73	2.0	3.1	1.2	1.5	1.4	4.6	17.2
Fe_2O_3	19.3	18.7	35.0	29.0	37.4	24.1	20.0	11.3	20.0	16.3	1.2
FeO	7.2	10.7	17.5	13.8	9.7	21.6	21.0	25.6	31.2	29.2	11.4
MgO	.36	1.2	2.0	1.5	.84	4.3	1.0	3.4	4.9	3.8	3.6
CaO	.09	.05	.20	.06	.11	.38	.42	2.0	.23	.86	1.8
Na_2O	.00	.00	.03	.02	.08	.06	.08	.12	.05	.08	2.6
K_2O	.08	.15	.12	.18	.33	.75	.04	.21	.22	.08	2.4
H_2O-	.75	.04	.09	.07	.44	.23	.13	.05	.06	.17	.12
H_2O+	.00	.60	.83	.51	1.7	1.5	.87	1.3	1.3	1.2	3.3
TiO_2	.03	.03	.03	.03	.04	.09	.04	.04	.06	.15	.51
P_2O_5	.00	.02	.22	.16	.17	.22	.08	.10	.17	.16	.15
MnO	.00	.23	.26	.18	.37	.52	.20	.29	.61	.52	.12
CO_2	<.05	<.05	.06	<.05	.08	.15	<.05	<.05	<.05	<.05	<.05
Total	99	100	100	100	100	101	100	100	100	99	100
Fe	19.1	21.4	38.1	31.0	33.7	33.7	30.3	27.8	38.3	34.1	9.7
P	.00	.01	.10	.07	.07	.10	.03	.04	.07	.07	.07
Mn	.00	.18	.20	.14	.29	.40	.15	.22	.47	.40	.09

DESCRIPTION OF SAMPLES

1. 102B, Quartz-rich itabirite, biotite zone: quartz-magnetite (-chlorite-pyrite); grab sample.
2. 253F, Quartz-rich itabirite, garnet zone: quartz-magnetite (-chlorite-grunerite); grab sample.
3. 84F, Itabirite, approximately on garnet isograd: quartz-magnetite (-grunerite-chlorite-siderite); grab sample; slightly weathered.
4. 144D, Grunerite itabirite, garnet zone: quartz-magnetite-grunerite (-chlorite); grab sample.
5. 115L, Interbedded itabirite and silicate iron-formation, biotite zone: quartz-magnetite-silicates (-carbonate?); chip sample, spacing 1.5 m, across 150 m of beds; slightly weathered.
6. 99C, Silicate itabirite, garnet zone: quartz-magnetite-silicates (-carbonate?); chip sample, across 4 m of beds.
7. 235C, Grunerite iron-formation, garnet zone: quartz-grunerite-magnetite (-garnet); grab sample.
8. 140F, Grunerite iron-formation, staurolite zone: grunerite-quartz-magnetite-hornblende (-biotite); grab sample.
9. 253D, Grunerite iron-formation, garnet zone: grunerite-magnetite (-garnet-chlorite-quartz); grab sample.
10. 81F, Grunerite iron-formation, approximately on staurolite isograd: grunerite-magnetite-garnet (-chlorite-quartz); grab sample.
11. 129E, Quartz-biotite phyllite, biotite zone: quartz-biotite-oligoclase(An_{20})-chlorite (-muscovite-microcline); grab sample.

Few complete analyses of iron-formation from elsewhere in Liberia are available (table 3), but these generally are similar to those from the Wologizi Range. Other, partial analyses (not listed in table 3) are similar. Published descriptions and my own observations of iron-formations in

TABLE 3. — *Selected chemical analyses, in percent, of iron-formation from Liberia*

Analysis No.	1	2	3	4	5	6	7	8	9	10
SiO_2	36.58	39.7	40.4	39.8	40.4	41.24	41.96	35.47	12.12	28.60
Al_2O_3	.39	.14	.86	.25	.44	.87	.58	1.21	2.34	2.45
Fe_2O_3	----	44.0	41.4	33.1	35.5	40.45	40.27	57.92	78.04	60.51
FeO	----	12.9	13.3	17.4	18.1	12.95	12.82	2.69	.81	3.37
MgO	.16	.57	.07	1.76	1.83	1.35	1.36	.10	.10	----
CaO	.44	.34	1.23	2.26	1.81	.84	1.02	.10	.10	----
Na_2O	----	----	----	----	.18	.20	.00	----	----	----
K_2O	----	----	----	----	.18			----	----	----
H_2O+	----	----	----	----	----	.27	.21	2.23	6.03	----
TiO_2	.22	.03	.03	.04	----	.17	.06	----	----	----
P_2O_5	----	.145	.220	.17	.18	.13	.04	.12	.19	----
MnO	----	.021	.09	.12	----	.16	.21	----	----	----
CO_2	----	----	----	----	----	.19	.21	----	----	----
Total	----	97.8	97.6	94.9	99.5	98.82	98.74	99.84	99.73	----
Fe	43.77	40.8	39.3	36.6	38.9	38.36	38.13	42.60	55.21	45.08
P	.071	.063	.096	.07	.08	.058	.018	.052	.082	.050
S	.052	----	----	----	----	.03	.03	.013	.042	.046
Mn	.06	.016	.07	.09	----	.12	.16	----	----	----

DESCRIPTION OF SAMPLES AND SOURCE OF DATA

1. Bomi Hills, "Composite sample from selected fresh core essentially free from silicates; typical hematitic iron-formation"; from Newhouse, Thayer, and Butler (1945, p. 106, No. 125).
2. Nimba Range, "average of 102.46 meters of magnetic itabirite"; from J. W. Berge (unpub. data, 1971).
3. Nimba Range, "average of 32.6 meters of magnetic itabirite with noticeable silicate content"; from J. W. Berge (unpub. data, 1971).
4. Nimba Range, "single composite sample representing 20 meters of silicate-bearing iron-formation under Mt. Gbahm"; from J. W. Berge (unpub. data, 1971).
5. West of Nimba Range, "average of 295.75 meters of cored (silicate-bearing) iron-formation from Tokadeh and Yuelliton–Gangra Ridges"; total includes loss on ignition, 0.86; from J. W. Berge (unpub. data, 1971).
6. Bong Range, unweathered itabirite from boring Zaweah 1, depth 27–138 m; includes Cu, 0.02; Cr, 0.02; Pb and Zn, trace; As, Co, Ni, Sn, and V, 0.00; from Thienhaus (1963, table 5).
7. Bong Range, unweathered itabirite from boring Zaweah 1, depth 138–169.2 meters; includes Cu, 0.02; Pb and Zn, trace; As, Cr, Co, Ni, Sn, V, 0.00; from Thienhaus (1963, table 5).
8. Bong Range, weathered itabirite from boring Z 31, depth 29.5–101.7 m; from Thienhaus (1963, table 4, No. 8).
9. Bong Range, weathered itabirite from boring Z 31, depth 0–20.6 m; from Thienhaus (1963, table 4, No. 7).
10. Bea Mountains, "typical chemical analysis of soft, weathered" iron-formation; from Rehfeldt (1967, p. 66).

TABLE 4. — *Semiquantitative spectrographic analyses of unweathered iron-formation from the Wologizi group*

[Analysts: J. L. Harris (analyses 1–4, 7–11) and W. B. Crandell (analyses 5, 6), U.S. Geol. Survey. Sample numbers and descriptions same as in table 2. Values are reported in weight-percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, and so forth, which represent approximate midpoints of interval data on a geometric scale. The assigned interval for semiquantitative results will include the quantitative value about 30 percent of the time. Also looked for but not found: Ag, As, Au, B, Bi, Cd, Eu, Ge, Hf, Hg, In, Li, Nb, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. *, high Fe interference; Mo, if present, <0.001]

Analysis No.	1	2	3	4	5	6	7	8	9	10	11
Sample	(102B)	(253F)	(84F)	(144D)	(115L)	(99C)	(235C)	(104F)	(253D)	(81F)	(129E)
Ba	0.005	0.002	0.003	0.005	0.015	0.007	0.0015	0.003	0.005	0.005	0.07
Be	0	0	0	0	0	0	0	0	0	0	.0001
Ce	0	0	0	0	0	0	0	0	0	0	.01
Co	0	0	0	0	0	.0003	0	0	0	.001	.002
Cr	.0007	.001	.0005	.0015	.001	.001	.005	.002	.0015	.007	.05
Cu	.03	.02	.02	.01	.001	.002	.015	.005	.03	.003	.007
Ga	.0005	.0005	.0005	.0007	0	0	.0007	.0005	.0007	.0007	.001
La	0	0	0	0	0	0	0	0	0	0	.007
Mo	.001	.002	.001	.0015	*	*	.0015	.0015	.0015	.0015	.002
Ni	<.001	<.001	<.001	<.001	.002	.002	.003	<.003	<.003	.015	.015
Pb	.005	.002	.005	0	.0005	.007	0	0	.005	0	.002
Sc	0	0	0	0	0	0	0	0	0	0	.002
Sr	0	0	0	0	0	0	0	0	0	0	.03
V	.0001	.0003	.0001	.0003	.0007	.0005	.001	.0001	.0003	.001	.007
Y	0	0	0	0	0	0	0	0	0	0	.002
Yb	0	0	0	0	0	0	0	0	0	0	.0002
Zr	.007	.007	.007	.01	0	0	.02	.01	.015	.015	.015

Liberia indicate a general dominance of magnetite over specularite (with a few exceptions, such as the Goe Range; Berge, 1966a), widespread grunerite and garnet, and a paucity of iron carbonate. The composition of many other iron-formations in Liberia therefore may be comparable to that in the Wologizi group. Some of the others are richer in iron.

The low minor-element content of the iron-formation (table 4) is a recognized characteristic of Precambrian iron-formation (James, 1966, p. 46), although the copper content is generally higher than the values compiled by James (1966, p. 45). Two analyses of itabirite from the Bong iron mine indicate comparably high copper values (table 3, Nos. 6, 7). Sparse chalcopyrite, found with pyrite in a silicate iron-formation in the Wologizi group, may be the chief copper-bearing mineral.

Chemical differences between itabirite and silicate iron-formation are evident from table 2, in which analyses 1 to 10 are listed in the approximate order of increasing silicate-mineral content. Aluminum, ferrous iron, magnesium, and combined water are higher in silicate iron-formation than in itabirite and are reflected directly in the mineralogy. Apparent irregularities in the aluminum trend are due to variable amounts of chlorite and garnet from rock to rock. Silica and ferric iron vary with the proportions of quartz and magnetite. Calcium, sodium, titanium, and manganese also tend to be higher in silicate iron-formation than in itabirite. Pyrite is more common in silicate iron-formation, which consequently may have the higher sulfur content, although sulfur has not been determined. No clear trends can be recognized in the other minor elements (tables 2, 4).

An analysis of a laminated pelitic phyllite is also listed (tables 2, 4, No. 11). This rock is petrographically and chemically quite distinct from iron-formation but, in the field, is difficult to distinguish from the phyllitic variety of silicate iron-formation. Note that the variety and abundance of minor elements in the pelitic phyllite (table 4) are greater than those in iron-formation. This is probably an effect of a detrital clay component in the pelitic rock.

ORIGIN OF THE IRON-FORMATIONS

Oolitic and clastic textures have not been observed in oxide iron-formation, and there is no great variety of heavy minerals, as might be expected in a clastic rock. Furthermore, structures such as crossbedding, graded bedding, and ripple marks were not observed. Consequently, the oxide iron-formation is presumed to have originated as a laminated chemical sediment, which consisted of chert, magnetite or a hydrated iron-oxide precursor, and one or more iron-silicate minerals. Silicate iron-formation grades laterally into pelitic rock, and locally contains relict detrital quartz grains of silt size. Probably, it also represents a chemical sediment, though deposited under slightly different conditions and mixed with varying amounts of fine clastic material.

The environment of deposition of iron-rich sediments has been the subject of considerable scientific discussion and debate. Little firm evidence contributing to the solution of this controversy was discovered during this study. Amphibolites, or probable metavolcanic rocks, are associated with iron-formations in the Wologizi Range, as well as at many other places in Liberia. This association lends support to the volcanic exhalative–sedimentary hypothesis of origin of iron-formation. However, Berge (1968, p. 28) pointed out that the amphibolites in the metasedimentary sequence in the Nimba Range are wholly older than, not contemporaneous with, associated iron-formations. Close scrutiny indicates the same age relationship for several of the better known iron-formation–metasedimentary rock sequences in Liberia (Bea Mountains: Rehfeldt, 1967, p. 67; Bong Range: Thienhaus and Stobernack, 1967, p. 54; Mano River mine: White and Baker, 1968, p. 57). In the Wologizi group the amphibolites also are mostly if not wholly older than the itabirite, although they are interbedded with silicate iron-formation and other metasedimentary rocks in the lower part of the section. The possible volcanic association is not so clear-cut as it one seemed (Offerberg and Tremaine, 1961, p. 21, 28; White and Leo, 1969, p. 8).

Note that derivation of the iron-formations found in the Wologizi Range from volcanic rocks would require all of the iron from about 70 cubic kilometers of tholeiitic basalt, whereas only small amounts of possible metamorphosed basalt (amphibolite) are found in the area of the Wologizi Range. Association of a small amount of possible volcanic rocks with the iron-formation does not constitute very convincing evidence of a cause-and-effect relationship.

WEATHERING OF IRON-FORMATIONS

Lateritic weathering has modified and in part enriched the primary iron-formations in the Wologizi Range; appraisal of the economic potential of the iron-formations requires a thorough knowledge of the effects of weathering. Weathering profiles on iron-formation in Liberia have been described by Newhouse, Thayer, and Butler (1945), Beyer (1959), Thienhaus (1963, 1964), Berge (1966b), and Rehfeldt (1967). These profiles are all similar. Thienhaus' reports (1963, p. 1091; 1964, p. 91), encompassing work elsewhere in Africa and in India, present a model that probably is applicable to most iron-formations in Liberia. He recognized four gradational zones in a complete profile:

Zone 1, Porous cemented hard hematite or goethite crust. — Commonly the cemented crust is fragmental (canga), but the relict bedding may be preserved in situ.

Zone 2, Porous platy or powdery soft hematite or goethite ore. — Relict bedding generally is preserved, though it may be disturbed by collapse near the surface. Leaching of quartz is virtually complete, and the material lacks cohesion.

Zone 3, Weathered iron-formation. — Magnetite has been oxidized to hematite (martite), and iron silicates have been weathered to an aluminous, limonitic residue. Slight leaching of quartz has reduced the strength of the rock.

Zone 4, Unweathered iron-formation.

The iron content increases progressively from zone 4 to zone 1, but the ultimate grade depends upon the degree of enrichment and hydration, as well as on the grain size and on the iron, silicate-mineral, and aluminum content of the unweathered iron-formation. The thickness of the zones is extremely irregular, and such features as synclines, faults, joints, cross folds, and adjacent impervious rocks are important in controlling the depth of weathering (Thienhaus, 1963, p. 1092). From drilling and excavation of iron-formation at the Bomi Hills, Bong, Mano River, and Nimba mines and in the Bea, Mountains and the Goe Range (Berge, 1966b, p. 38, 39, 43; 1971, p. 951–953; Beyer, 1959, p. 52–59; Johnson, 1967, p. 38, 39; Lersch, 1966, p. 19; Rehfeldt, 1967, p. 63, 65, 68; Thienhaus, 1963, p. 1091, 1094; 1964; Zigtema and McCrary, 1968, p. 20, 23), the following thickness and grade can be expected in each zone:

Zone 1 generally is no more than 5 m thick and may be considerably thinner. The iron content typically is 55 to 63 percent (for example, table 5, Nos. 1, 3, 4, 6), higher values occurring only in ores with very low contents of goethite, gibbsite, or clay minerals. The aluminum content is relatively high (commonly 3 to 7 percent).

Zone 2 may extend to depths as great as 100 m, but the average depth is about 30 m. The iron content, 45–65 percent, represents a concentration of 1.2 to 1.8 times that of unweathered iron-formation. The aluminum content generally is lower than that in zone 1 but is somewhat higher than that in the less weathered zones, especially in silicate iron-formation.

Zone 3 may extend to depths greater than 100 m, but the average depth is about 75 m. The iron content commonly is increased by 1.05 to 1.2 times that of the unweathered iron-formation. (See table 3, Nos. 8–10 for examples.) The iron content of most unweathered, unenriched iron-formation in Liberia is 25 to 40 percent.

All four zones described by Thienhaus have been recognized in the Wologizi Range, although zone 2 is exposed in only a very few places at high elevation where the overlying canga capping is undercut by erosion. Subsurface work was not possible during this study; so the approximate thicknesses of the weathered zones reported herein are based on visual estimates and on altimeter readings taken on steep forested canyon walls.

The lateritic iron deposits of the Wologizi Range were worked by local people at some time in the past. Small amounts of iron-rich slag are found at several places in lower parts of the range. However, no actual remnants of furnaces were seen, such as those found in the Putu Range in eastern Liberia (Schulze, 1964).

TABLE 5. — *Selected chemical analyses, in percent, of hematitic iron ores from Liberia and Sierra Leone*

[Tr., trace; ---, not reported]

Analysis No.	1	2	3	4	5	6
SiO_2	1.74	2.66	1.95	1.32	4.19	3.10
Al_2O_3	6.20	.78	6.05	5.95	9.02	8.10
Fe_2O_3	82.65	95.32	84.71	82.65	74.95	79.29
FeO	.0	.27	.39	.43	.44	.91
MgO	.18	.05	Tr.	Tr.	Tr.	.0
CaO	.80	.10	.00	.00	.00	.0
Na_2O	----	----	----	----	----	----
K_2O	----	----	----	----	----	----
H_2O-	----	----	----	----	----	----
H_2O+	9.0	.53	----	----	----	9.22
TiO_2	.18	<.01	.22	.17	.38	.8
P_2O_5	.16	.06	.19	.29	.25	.2
MnO	.24	.10	.04	.03	.03	.30
S	----	----	.022	.043	.043	----
Loss on ignition	----	----	6.56	9.22	10.78	----
Total	101.15	99.87	100.13	100.10	100.08	101.9
Fe	57.80	66.38	59.6	58.1	52.8	55.50
P	.07	.029	.083	.13	.11	.09
S	.09	<.005	.022	.043	.043	.07
Mn	.19	.08	.03	.02	.02	.23

DESCRIPTION OF SAMPLES AND SOURCE OF DATA

1. Mano River mine, high-grade lateritic ore derived from itabirite, after washing; from Thienhaus (1963, table 3).
2. Nimba Range, blue hematite ore, complete section across Main ore body in Nimba tunnel on peak 2; includes V_2O_5, 0.00; Cr, <0.01; Cu and Ni, no trace: Fe_2O_3 and FeO recalculated from Fe_2O_3 and Fe_3O_4; from Beyer (1959, table 1).
3. Nimba Range, shallow capping of soft brown ore on central Gbahm; predominantly goethite and martite; from Beyer (1959, table 3).
4. Nimba Range, surface crust of lateritic ironstone on central Gbham; from Beyer (1959, table 3).
5. Nimba Range, canga derived from conglomerate in Upper Grassfield at Headquarters Camp; from Beyer (1959, table 3).
6. Tonkolili, Sierra Leone; lateritic ore similar to that at the Mano River mine; from Thienhaus (1963, table 3).

POTENTIAL LOW-GRADE ORES

The potential low-grade iron ores in the Wologizi Range include both weathered and unweathered iron-formations (zones 3 and 4 of Thienhaus, 1963). Magnetite is the only iron-oxide mineral that has been recognized in unweathered iron-formation; so a high-grade concentrate could probably be prepared from unweathered iron-formation by simple magnetic separation. According to the United Nations (1966, p. 10), "low intensity magnetic methods are amongst the cheapest, simplest, and most efficient of those employed in ore preparation." The iron content of unweathered iron-formation of both oxide (itabirite) and silicate facies averages about 33 percent (table 2, Nos. 2–10).

A huge tonnage of iron-formation is suggested by the mapping done in this study. A total of 37 billion metric tons of itabirite is inferred, of which 94 percent — 35 billion tons — is on or near divides in areas where the outcrop width is at least 1 km; consequently, it is suitable for open-pit mining. Adjacent areas mapped as silicate iron-formation are inferred to contain an additional 17 billion tons of rock, much of which is at low elevations and on slopes. The conterminous mass of itabirite along the axis of the Wologizi

Range has an outcrop area of 26.6 sq km, as shown on plate 1. Tonnage of this mass has been calculated by subdividing it into 14 increments of inferred uniform cross section — assuming a depth equal to one-half the outcrop width or 500 m, whichever is less, and a density of 3.0 tons per cubic meter. Tonnage of silicate iron-formation was calculated by use of similar assumptions.

In the beneficiation of low-grade iron ores, fine grinding has been found to be the most costly part of the process (United Nations, 1966, p. 11, 18, 54–55). The grain size of the iron-formation in the Wologizi Range, and therefore the fineness of grinding necessary for liberation of the iron minerals, is controlled by the degree to which the iron-formation has been metamorphosed. From the ranges in grain size of magnetite and quartz in itabirite in the various metamorphic zones (p. 9) and from the metamorphic isograds (pl. 1), one can predict areas wherein the grain size is likely to be coarsest, thereby minimizing grinding costs in beneficiation.

Unfortunately, the bulk of the itabirite (more than 70 percent of the inferred tonnage) is extremely fine grained because it is located within the biotite zone of metamorphism. Only about 1 percent, or perhaps 400 million tons, of the conterminous mass of itabirite is located in the staurolite zone and has a grain size comparable to that of some low-grade deposits currently being exploited elsewhere (United Nations, 1966). The isolated infolds of iron-formation mapped as itabirite in the low hills east of the axis of the range (pl. 1) are located within an area of high metamorphic grade and are relatively coarse grained. However, the extent of those deposits and the proportion of silicate facies therein are poorly known.

The stratigraphic succession and the arrangement of metamorphic zones in the Wologizi group determine that the silicate iron-formation has been, in general, more highly metamorphosed and, accordingly, is coarser grained than the itabirite. Only 30 percent of the inferred tonnage of silicate iron-formation is in the biotite zone of metamorphism, whereas 10 percent or more is in the staurolite zone. Iron silicates in such ores are generally not recoverable in iron-ore beneficiation (United Nations, 1966, p. 8) and currently are not considered to be iron-ore minerals. The somewhat lower and variable content of magnetite in the silicate iron-formation, as compared with itabirite, also decreases its suitability as a low-grade iron ore.

Weathered iron-formations constitute a more probable low-grade ore than the unweathered iron-formations. In general, unweathered iron-formation is found only in or near the bottoms of canyons, whereas weathered iron-formation is found over a vertical range of as much as 300 m on some steep canyon walls. The 300-m figure is not thought to be representative of the true depth of weathering, because the base of weathering probably is roughly parallel to the ground surface. A maximum of 100 m seems a more probable depth of weathering.

The inferred tonnage of weathered itabirite, assuming a conservative depth of weathering of 50 m, is 3 billion metric tons (calculated only for the area mapped as itabirite along the axis of the range, assuming a density of 2.5 tons/m^3). Of this, almost 1 billion tons is in the garnet zone of metamorphism. No analyses of the weathered itabirite are available, but by comparison with the degree of enrichment observed elsewhere in Liberia, the iron content can be expected to average 34 to 40 percent, the higher values being near the surface. Weathered magnetite retains some of its magnetism except in the surficial zone; magnetic concentration of the iron in weathered itabirite may, therefore, be possible. Iron silicates have been converted to aluminous limonite by weathering, but such iron probably would be lost in beneficiation. Weathered itabirite is partially disintegrated and, accordingly, is much easier to crush than unweathered itabirite. For these reasons, weathered itabirite seems to have much better potential as a low-grade iron ore than does unweathered itabirite.

In summary, only a small tonnage (at most, a few hundred million tons) of itabirite in the Wologizi Range has a grain size as coarse as that of the finest grained low-grade deposits currently being beneficiated elsewhere in the world. (For some such deposits, local conditions of proximity to iron industry and market, both lacking in Liberia, are decisive factors permitting their economic utilization.) A somewhat larger tonnage of the itabirite (perhaps 1 billion tons in the garnet zone of metamorphism) has been so weathered that costs for grinding should be considerably less than costs for grinding unweathered itabirite; economic beneficiation might be possible despite the fine grain size. A relatively large tonnage of silicate iron-formation (more than 1 billion tons) is of grain size approaching that currently necessary for economic beneficiation, but the magnetite content is rather low and variable. Despite the approximate nature of these estimates, the tonnage of iron-formation in the Wologizi Range clearly is large enough that it is not a limiting factor in the possible utilization of the deposit as low-grade iron ore. The critical factors are, instead, the economics of beneficiation and marketing; special studies of these factors will be required before a decision on development of the deposit can be reached.

Prediction of future trends in the world iron-ore market is beyond the scope of this paper; nevertheless, one might speculate that the low-grade deposit in the Wologizi Range will appear increasingly favorable as higher grade reserves elsewhere become depleted. Regardless of its present economic potential, the deposit is undoubtedlv a substantial ore resource for the future.

HIGH-GRADE ORES

James (1955, p. 1478) pointed out the importance of metamorphic zonation in controlling the position of economically high-grade, postmetamorphic iron deposits derived from iron-formation; in northern Michigan ore production from such deposits is virtually limited to areas of low metamorphic grade. The grain size of the quartz in iron-formations in such areas is thought to control the degree of enrichment. Fine grain sizes, with closely spaced grain boundaries and large internal surface areas, promote thorough leaching of quartz and so lead to iron-rich secondary deposits. Removal of quartz is less thorough in areas of coarser grain size (that is, of higher metamorphic grade); thus, secondary deposits tend to be smaller or of lower iron content there. Detailed exploration in the Wologizi Range might show a similar relationship, although none became evident in the course of this work. The range should be considered as potentially favorable for iron-rich secondary deposits because of the large outcrop area of itabirite metamorphosed at low grade, even though exploration so far has failed to disclose any great volume of such economically high-grade deposits.

Several small areas of hard high-grade iron ore have been recognized and mapped in the Wologizi Range (pl. 1). The ore minerals are earthy hematite, goethite, bluish martite, and relict magnetite; the chief diluents are gibbsite, small amounts of kaolinite-group clay, relict quartz, and botryoidal manganese oxide. X-ray diffraction studies show that hematite is dominant over goethite in most samples (except in No. 2, table 6) and that gibbsite is detectable in all samples in amounts ranging from about 2 percent (No. 7, table 6) to at least 20 percent (No. 8, table 6). X-ray analyses also confirm that the proportions of hematite and goethite can be estimated in the field according to the streak, which is readily determined by observing the color of hammer marks on outcrops. The amount of relict magnetite, too, can be estimated by the effect of a magnet on the powdered sample, and the presence of gibbsite is shown by tiny white crystals and encrustations in vugs in the hard ore. Sparse grains and fragments of quartz were observed during sampling at three localities (Nos. 5–7, table 6), but quartz must be a trace constituent, inasmuch as it is not detectable by X-ray analysis of the homogenized samples, and it is not reflected in the silica content of those samples.

The high-grade ores in the Wologizi Range are surficial; they apparently have been derived from iron-formation by lateritic weathering and correspond to Thienhaus' (1963) zone 1. The ore bodies have three different shapes and topographic positions: (1) cappings on high ridges and spurs, (2) broader sheets on lower spurs and slopes, and (3) a crust on conglomerate that forms an alluvial plain at the base of the range. Those in the first two positions were mapped in this study (pl. 1).

HIGH CAPPINGS

Narrow strips of hard, porous high-grade ore are found as cappings along the relatively flat, narrow crests of high steep-sided ridges and on gently sloping though steep-sided spurs. Weathered iron-formation crops out on steep pitches along such ridges and spurs, and the high-grade crust is missing there. The relict bedding is preserved in situ in some of the high-grade crust; this ore type is referred to in table 6 as enriched iron-formation. Traverses down the steep sides of ridges and spurs that are oblique to the

TABLE 6. — *Chemical analyses, in percent, of hard lateritic iron ores from the Wologizi Range*

[Analyses 1–8: Rapid rock analyses by Paul Elmore, H. Smith, Lowell Artis, James Kelsey, S. D. Botts, Gillison Chloe, and J. L. Glenn, U.S. Geol. Survey. Analyses 9, 10: From Newhouse, Thayer, and Butler (1945, p. 108); ---, not reported. Sample localities are shown on pl. 1]

Analysis No.	1	2	3	4	5	6	7	8	9	10
Sample	(90E)	(103J)	(101C)	(173I)	(106G)	(143A)	(107J)	(136D)	(K1)	(K11)
SiO_2	1.0	2.2	3.0	2.3	1.8	1.3	3.3	1.6	5.28	12.41
Al_2O_3	6.0	6.7	7.2	5.8	10.4	8.2	3.1	15.1	10.28	3.18
Fe_2O_3	82.7	80.9	81.0	82.0	74.9	74.0	73.8	69.6	----	----
FeO	.72	.32	.92	.24	2.8	7.0	12.7	.16	----	----
MgO	.07	.07	.07	.08	.18	.07	.08	.03	----	----
CaO	.15	.05	.09	.00	.24	.02	.05	.09	----	----
Na_2O	.03	.06	.08	.00	.15	.05	.09	.00	----	----
K_2O	.09	.35	.05	.16	.36	.24	.44	.00	----	----
H_2O-	.92	.54	.84	1.0	.87	1.0	.50	1.1	----	----
H_2O+	6.3	7.2	6.1	7.2	5.8	6.6	4.3	10.7	----	----
TiO_2	1.5	.09	.15	.15	.16	.14	.09	.64	----	.06
P_2O_5	.36	.55	.39	.41	.36	.40	.37	.26	----	----
MnO	.06	.12	.16	.06	1.1	.29	.18	.02	----	----
CO_2	<.05	.05	<.05	<.05	<.05	.05	<.05	<.05	----	----
Total	100	99	100	99	99	99	99	99	----	----
Fe	58.4	56.8	57.4	57.6	54.6	57.2	61.5	48.9	51.20	56.93
P	.16	.24	.17	.18	.16	.17	.16	.11	.068	.069
S	----	----	----	----	----	----	----	----	.029	.034
Mn	.05	.09	.12	.05	.9	.22	.14	.02	----	.18

DESCRIPTION OF SAMPLES

1. 90E, Canga; hematite-goethite (-gibbsite): chip sample from boulders, spacing 1–5 m, for 440 m along crest of spur.
2. 103J, Canga; goethite-hematite (-gibbsite): chip sample from boulders, spacing 1–5 m, for 380 m along crest of spur.
3. 101C, Enriched iron-formation, fragmental in part; hematite-goethite (-gibbsite-kaolinite group): chip sample from outcrop and boulders, spacing 1–3 m, for 50 m (vertically) down south side of spur.
4. 173I, Enriched iron-formation; hematite-goethite (-gibbsite-kaolinite group): chip sample from outcrop, spacing 1–3 m, obliquely across 45 m of beds.
5. 106G, Enriched iron-formation, slightly magnetic; hematite-gibbsite (-goethite-magnetite-botryoidal manganese oxide): chip sample from outcrop, spacing 1–5 m, for 260 m along crest of spur.
6. 143A, Enriched iron-formation, slightly magnetic; hematite-goethite-gibbsite (-magnetite): chip sample from outcrop and boulders, spacing 1–3 m, for 160 m along crest of ridge.
7. 107J, Enriched iron-formation, strongly magnetic; hematite-goethite-magnetite (-gibbsite-kaolinite group-botryoidal manganese oxide): chip sample from outcrop, spacing 0.6 m, across 8 m of beds; on north side of notch on crest of ridge 40 m north of summit of Mount Balagizi.
8. 136D, Enriched silicate iron-formation, derived from garnet phyllite; hematite-goethite-gibbsite (-kaolinite group): grab sample from boulder.
9. K1, "Canga fragments from shallow pit near stream crossing in field No. 2, west of Kpandemai Mountains [Wologizi Range]. Thoroughly leached and recemented iron formation."
10. K11, "Chip sample across 33 feet of vertical beds in middle of west face of Wutivi Peak [Mount Wuteve], 350 feet below summit. Higher grade than average iron formation, leached and secondarily enriched."

bedding have proved that this ore passes, along the steeply dipping bedding, into weathered itabirite within a maximum distance of 60 m; such ore does not represent bedded high-grade ore analogous to the blue ore of the Nimba Range (Beyer, 1959; Berge, 1966b). Between the hard enriched iron-formation on the crest and the nearest lower outcrop and float blocks of weathered itabirite, there generally is an unexposed zone littered with blocks of hard enriched iron-formation; this zone probably is underlain by soft friable enriched iron-formation analogous to Thienhaus' (1963) zone 2.

Elsewhere along the crests of spurs and ridges the high-grade ore is a porous cemented crust, or canga, consisting of disoriented fragments of enriched iron-formation cemented by goethite and hematite. There, the high-grade ore is relatively flat topped and is bounded by low (4–7 m) cliffs which mark the eroding edges of the canga sheet. In a few places the crust is undercut, and the canga sheet can be seen to lie directly on friable enriched iron-formation of zone 2.

SHEETS OF CANGA ON SLOPES

Broader sheets of high-grade ore are found on broader spurs and slopes at lower elevations than the ore just described. This ore is the canga type, and it commonly is bounded laterally by low cliffs which mark the edges of the sheet of canga. It may be continuous upslope with a narrow strip of high-grade capping on the sharper part of a spur; downslope, it becomes discontinuous or is broken up, and large blocks of canga and of enriched and weathered itabirite float in a red clay-rich soil. The sheet of canga is missing on steep slopes.

This ore overlies itabirite, silicate iron-formation, schist, amphibolite, serpentinized dunite, and even granitic gneiss. Ore overlying dunite may be derived wholly or partly from the dunite, but ore overlying other low-iron-content rocks is always found downhill from itabirite or silicate iron-formation. Evidently, creep was an important factor governing the position of the downslope edge of the ore. Similar canga at the Bomi Hills mine (Newhouse and others, 1945, p. 70), the Mano River mine (White and Baker, 1968, p. 63), and the Nimba mine (Beyer, 1959, p. 57) also overlies a diversity of rock types downslope from iron-formation as a result of creep. In at least one place in Liberia, exploration geologists mistook tilted blocks of enriched iron-formation, in colluvium, for outcrops of bedded high-grade ore and were disappointed when their borings penetrated granitic rock at shallow depth. Creep must be considered in evaluating iron-ore prospects in Liberia.

The ore potential of the mapped high-grade areas, including both the high cappings and the lower sheets, aggregates 18 million metric tons per meter of depth (calculated for a measured surface area of 5.3 sq km, using an assumed density of 3.5 tons/m^3); half of this amount is in the three largest bodies. The maximum observed thickness of enriched crust is 9 m and the proportion of diluents is noticeably greater at the base of the crust than at the top. The crust may be underlain by soft friable enriched iron-formation of moderately high grade, but, even so, the total thickness of high-grade ore (zones 1 and 2) probably does not exceed a few tens of meters, except locally. If the high-grade ore is 10 m thick, the largest mapped body (5 km north-northeast of Mount Wuteve) may contain 30 million tons of ore.

Several chip samples of enriched iron-formation and of canga overlying itabirite indicate iron contents of 54 to 61 percent, with relatively high aluminum, phosphorus, and water contents (table 6, Nos. 1–7, 10). A specimen of lateritic ore derived from garnet-bearing phyllitic silicate iron-formation has a somewhat lower iron content and a markedly higher aluminum content (table 6, No. 8). X-ray diffraction analysis shows it to contain more than 20 percent of gibbsite. The aluminum contents of all of the analyzed samples correlate closely with the content of gibbsite as estimated by the intensity of the 4.85-A diffraction peak. Selected analyses of lateritic iron ores from other areas of Liberia and from Sierra Leone show a comparable range of iron, aluminum, phosphorus, and water (table 5, Nos.

1, 3, 4, 6). Aluminum and phosphorous are considerably less abundant in unweathered iron-formation (tables 2, 3) than they are in lateritic ore, indicating that they, together with iron, are enriched during formation of lateritic iron ore.

Low aluminum, phosphorus, and water and high iron in the bedded high-grade blue hematite (martite) ore in the Nimba Range (table 5, No. 2) suggest that it is not a typical lateritic ore. Indeed, a lateritic process is considered inadequate to explain the origin of the blue ore at Nimba, which extends to depths as great as 600 m (Berge, 1966b, p. 42). Sample 107J (table 6, No. 7) was the only ore found in the Wologizi Range that resembles the blue ore in the Nimba Range. This ore superficially resembles the other enriched iron-formations but differs in its rather high content of relict magnetite, higher iron, and lower aluminum and combined water. It forms an extremely sharp ridge bounded by near-vertical dip slopes. (See Mount Balagizi in fig. 2.) The 8-m section that was sampled was the only one accessible without the use of a rope or other aid. Although the ore strikes nearly parallel to the ridge, it does not seem to extend very far north of the sampling site along the ridge. Nevertheless, it merits closer examination to determine whether it is a bedded high-grade ore rather than a surficial one.

Spectrographic analyses of the high-grade ores are also reported (table 7). The minor elements are similar in variety and amount to those of the primary iron-formations (tables 2, 4). A tendency is apparent for cobalt, chromium, scandium, titanium, and vanadium to be enriched and for lead, nickel, potassium, and sodium to be essentially unchanged relative to unweathered iron-formation. But, because only a few layers were sampled and the spectrographic analyses are only semiquantitative, these trends cannot be regarded as firmly established.

TABLE 7. — *Semiquantitative spectrographic analyses of hard lateritic iron ores from the Wologizi Range*

[Analysts: W. B. Crandell (analyses 1–3, 5–7) and J. L. Harris (analyses 4,8). Sample numbers and descriptions same as in table 6. Values are reported in weight-percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, and so forth, which represent approximate midpoints of interval data on a geometric scale. The assigned interval for semiquantitative results will include the quantitative value about 30 percent of the time. Also looked for but not found: Ag, As, Au, B, Be, Bi, Cd, Ce, Eu, Ge, Hf, Hg, In, La, Li, Nb, Pd, Pt, Re, Sb, Sn, Sr, Ta, Te, Th, Tl, U, W, Y, Yb, Zn. *, indicates high Fe interference, Mo if present <0.001]

Analysis No. ______ Sample __________	1 (90E)	2 (103J)	3 (101C)	4 (173I)	5 (106G)	6 (143A)	7 (107J)	8 (136D)
Ba	0	0.0007	0.015	0.0003	0.015	0.002	0.001	0.0003
Co	0	.0005	0	0	.0003	.0003	.0003	.001
Cr	.005	.015	.003	.01	.002	.003	.002	.05
Cu	.001	.003	.0015	.005	.001	.0007	.0003	.01
Ga	0	0	0	.001	0	0	0	.002
Mo	*	*	*	.002	*	*	*	.002
Ni	0	.01	.0015	<.001	.001	.001	.003	<.001
Pb	.005	.001	.002	0	.0007	.0015	.0005	0
Sc	.0007	.001	.0005	0	.0005	.0005	0	.003
V	.002	.001	.0015	.0015	.0015	.001	.0005	.007
Zr	0	0	0	.02	0	0	0	.02

CRUST ON CONGLOMERATE PLAIN

The surface of the conglomerate plain west of the Wologizi Range has been so weathered and enriched in iron as to constitute a moderately high grade deposit. (See also Newhouse and others, 1945, p. 98.) The ore is a canga crust similar to that on the western slopes of the range, except that it is developed from alluvium which includes detritus other than iron-formation, rather than from colluvium made up dominantly of iron-formation. In a few places the canga sheets on the lower slopes of the range reach the conglomerate plain, and the canga derived from colluvium grades into, and is difficult to distinguish from, that derived from alluvium.

The canga crust on the conglomerate is thin, and none exceeding 2 m in thickness was seen. The crust grades downward through enriched conglomerate cemented by goethite and hematite into conglomerate which is less well cemented. The maximum observed thickness of the enriched zone is 4 m, and that of the conglomerate is 15 m. Conceivably, both may be thicker locally, but they probably do not exceed a few tens of meters. The crust is much less well developed or preserved on the small fans of conglomerate east of the range.

The conglomerate covers more than 100 sq km west of the Wologizi Range. The lateritic crust is not everywhere developed or preserved, however, and was not separately mapped in this study. If 10 percent of the area of conglomerate is mineralized, the ore potential of the conglomerate plain is about 30 million metric tons per meter of depth (assuming a mineralized area of 10 sq km and a density of 3.0 tons/m^3). A single analysis of this material is available (table 6, No. 9). Canga in the Upper Grassfield area at the western foot of the Nimba Range is in a similar topographic position, has a similar parent, and has a comparable iron content (table 5, No. 5). Both cited analyses show a relatively low iron content (approximately 52 percent) and a high alumina content (to 10 percent) compared to other lateritic ores in the respective areas. These differences probably are due to the mixed (though itabirite-rich) composition of the parent materials and, possibly, to a slightly different weathering and enrichment process governed by different topography, permeability, and groundwater composition and movement.

FORMATION AND AGE OF THE HIGH-GRADE CRUST

Prolonged weathering and protection from erosion are essential features of the past history of lateritic iron deposits observed today. Ancient weathering is thought to be more important than any modern weathering (Thienhaus, 1963, p. 1092).

The high-grade lateritic crust described herein is found over a vertical range of more than 600 m (determined by numerous altimeter readings); a complete gradation is visible, from enriched iron-formation at highest elevation, through canga derived from iron-formation colluvium, to canga derived from iron-formation alluvium at lowest elevation. The crust is lacking on the relatively flat (though narrow) crest of the ridge (about 1,300 m in elevation) near Mount Wuteve, but otherwise the actual elevation does not seem to be an important factor governing its distribution. Some of the high-grade crust caps relatively flat-topped, gently plunging spurs, but there is no general accordance of level from one spur to another. Other sheets of lateritic crust differ in elevation from place to place along a given spur. Indeed, the largest of the mapped sheets of high-grade crust is stratigraphically continuous over a vertical distance of about 400 m on a uniform slope averaging 15°. No evidence was seen for any single level or series of erosion levels such as have been advocated in the Nimba Range (Beyer, 1959, p. 82–85; Berge, 1966b, p. 41) and elsewhere in Liberia (Offerberg and Tremaine, 1961, p. 43; Knopf, 1964, p. 63).

Instead, the lateritic crust provides every indication of having formed at various elevations, controlled only by suitable parent material (iron-rich bedrock, colluvium, or alluvium), position on or downhill from iron-formation, and the local slope of the ground (no more than about 15°). The vertical distribution of the lateritic crust on the present mature topography of the Wologizi Range precludes any hypothesis of formation on a peneplain. There is no reason — other than a tendency in the geologic literature of West Africa to equate all high-level lateritic crust with peneplain remnants, thereby requiring for each "level" a different age — to suspect that the crust could not have formed at the various elevations almost simultaneously.

The age of the lateritic crust is not well known. Near the coast of Liberia, wackes of Early Cretaceous age have well-developed lateritic weathering profiles, but the lateritic soils are overlain by sparsely weathered unconsolidated sands of presumed Quaternary age (White, 1969). This implies a post-Early Cretaceous, pre-Quaternary age for much of the weathering. Elsewhere in Africa, lateritic weathering profiles of various ages from Cretaceous to late Tertiary have been recognized (Dixey, 1955). Weathering profiles cannot be definitely correlated, but a Tertiary age seems probable for the lateritic crust in the area of the Wologizi Range.

OTHER LATERITIC DEPOSITS

Small amounts of botryoidal manganese oxide are found locally in cavities in the high-grade iron ores. (For example, see table 6, No. 5.) The largest specimen seen was a loose slab 5 cm thick, found on the west side of Mount Wuteve, 150 m below the summit. Manganese-rich silicate minerals should be easy to recognize in weathered rock because of the black oxide stain which typically forms on the surface, but none were seen in the area of the Wologizi Range. The garnet in the iron-formation is thought to be almandine with no more than the normal amount of spessartine component. Probably the manganese is a minor component of all the iron-silicate minerals and is concentrated by weathering.

Comparison of the average manganese content in unweathered iron-formation (table 2) and in lateritic ore derived from iron-formation (table 6) suggests that manganese is depleted, rather than enriched, during formation of lateritic iron ore. Consequently, the observed concentrations of manganese oxide are attributed to the separation of iron and manganese during lateritic weathering of minerals containing ferrous and manganous ions (iron-silicate minerals). As is well known, ferrous iron is readily oxidized to the relatively insoluble ferric state during lateritic weathering; in contrast, manganese remains in the relatively soluble manganous state unless it meets strong oxidizing conditions, whereupon it precipitates relatively free of iron. The botryoidal manganese oxide observed sparingly in the lateritic iron ores probably is to be found only near the surface.

Cobble-size pieces of bauxite float are found in a few widely scattered localities in the granitic terrane surrounding the Wologizi Range. Most commonly, these are seen on broad drainage divides or hilltops on which bedrock outcrops are few. Fragments of sparsely weathered granitic rock and of vein quartz, which occur nearly everywhere in those same soils, indicate that weathered bedrock is at a shallow depth and that the potential for economic bauxite deposits is slight.

ALLUVIAL SAMPLING

Panned concentrates of heavy minerals in stream gravels were collected routinely during this study as a means of prospecting. S. P. Srivastava, of the Liberian Geological Survey, mineralogically examined 140 such samples from the mapped area, including some collected by A. E. N. Jones and W. E. Stewart during their studies of adjacent areas.

ALLUVIAL GOLD

Small amounts of fine-grained gold were found in the gravels of several streams draining the Wologizi Range (pl. 1). The richest gravel found (from a small stream 3 km south of Bitiba) contained about 25 flakes in a sample of about 25 kg (kilograms) from a depth of less than 1 m. Gold-bearing gravels on other streams are found at comparable depth, but, commonly, they contain only a few flakes of gold in a sample of that size.

Evidence of former placer mining for gold, said to date from various times including 1937, 1947, and 1954, was seen on Babo and Magua Creeks. (See also Sherman, 1947, p. 24.) According to G. K. Massaquoi (oral commun., 1967), P. F. de Groot of the Holland Syndicate discovered a fairly good placer prospect containing some coarse-grained gold on a small swampy tributary of Maaso Creek; the source of the gold was thought to be a quartz vein found in granitic rock in or near the swamp. During the present study, a 1-day search failed to relocate the locality. Large boulders of vein quartz were found in the upper parts of the north forks of Windia and Ziaki Creeks, but no gold was found in either creek.

Several of the gold-bearing gravels are from streams flowing within the alluvial plains of conglomerate. The possiblity that gold is present in the conglomerate, as well as in the Holocene stream gravels, was not evaluated during the present study. Because of the large volume of material, the conglomerates seem a much better prospecting target for alluvial gold than the

Holocene stream gravels. Yet, Sherman (1947, p. 24) considered the entire area to have little potential for gold placer operations.

TANTALITE

Coarse tantalite has been reported in two panned concentrates from streams 6 km east and 4 km north-northeast of Kpademai, collected in 1949 by G. K. Massaquoi (T. P. Thayer, written commun., 1950). That reported find did not come to light until after the present fieldwork had been completed, and the locality has not been resampled. The two localities are indicated on plate 1 according to G. K. Massaquoi's later descriptions (oral commun., 1967).

CHROMITE

Chromite has been identified in several heavy-mineral samples from the Wologizi Range (Leo and Holmes, 1967; S. P. Srivastava, written commun., 1967), most of which were collected downstream from known ultramafic bodies. Two of the samples are from the area between Wobanyamai and Babo Creek where no ultramafic bodies are known. Such bodies no doubt exist there but were missed during mapping, owing to widely spaced traverses and poor exposures. None of the detrital chromite is in large fragments, which would suggest chromitite layers, and only disseminated chromite was seen in situ.

IRON MINERALS

Magnetite dominates in the heavy-mineral suite of those streams draining the Wologizi Range, but it and garnet decrease abruptly away from the range. Within the granitic terrane, magnetite generally is found only in the modern bed gravels that are characterized by limonite-stained quartz. The quartz in gravels that are buried more than about half a meter generally is clean of limonite stains; magnetite is much less abundant in buried gravels than in the bed gravels. Apparently, the magnetite is unstable in the buried gravels and is destroyed by intrastratal solution.

Siderite was identified by S. P. Srivastava (oral commun., 1967) in heavy-mineral samples from three streams crossing that part of the conglomerate plain upon which Kpademai is situated. The mineral forms elongate doubly terminated crystals, which are extremely unlikely to be relics that have survived weathering and erosion of iron-formation. The siderite probably has formed as a diagenetic mineral in the conglomerate.

ZIRCON, MONAZITE, AND OTHER HEAVY MINERALS

Zircon and ilmenite are the predominant heavy minerals in stream gravels in the granitic terrane near the Wologizi Range. Monazite and rutile, in lesser amounts, are widespread, whereas xenotime is of more restricted occurrence. Cassiterite and wolframite are lacking.

Monazite is a predominant constituent of the detrital heavy-mineral suite in an area north of the road between Voinjama and Kolahun, north of the area shown on plate 1 (S. P. Srivastava and Samuel Rosenblum, unpub.

data, 1970). Monazite, together with magnetite, ilmenite, zircon, and rutile, is an accessory constituent of the granitic rocks in that area; no evidence of any vein deposits of monazite was found.

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