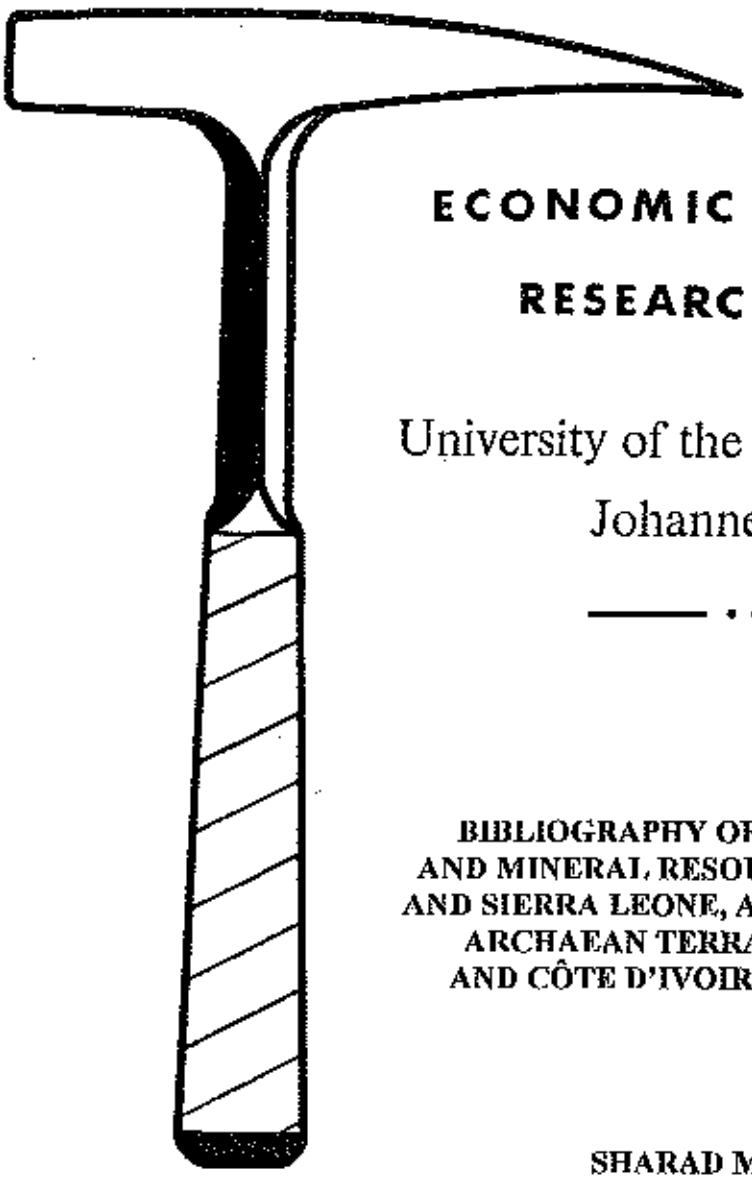

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BIBLIOGRAPHY OF THE GEOLOGY AND MINERAL RESOURCES OF LIBERIA AND SIERRA LEONE, AND THE ADJACENT ARCHAEAN TERRAINS OFGUINEA AND CÔTE D'IVOIRE, WEST AFRICA

SHARAD MASTER

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by

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INTRODUCTION

Liberia and Sierra Leone are two West African countries that have been devastated by recent civil wars. Both countries are situated on the Archaean Man or Liberian craton, which is rich in minerals, such as gold, diamonds and iron ore. Ironically, it is this very mineral wealth, especially the diamonds, that has fuelled the civil wars, and has led to call for a boycott of West African diamonds (Doyle 1999a,b,c, 2000; Global Witness, 1999; Standley, 1999). More recently, the new unity government of Sierra Leone has suspended all licenses and has called for the cessation of all diamond mining activities, until they can be brought under the control of the central government, for the benefit of the whole country (Doyle, 2000b).

This bibliography has its origins in an initiative started in 1997 by Prof. M. J. Viljoen of the Geology Department at the University of the Witwatersrand to synthesise the geology, geophysics and mineral resources of the Republic of Liberia (Master, 1997a,b). Because relatively little research has been done on the geology of Liberia, in comparison to the surrounding countries (especially Sierra Leone), it was decided to include in the comprehensive bibliography details about the geology and mineral resources of Sierra Leone, as well as the adjacent regions of Guinea and Côte d'Ivoire (formerly the Ivory Coast) that border on Liberia. Thus this bibliography is the most complete bibliography to date on the entire geology and mineral resources of Liberia and Sierra Leone, as well as on the Archaean Man Craton, which extends into the adjacent regions of southeastern Guinea and western Côte d'Ivoire.

Structure of the bibliography

The bibliography has been structured in two main ways:

1. by country (Liberia, the Ivory Coast, Guinea, Sierra Leone); and
2. according to the following topics (for Liberia and Sierra Leone):

    a. General
    b. Archaean
    c. Palaeoproterozoic
    d. Pan-African & Palaeozoic
    e. Mesozoic
    f. Cenozoic

Under the heading General are placed items such as books and articles dealing with the whole country, geological, geophysical and topographic maps of the country, etc.

Reference sources

The compilation of this bibliography entailed a search through many different sources of information. Initially, a word search was conducted on "Liberia", "Sierra Leone", "Guinée", "Côte d'Ivoire", etc., on the online Wits University Library Catalogue. This search threw up many general works, as well as maps and Geological Survey publications, and country bibliographies. Books such as Von Gnielinski's "Liberia in Maps" and Clarke's "Sierra Leone in Maps" proved particularly useful. Search for geological literature was initiated by looking in well-known textbooks such as Cahen et al. (1984) and Bessoles (1974). The references listed in the U.S. Geol. Surv. Geological Map Series on Liberia were compiled, and those references published in the mainstream literature were obtained from the Earth Sciences Library at the University of the Witwatersrand, and from the Bernhard

Kummel and Widener libraries at Harvard University. Further searches were made in the bibliographies of these published papers. By going back in this way, and relying on published papers which were available in the libraries, a fairly comprehensive list was made of all published literature on the subject, as well as of many unpublished reports and theses. For the more recent literature, a search was made, using keywords, on the Science Citation Index (available on CD-ROM), as well as the on-line Geological database GeoRef©, which was queried via the Internet. Many references to unpublished Liberian Geological Survey reports were obtained from a bibliography acquired from the Liberian Geological Survey in Monrovia. References to unpublished reports concerning the Mount Nimba iron ore deposits in Guinea were obtained from Ward (1999) and from Kobus Olivier (Billiton).

How to use the bibliography

Since the bibliography is structured according to country and time slices, one needs to know the broad age of the geological entity one is researching, or the age of a mineral deposit or its host rocks. If the age of, say, a mineral deposit is unknown, then a quick search through all references can lead one to the correct reference. A researcher interested in a particular time frame can immediately turn to the relevant section, and find related references placed together. Mineral deposits are placed in the category of the geological time unit when the deposits were formed, or the age of the sequences which host the deposits (e.g. lode gold deposits will come under Archaean and Palaeoproterozoic, while alluvial gold deposits will be listed under Cenozoic). References dealing with kimberlite pipes and their mantle nodules are found under Mesozoic, while alluvial diamond deposits will be found listed under Cenozoic. Iron ore deposits are listed under Archaean. Oil and gas deposits, as well as heavy mineral sands are listed under Cenozoic.

Bibliographic overview of the geology and mineral resources of Liberia and Sierra Leone, and of adjacent parts of Guinea and Côte d'Ivoire

The coastline of West Africa has been described since the mid-15th Century, when the first Portuguese navigators reached, and named, Sierra Leone (as Serra Leoa) in 1460 (Kup, 1961). Early descriptions of the coastline, islands and estuaries of the Sierra Leone coast were given by Alvares (1616) and Smith (1744). Little was known about the interior of Sierra Leone and Liberia until the second half of the 19th Century, when the first accounts of the geology and mineral wealth of these regions started appearing (Tracy, 1855; Bowen, 1857; Davies, 1887; Gurich, 1887; Büttikofer, 1890; Anon, 1893; Raisin, 1893; Murray et al., 1895). With the advent of colonial rule in the late 19th Century, Sierra Leone became a British protectorate, while Guinea and Côte d'Ivoire became part of French West Africa (Afrique Ouest Française). These countries became independent from 1958 to 1961, whereas Liberia had already gained its independence by 1847. In Sierra Leone, systematic mapping started with the work of Dixey (1925) and Junner (1930a), and was completed by 1963. In the Archaean regions of Guinea and Côte d'Ivoire, mapping started with the work of Chevalier (1909, 1910), Lacroix (1910, 1911) and Azema (1914a,b), and the geological maps were published from the 1930's through to the 1970's (Obermuller, 1938, 1941a,b; Bolgarsky, 1948, 1950; Bolgarsky & Obermuller, 1948; Tagini, 1965, 1971; Papon, 1973). In Liberia, systematic mapping was done by the U.S. Geological Survey in collaboration with the Liberian Geological Survey, during the period 1969 to 1973.

Although relatively little research has been done on the geology of Liberia, the country has nevertheless been completely mapped geologically on a scale of 1:250,000. The 1:250,000 map series covers the whole of Liberia in 10 quadrangles (U.G. Geological Survey & Liberian Geological Survey, 1973a-j). Each quadrangle has 4 map sheets: a Geographic Map, a Geological Map, an Aeromagnetic Map, and a Total-Count Gamma Radiation Map (Behrendt & Wotorson, 1974a-s). Some areas, such as the Monrovia Quadrangle, also have a Gravity Map at the same scale. There are many accounts of the general geology of Liberia (Anon, 1893; Terpstra, 1937; Mikhaylov, 1969; White & Leo, 1969, 1970; Jones, 1972a; Jones & Stewart, 1972; Anon, 1983; Liberian Geological Survey, 1983; Tysdal & Thorman, 1983; Shannon, 1985; Tysdal, 1988). There are also numerous accounts of the mineral resources of Liberia (Anon, 1947, 1968a, 1971, 1983; Hanson, 1947; Sherman, 1947, 1951; Srivastava, 1961; Obermuller, 1962; Denton, 1963; Durazzo & Gordon, 1967; Goudarzi, 1967; Jones,

1967, 1972b; Mikhaylov, 1969; van Griethuysen, 1970; Stipp, 1974; Richardson, 1980; Shannon & Sangmor, 1982, 1983; Shannon, 1985; Wright et al., 1985; Dorbor, 1986; Kornhauser, 1986; Viljoen, 1997a)

Sierra Leone has been completely mapped geologically on a scale of 1:50,000, published as a set of 133 geological maps by the Directorate of Overseas Geological Surveys (1963). This data had been compiled earlier as a 1:1 million map (Directorate of Overseas Geological Surveys (1960). Accounts of the general geology of Sierra Leone are given by Dixey (1925), Junner (1930a), Bolgarsky (1947), Pollet (1951), Andrews-Jones (1971), Hawkes (1972), Morel (1976, 1979), and Anon (1998). The mineral resources of Sierra Leone have been described by Junner (1930a), Bolgarsky (1947), Pollet (1937, 1951), van der Laan (1965), Hall (1968, 1973), Punna (1972), Morel (1976, 1979), Cleeve (1997) and Anon (1998).

Geologically, the oldest parts of Liberia and Sierra Leone consist mainly of an amphibolite to granulite-grade Archaean terrain, which is part of the Man Craton (also known as the Liberian or Leo Craton). The Archaean terrain consists of granitic gneisses and granites, together with mainly metasedimentary supracrustal sequences containing schists, quartzites, and important iron formations (Obermuller, 1941a,b; Rollinson, 1978, Macfarlane et al., 1981; Camil, 1984). In Sierra Leone, lower grade "greenstone belts" are found juxtaposed with granulites (Rollinson, 1982). Whole-rock Rb-Sr dating of Archaean rocks in Liberia by Hurley and his co-workers at M.I.T. from 1968 to 1971 showed ages in the range 2600 to 2700 Ma. Rocks of this age were referred as being part of the "Liberian age province". More recent work has been done on granulites from western Côte d'Ivoire by Camil and co-workers from 1982 to 1984. Camil and Tempier (1982) showed that hypersthene-bearing granulites had a metamorphic age of 2850 Ma. Camil et al. (1983) showed that magnetite quartzites had undergone the same granulite facies metamorphism as the hypersthene granulites. Camil et al. (1984) dated an intrusive charnockite containing enclaves of quartzites at 2782 ±15 Ma, thus proving the Liberian age of the quartzites.

The Archaean rocks of the Man craton host important iron ore deposits, including the world-class Nimba deposits of Liberia, which extend into Guinea and also into Côte d'Ivoire. In Sierra Leone, the Marampa iron ore deposits have been exploited since the 1930's (Anon, 1936, 1961, 1967, 1968, 1970; Fowler-Nunn, 1933a,b; Edwards, 1940; Pedler, 1955; MacFarlane et al., 1981; Neubauer, 1982). The iron ores of Liberia have been known historically since at least the mid-19th Century (Tracy, 1855; Bowen, 1857). A large number of reports exist on the ore processing, metallurgy, mining and economics of the iron deposits of the Nimba range (Anon 1953a-1994). A number of papers have been published on the iron deposits, mainly by J.W. Berge (1966-1974). Many other papers are listed in the section: Liberia - Iron Ore Processing and Metallurgy, Mining, and Economics. The company Mifergui and its joint venture partners have done the most work on the Nimba iron ore deposits in Guinea (Anon, 1967-1998; Richaud, 1971; Tractionel, 1970, 1971; Kaiser, 1978; BRGM, 1987-1996; Billiton, 1991-1996). Iron ores have also been worked in western Côte d'Ivoire (Anon, 1971, 1973; Caibor, 1974). Most of the primary gold deposits in Liberia are also hosted by Archaean rocks. Although there are no hard-rock Au mines, there seems to be a spatial relationship of Au deposits to areas of major iron formations. There appears to be almost no published information concerning Liberian gold deposits (but see Anon, 1999; Viljoen et al., 2000). In central Liberia, there are deposits of tin and tungsten which are associated with intrusive granites (Anon, 1968b).

In the south-east of Liberia, there is a Palaeoproterozoic terrain, which is an extension of the Baoulé-Mossi Domain of the Birimian of Ivory Coast. The major Ity gold deposit in Ivory Coast (Verhaeghe et al., 1980, 1982) is just across the border from Liberia, and there is potential for similar Au deposits being located on the same major structure in Liberia. There are no Palaeoproterozoic rocks in Sierra Leone.

There is a Pan-African domain, the Rokelide belt, which strikes parallel to the coast, and is mainly developed in Sierra Leone, but extends into NW Liberia (Allen, 1965-1980; Bufeyev, 1972; Thorman, 1972; Culver et al. 1978-1991; Dallmeyer, 1989; Lécorche et al., 1989; Magee & Culver, 1985, 1986; Umeji, 1988; Williams & Culver, 1983, 1988). In this domain, radiometric dating reveals Pan-African ages (c. 500 Ma). Because the dating is mainly in the form of Rb-Sr whole rock ages, it is

uncertain how much of the Pan-African age domain is due to re-working of older crust during the Pan-African, and how much due to juvenile accretion of material during Pan-African orogenesis.

During the Mesozoic breakup of Gondwana, and the rifting that produced the Atlantic Ocean, the Precambrian structures parallel to the Pan-African belts were re-activated (Behrendt et al., 1974; Jones & Mgbatogu, 1977, 1982; Venkatakrishnan & Culver, 1989), and were also intruded by a major dykes swarm which parallels the coastline of Liberia and Sierra Leone (Bowen, 1857; Snelling, 1966; May, 1971; Dalrymple et al., 1975; Mauche, 1985, 1989; Dupuy et al., 1988). In Sierra Leone, the Freetown Complex is a layered gabbroic complex related to this episode of magmatic activity (Gurich, 1887; Shand, 1918; Dixey, 1922; Junner, 1930c; Wells, 1962-1981; Hawkes, 1967; Umeji, 1972-1985; Bowles, 1976-1978; Chalokwu et al., 1994, 1995), and was emplaced during continental breakup (Krause, 1963; Jones et al., 1977-1988; Kharin, 1988; Mgbatogu, 1988, 1990). A gravity survey of the Freetown Complex was done by Baker & Bott (1961), while isotopic studies (Os, Sr, Nd) were done by Hattori et al. (1991-1996). The Freetown Complex has lateritic Platinum Group Element mineralization associated with it (Stumpfl, 1966; Bowles, 1981-1995). Recently, a PGE-bearing horizon, the "Bowles Reef" has been discovered in the Complex (Bowles, 1998).

Diamondiferous kimberlites were intruded into the Man craton in Sierra Leone and Liberia during the Mesozoic. Most of the research on the kimberlites and diamonds of Sierra Leone and Liberia has been done by Prof. Stephen Haggerty and his students at the University of Massachusetts in Amherst, Mass., USA (Haggerty et al., 1979-1990; Bence & Haggerty, 1979; Tompkins, 1982-1985). Additional work on the kimberlites of Sierra Leone was done by Bardet (1963-1974), Stracke (1963), King (1965-1972), Hubbard (1967-1986), Williams and Williams (1976, 1977), Hastings & Sharp (1979), and Brown & Maluti (1980). Haggerty and his students have also studied the mantle xenoliths from these kimberlites (Haggerty, 1983; Haggerty & Tompkins, 1982-1992; Hills, 1988, 1989; Pang, 1994-1995; Barth, 1998-1999), as has Rollinson (1997).

Following the Atlantic rifting, Cenozoic coastal basins were formed onshore and offshore in both Sierra Leone and Liberia (White 1969a,b, 1972a,b; Anthony, 1985-1991). These coastal basins contain oil and gas deposits, as revealed by drilling done in the 1960's and 1970's, during an exploration boom involving up to a dozen mainly American oil companies (Wilson, 1959; Cortesini & Minner, 1973; Paterson & Klemme, 1986; Stewart & Kromah, 1987; Kulke, 1995; Anon, 1996; Hancox & Brandt, 1997; WorldEnergy, 1997). The exploration resulted in a number of seismic surveys (Continental, 1968; Chevron, 1969, 1970; Syracuse, 1969; Union Carbide, 1969, 1970; Frontier, 1970; Mobil, 1970; Crystal, 1971; Idoc, 1971; Ashland, 1972; IFP/CEPN, 1977, 1980; Ministry of Lands and Mines, 1981, 1984; Amoco, 1983, 1984) as well as detailed airborne magnetic mapping of the offshore sedimentary basins. A number of offshore wells were drilled, and sedimentary sections were compiled (Anon, 1996). Information concerning the offshore oil exploration done in the 1970's is mainly unpublished, and will have to be obtained from the various oil companies concerned. The continental shelf off Sierra Leone and Liberia has been well mapped by Behrendt & Wotorson (1969-1972), McMaster et al. (1969-1975), Sheridan et al. (1969), Somers (1969), Egloff (1972), Schlee (1972), Emery et al. (1975), McGrail (1982), Vogel (1982), Jacobi & Hayes (1982), Jones & Mgbatogu (1982), and Blavez & Mascle (1986). The coastal sediments of both Sierra Leone and Liberia have economic concentrations of ilmenite and monazite-bearing heavy mineral sands (Anon, 1957, 1959, 1966, 1967a,b, 1968b,d, 1970, 1995, 1996; Rosenblum, 1969a,b, 1973, 1974; UNDP, 1972b, 1974; Raufuss, 1973; Lismore, 1974; Randle, 1974; Lang, 1975; Davies et al., 1994; Barclay, 1997; Hancox & Brandt, 1999). Silica sand deposits near Monrovia have been described by Rosenblum & Srivastava (1969, 1970) and Sangmor (1976). Both Liberia and Sierra Leone have a number of diamondiferous kimberlite pipes, and numerous alluvial diamond fields, which, together with alluvial gold, have been, and are being, mined on a small-scale by thousands of artisanal workers (Johnston, 1906; Wagner, 1914; Legoux, 1935; Stutzer, 1935; Pollet, 1937; Anon, 1937/38, 1957, 1967c,d, 1968a,c, 1995; Berg, 1938; Gordon, 1945; Fleming, 1957; Burke, 1959; Barber, 1963; Fairbairn, 1965, 1981a,b; van der Laan, 1965; Leoria, 1966a,b, 1967; Lawrence, 1967; Stoft-Cooper, 1967; Hall, 1968, 1973; von Gnielinski, 1969; Applin, 1972; Haggerty, 1979; Binn, 1982; Sangmor & Dehkee, 1982; Thomas et al., 1985; Zack-Williams, 1990). Studies of cosmogenic (implanted) helium in Sierra Leone alluvial diamonds were done by McConville & Reynolds (1987, 1989).

The soils and laterites of Liberia have been described by Reed (1961), Jones (1962), Worral (1965a,b), Broneyev et al. (1971), Odokiy (1971) and von Gnielinski (1972c). Bauxite deposits have been described by Institut (1953), Mason (1979, 1980), and Bortnikov & Barri (1995). Gold nugget development in lateritic soils has been described by Boadi & Norman (1990). The landforms and geomorphology of Liberia have been described by, *inter alia*, Büttikofer (1890), Rancurel (1965), and von Gnielinski (1972b). The soils and laterites of Sierra Leone have been described by Dixey (1920c), Martin (1927, 1930), Doyne (1933, 1937), Tomlinson (1957a,b), Hart (1959, 1963), Hesse (1961a,b, 1963), Stobbs (1963), Geldhof (1965), Schulze (1966), Odell & Dijkerman (1967) and Bowden (1997). The landforms and geomorphology of Sierra Leone have been described by Dixey (1922), Jaeger (1953), Gregory (1961), Grandin & Hayward (1975), Thomas (1980, 1985), Thomas & Thorp (1980, 1985), Anthony (1985, 1990), and Teeuw et al. (1994).

Although no meteorites have been found in Liberia or Sierra Leone, tektites (part of the Ivory Coast tektite strewnfield) have been found in eastern Liberia some 780 km from their source, the Bosumtwi crater in Ghana (Preuss & Meyer von Greyhold, 1968; Preuss, 1969).

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