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Review

# A review of the mineral potential of Liberia

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ABSTRACT

The Republic of Liberia in West Africa is underlain mostly by Precambrian rocks of Archaean (Liberian) age in the west and of Proterozoic (Eburnean) age in the east. By analogy with similar terranes elsewhere in the world, and in West Africa in particular, the geology of Liberia is favourable for the occurrence of deposits of a wide range of metals and industrial minerals, including gold, iron ore, diamonds, base metals, bauxite, manganese, fluorspar, kyanite and phosphate.

Known gold deposits, mostly orogenic in style, occur widely and are commonly associated with north-east-trending regional shear zones. Gold mining commenced at the New Liberty deposit in western Liberia in 2015, while significant gold resources have also been identified at several other sites in both Archaean and Proterozoic terranes. Liberia has large resources of itabirite-type iron ores, most of which are located in the Liberian terrane, and was the largest producer in Africa prior to the onset of civil war in 1989. Production of iron ore is currently restricted to a single mine, Yekepa, in the Nimba Range. Other important deposits, some of them previously mined, include Bong, the Western Cluster, Putu and Goe Fantro. There is a long history of alluvial diamond production in western and central Liberia, together with more than 160 known occurrences of kimberlite. Most of the known kimberlites occur in three clusters of small pipes and abundant dykes, located at Kumgbor, Mano Godua and Weasua, close to the border with Sierra Leone. Many of these are considered to be part of a single province that includes Jurassic age diamondiferous kimberlites in Sierra Leone and Guinea.

Deposits and occurrences of a wide range of other metals and industrial minerals are also known. Several of these have been worked on a small scale in the past, mainly by artisanal miners, but most are poorly known in detail with sub-surface information available at only a few localities. By comparison with most other countries in West Africa, the geology of Liberia is poorly known and there has been very little systematic exploration carried out for most commodities other than gold, iron ore and diamonds since the 1960s and 1970s. Further detailed field and laboratory investigations using modern techniques are required to properly evaluate the potential for the occurrence of economic deposits of many minerals and metals in a variety of geological settings. Digital geological, geochemical, geophysical and mineral occurrence datasets, including new national airborne geophysical survey data, provide a sound basis for the identification of new exploration targets, but in almost every part of the country there is a need for new and more detailed geological surveys to underpin mineral exploration.

## 1. Introduction

The Republic of Liberia is located in West Africa, bordered by Sierra Leone, Guinea, Côte d'Ivoire and to the south-west by the Atlantic Ocean (Fig. 1). With a land area of about 111,000 km$^2$ and a population of nearly 4.1 million, much of Liberia is sparsely populated, comprising rolling plateaux and low mountains away from a narrow flat coastal plain. The highest point in the country is Mount Wutivi in Lofa County with an elevation of about 1400 m. The climate is typically tropical, hot and humid at all times, with most rain falling in the summer months. The country is divided into fifteen counties for administrative purposes.

The mineral industry, in particular iron ore, has long played a crucial role in the nation's economic development. From the early 1960s until the civil crisis of the 1990s the iron ore mining sector contributed more than 20 per cent of the gross national product and employed more than 50,000 people, or approximately 15 per cent of the country's total workforce. The artisanal mining of alluvial gold and diamonds has also made a modest contribution to the national economy

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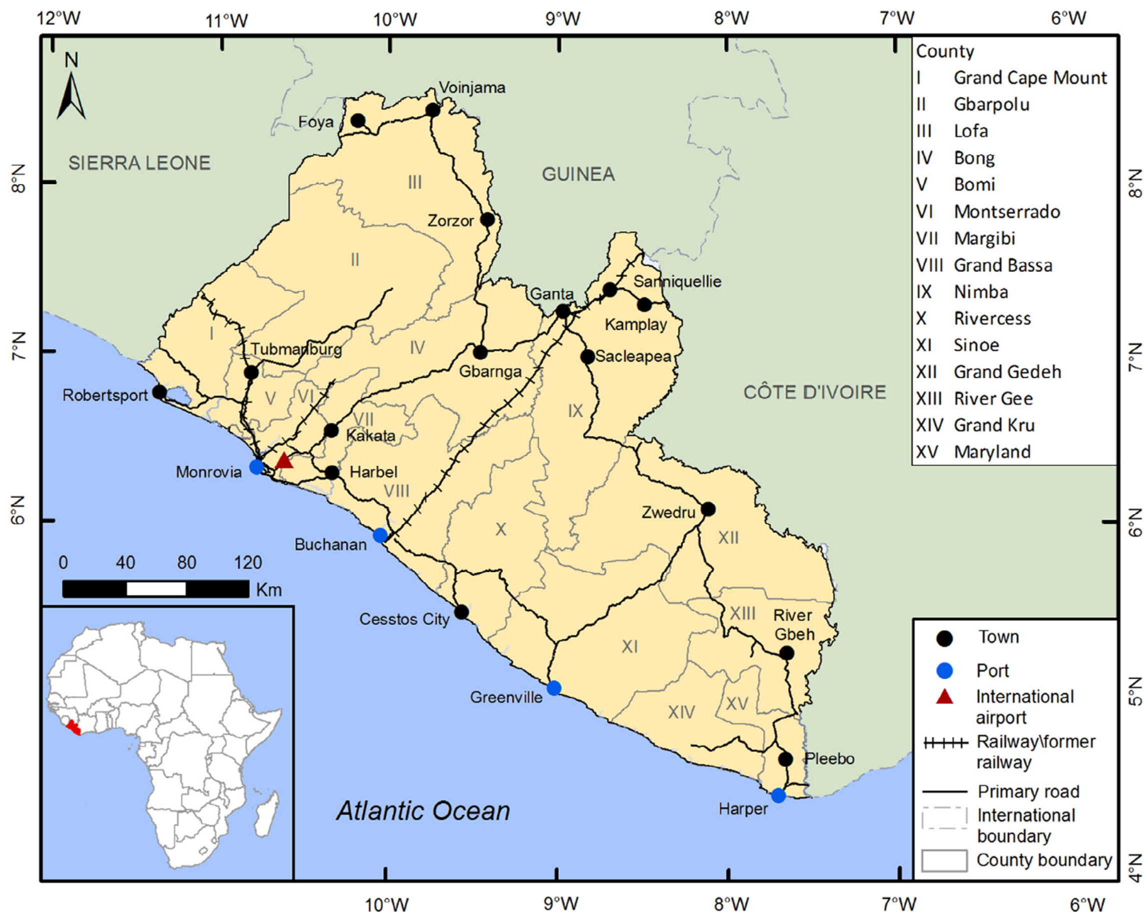


**Fig. 1.** Location of main settlements, counties and transport infrastructure in Liberia.

over a long period.

Following 14 years of war and civil unrest between 1989 and 2003, democratic elections were held in late 2005. The installation of a democratically-elected government, backed by the presence of a United Nations peacekeeping force until mid-2016, served to reinforce investor confidence in Liberia. Since the cessation of hostilities the country has made strenuous efforts to strengthen its mineral and agricultural industries, mostly timber and rubber.

The geological setting of Liberia, within the West African Craton, is prospective for a variety of metallic mineral deposits. Much of the bedrock geology comprises Archaean to Palaeoproterozoic gneisses, with a number of greenstone belts, similar to those with which most of the gold and iron ore deposits in West Africa are associated. In recent years it has been recognised that, besides the country's 'traditional' minerals (iron ore, gold and diamonds), there is significant potential for other minerals. These include barite, heavy mineral beach sands (rutile, zircon, ilmenite and monazite), phosphate, clays, silica sand, copper, zinc and chromite. Nevertheless, with the exception of iron ore and gold, there has been very little systematic modern exploration for most of these materials.

This paper provides the first summary of the mineral resources and mineral potential of this largely under-explored country and shows that the outlook for the minerals industry in Liberia is positive.

## 2. Regional geology of West Africa

The West African Craton comprises Archaean and Palaeoproterozoic rocks underlying about 4.5 million km$^2$ in West Africa (Markwitz et al., 2016). Much of the craton is covered by younger lithological units, but large areas in the north and south of the craton are exposed. The northern part of the craton is known as the Reguibat Shield. The southern portion has been referred to by various alternative names, but recent usage has settled on the Leo-Man Shield (or Leo-Man rise) (de Waele et al., 2015; Rollinson, 2016; Parra-Avila et al., 2016).

The outcrop of the Leo-Man Shield extends more than 1500 km, from Senegal, Guinea, Sierra Leone and Mali in the west to Ghana and Niger in the east. The western part of the Leo-Man Shield (the Kénéma-Man domain) comprises Archaean gneisses, whereas the eastern part (the Baoulé-Mossi domain) is largely Paleoproterozoic in age; the boundary between these two domains is marked by major regional shear zones, which cut across Liberia (Fig. 2).

The Archaean geology of Sierra Leone, Guinea, Côte d'Ivoire and Liberia comprises predominantly migmatitic TTG (tonalite-trondhjemite-granodiorite) gneisses, typical of Archaean cratons globally (Rollinson, 2016). In addition supracrustal sequences of metavolcanic and metasedimentary rocks form linear greenstone belts throughout the region. On the basis of field relationships, the Archaean history of the Kénéma-Man domain was originally considered to comprise two major orogenic cycles, the Leonian and the Liberian, which were only imprecisely dated (Beckinsale et al., 1980; MacFarlane et al., 1981; Feybesse and Milési, 1994). These orogenic cycles were recognised in northern Sierra Leone, on the basis that Leonean folds typically had E-W trends, whereas Liberian folds had more widely varied trends from NNW to NE (MacFarlane et al., 1981). Subsequent work identified older gneisses of c. 3500–3400 Ma in Guinea, and proposed ages for the Leonian at c. 3200–3000 Ma, with the Liberian at c. 2900–2800 Ma (Thiéblemont et al., 2001, 2004). Modern geochronological work has shown that the individual events recognised in restricted field areas cannot be well correlated with zircon age systematics across the whole Kénéma-Man domain, and so the currently accepted model is that the

Kénéma-Man domain formed through development of a Palaeoarchaean core at c. 3540–3460 Ma, followed by near-continuous crustal growth with two main age groupings: c. 3260–3050 Ma and c. 2950–2850 Ma (de Waele et al., 2015; Rollinson, 2016). Gneisses of the two ages cannot be distinguished in the field.

The supracrustal sequences of metavolcanic and metasedimentary rocks within the TTG gneisses of the Kénéma-Man domain contain similar lithologies to the greenstone belts found in other Archaean cratons, but have been metamorphosed to higher grades (amphibolite- to granulite-facies; Rollinson, 2016). Many of these belts include banded iron formation (BIF) layers which represent major mineral resources in Sierra Leone, Liberia and Guinea; they are also important hosts for lode gold mineralisation. Despite their economic importance, very little work has been published on these supracrustal belts (Rollinson, 2016) and their ages are poorly constrained. In Guinea, metasedimentary rocks from the Nimba and Simandou supracrustal belts contain detrital zircons with ages as young as 2615 Ma (Billa et al., 1999; Thiéblemont et al., 2004). In contrast, some of the supracrustal belts in Sierra Leone are cut by a suite of late Archaean granitoids emplaced at about 2800 Ma (Thiéblemont et al., 2004). It is, therefore, evident that there was more than one episode of supracrustal belt formation in the Kénéma-Man domain.

The Archaean rocks of the Kénéma-Man domain are separated from the Palaeoproterozoic Baoulé-Mossi domain to the east and north by major regional shear zones. The Archaean – Palaeoproterozoic boundary has traditionally been considered as represented by the Sassandra fault zone and the Mount Trou fault in western and southwestern Côte d'Ivoire (Cahen et al., 1984). Hurley et al. (1971) showed the boundary in Liberia as an extension of the Mount Trou fault running north-east from a point north-west of Greenville. However, more recent work outside Liberia has shown that the boundary is marked by a zone in which the Archaean rocks have been extensively deformed and reworked during the Eburnean, with intrusion of Eburnean granitoids (Feybesse and Milési, 1994; Kouamelan et al., 1997; Egal et al., 2002; Eglinger et al., 2017). The mapping of Feybesse and Milési (1994) shows this complex zone in Liberia extending over a width of up to 200 km lying between the Cestos Fault Zone and the Dube Fault (Fig. 2).

The Baoulé-Mossi domain comprises large sedimentary basins and volcanic belts, together referred to as the Birimian, that were affected by the Eburnean orogeny (2150–1800 Ma) giving rise to regional greenschist facies metamorphism (John et al., 1999; Debat et al., 2003). These were subsequently intruded by several generations of voluminous Eburnean granitoids, which evolved over time from more calc-alkaline to potassic post-collisional types, and which occupy as much as 70 per cent of the Birimian terrane. The Birimian volcano-sedimentary belts have been dated between c. 2250 and 2100 Ma (Feybesse et al., 2006; Parra-Avila et al., 2016), and the granitoids were emplaced between c. 2200 and 2070 Ma (Baratoux et al., 2011; Tapsoba et al., 2013; Eglinger et al., 2017). These granitoids have widely variable isotopic compositions, reflecting varied crust and mantle sources (Eglinger et al., 2017). The Baoulé-Mossi domain is highly mineralised, most notably for gold (Markwitz et al., 2016; Goldfarb et al., 2017).

Along its western margin the West African Craton is bordered by a series of belts that have typically been considered to be Neoproterozoic in age (Pan African, 650–500 Ma), extending from the Mauritanides in the north, to the Bassarides in Senegal and the Rokelides in Guinea, Sierra Leone and Liberia in the south. Recent dating shows that Palaeoproterozoic protoliths are present in the Rokelides, but they have been affected by metamorphism and magmatism of Neoproterozoic age (de Waele et al., 2015; Villeneuve et al., 2015). A major, crustal-scale shear zone separates these belts from the Archaean Kénéma-Man Domain (de Waele et al., 2015).

The southern part of the craton is intruded by basaltic dykes and sills of late Triassic age (c. 200 Ma) which are part of the Central Atlantic Magmatic Province (CAMP) that was emplaced during the early stages of the break-up of the Pangea supercontinent and subsequent opening of the Atlantic Ocean. The CAMP includes the major 200 Ma Freetown Layered Complex in Sierra Leone (Callegaro et al., 2017).

Two periods of kimberlite emplacement are recorded in the Man Shield. A single Neoproterozoic cluster, dated at c. 800 Ma, is known at Weasua in western Liberia, while Jurassic age clusters are found in southern Guinea and eastern Sierra Leone (Skinner et al., 2004). Two additional clusters of uncertain age, although considered likely to be Jurassic, are found in Liberia close to Weasua, at Mano Godua and Kumgbo.

Prolonged periods of erosion led to the formation of a number of large intracratonic and coastal sedimentary basins, the largest of which is the intracratonic Taoudeni Basin which underlies an area of more than 2 million $km^2$ separating the Man Shield from the Reguibat Shield in Mauritania. The basin is filled with Neoproterozoic to Devonian-Carboniferous sedimentary rocks and recent cover sediments. Other major, largely undeformed sedimentary basins include the Bové basin, the Volta basin, the Tindouf basin and the Senegal-Mauritanian coastal basin (Markwitz et al., 2016; Villeneuve, 2005).

### *2.1. Mineral deposits in West Africa*

The West African craton hosts a wide range of mineral deposits, which have recently been comprehensively reviewed by Markwitz et al. (2016). The Archaean rocks of the Kénéma-Man domain are particularly known for BIF-hosted iron ore deposits within the greenstone belts. The largest is the Simandou deposit in south-east Guinea, while other economically important BIF deposits are found in the Mount Nimba Range, which extends from Guinea into Liberia and Côte d'Ivoire, and at Tonkolili in the Sula Mountains of Sierra Leone (Hagemann et al., 2016; Markwitz et al., 2016). These greenstone belts may also host structurally-controlled gold mineralisation, although most gold resources are found in the Baoulé-Mossi domain, which is one of the world's great gold provinces, with both orogenic gold mineralisation and palaeoplacers (Markwitz et al., 2016; Goldfarb et al., 2017). Major orogenic deposits are located in greenstone belts in Ghana, Mali, Senegal, Niger, Burkina Faso and Côte d'Ivoire (Fig. 2). At Ity in Côte d'Ivoire, located about 25 km from the Liberian border, more than 1 million ounces of gold has been produced since 1991 and probable reserves exceed 1.4 million ounces of contained gold (Coffey, 2015). Palaeoplacer deposits are more restricted in their distribution although the Tarkwa area at the southern end of the Ashanti gold belt in Ghana has large resources in deposits of this type. The total gold endowment of the West African province is about 10,000 tonnes, which is comparable with other major Precambrian gold provinces such as the Yilgarn craton of Western Australia and the Canadian Superior province (Goldfarb et al., 2017).

Substantial resources of bauxite are known in West Africa, notably in Guinea, Sierra Leone, Ghana and Mali. In 2015 Guinea was the sixth largest bauxite producer in the world with production of approximately 18.1 million tonnes (BGS, 2017). Manganese mineralisation is widespread across the West African Craton with deposits known in Ghana, Burkina Faso, Côte d'Ivoire, Mali and Togo (Hein and Tshibubudze, 2016). With the exception of Nsuta in Ghana, which has been a major producer for more than 100 years, these deposits are generally poorly known and have not been fully evaluated.

Known base metal deposits in West Africa are few in number and of relatively minor economic importance. However, there are a few notable exceptions (Fig. 2). For example, the massive sulfide zinc deposit at Perkoa in the Palaeoproterozoic Boromo-Goren greenstone belt in Burkina Faso, which entered production in 2013, is the most economically important. Reported reserves at the end of 2016 were 2.5 million tonnes at 15% Zn (Glencore, 2016; Schwartz and Melcher, 2003). Small porphyry copper deposits are present in the Boromo-Goren greenstone belt located in the Gaoua and Goren districts (Schwartz and Melcher, 2003; Le Mignot et al., 2017). Significant disseminated copper

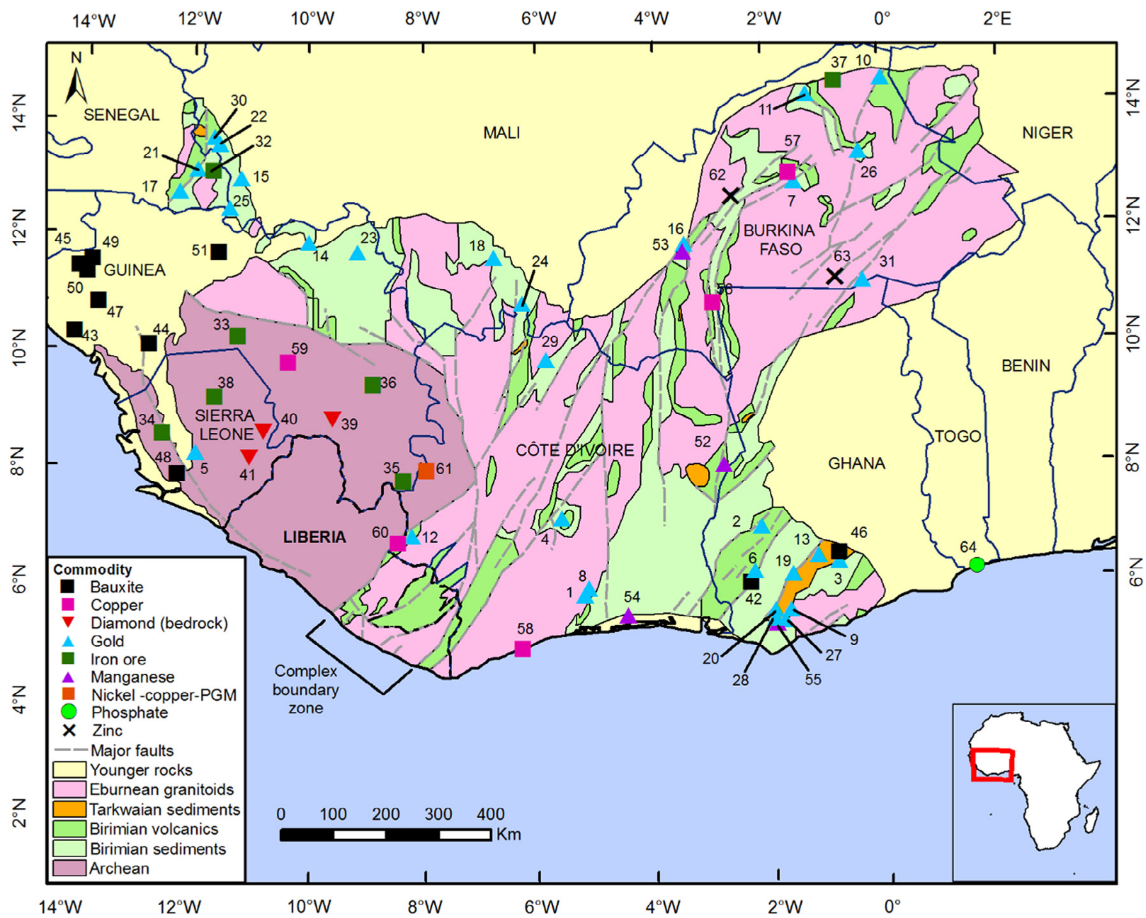


**Fig. 2.** The location of selected major metallic mineral deposits in West Africa. (Note: in south-east Liberia the boundary between the Kénéma-Man domain and the Baoulé-Mossi domain is considered to occupy a broad complex tectonic zone as shown). (1, Agbaou; 2, Ahafo; 3, Akyem; 4, Angovia; 5, Baomahun; 6, Bibiani; 7, Bissa; 8, Bonikro; 9, Damang; 10, Essakane; 11, Inata; 12, Ity; 13, Konongo; 14, Lefa; 15, Loulo-Gounkoto; 16, Mana; 17, Massawa; 18, Morila; 19, Obuasi; 20, Prestea; 21, Sabodala; 22, Sadiola; 23, Siguiri; 24, Syama; 25, Tabakato; 26, Taparko; 27, Tarkwa; 28, Teberebie; 29, Tongon; 30, Yatela; 31, Youga; 32, Falémé; 33, Kalia; 34, Marampa; 35, Nimba; 36, Simandou; 37, Tin Edia; 38, Tonkolili; 39, Baoule; 40, Koidu; 41, Tongo/Tonguma; 42, Awaso; 43, Bel Air; 44, Débélé; 45, Dian-Dian; 46, Ejuanema; 47, Friguia; 48, Gendama; 49, Koumbia; 50, Sangarédi; 51, Tougué; 52, Bondoukou; 53, Kiéré; 54, Lauzoua; 55, Nsuta; 56, Diénémera; 57, Goren; 58, Monogaga; 59, Sadeka; 60, Zéitou; 61, Samapleu/Yepleu; 62, Perkoa; 63, Tiebélé; 64, Kpemé).

occurrences are also known in possible Birimian rocks at Monogaga and Zéitouo in south-west Côte d'Ivoire, the latter located close to the border with Liberia (Schwartz and Melcher, 2003).

A number of nickel–cobalt laterite deposits are known in the vicinity of Sipilou in western Côte d'Ivoire close to the border with Guinea and Liberia (Gouedji et al., 2014). Magmatic nickel-copper-cobalt-PGE-bearing sulfide mineralisation has also been discovered nearby at Samapleu and Yepleu associated with the Palaoproterozoic Yakouba mafic–ultramafic complex which intrudes Archaean basement. The sulfide mineralisation in the Yacouba complex has been compared with the major feeder-type magmatic sulfide deposits at Jinchuan in China, Voisey's Bay in Canada and Kabanga in Tanzania (Gouedji et al., 2014).

Diamonds in West Africa are produced from both primary (bedrock) kimberlite sources, chiefly of Mesozoic age, and from secondary (alluvial) placers in Sierra Leone, Ghana, Guinea and Liberia. Together they account for about 0.9% of global diamond production, which was approximately 127 million carats in 2015 (BGS, 2017). Sierra Leone provides nearly half of the regional total. Most diamond production is derived from small-scale artisanal operations on alluvial placer and palaeoplacer deposits in Tertiary to Recent gravels (Markwitz et al., 2016). In Sierra Leone, the diamond-producing areas are concentrated in the Kono, Kénéma and Bo Districts of eastern Sierra Leone. In Ghana the most important producing area is the Akwatia alluvial diamond field in the upper Birim river in the east of the country (Yelpaala and Ali, 2005).

Deposits of a wide range of other metals and industrial minerals are also found in the region (Milési et al., 1992; Markwitz et al., 2016). These include world-class resources of rutile in fluvial placer deposits in the Rokelide belt of south-west Sierra Leone that have been exploited by Sierra Rutile since the 1960s (Sierra Rutile, 2017; Elsner, 2009). Sedimentary phosphate deposits are found in coastal and intracratonic basins in Togo, Senegal, Guinea-Bissau, Burkina Faso, Niger and Mauritania (Markwitz et al., 2016; Prian, 2014). Alluvial deposits of columbite-tantalite, cassiterite and rutile related to late-orogenic granites of Archaean age are worked on a small scale by artisanal miners in Sierra Leone (Melcher et al., 2017).

## 3. Geology of Liberia

Liberia lies in the centre of the Leo-Man Shield, across the boundary between the Archaean and Paleoproterozoic domains (Fig. 3). The Archaean basement (3260–2850 Ma) extends across central and western Liberia, and is characterised by TTG gneisses, locally migmatitic, which are infolded with supracrustal metavolcanic and metasedimentary rocks and intruded by late-Archaean granitoids dated at c. 2800 Ma (Rollinson, 2016). The supracrustal rocks form discontinuous narrow, elongate greenstone belts which have not been studied in detail. The metamorphic grade is generally amphibolite facies with greenschist facies dominating the greenstone belts (Liberian Geological Survey, 1982).

The boundary between the Archaean and Paleoproterozoic age rocks (Eburnean age province, 2150–1800 Ma) is not well defined in eastern Liberia, but, on the basis of mapping and geophysical data acquired by the LGS and the USGS, it was long considered to lie along the north-east-trending Cestos Shear Zone (Fig. 3). However, recent authors (e.g. Rollinson, 2016; Markwitz et al., 2016; Parra-Avila et al., 2016) have placed this boundary in a different position located further east, following the BRGM SIG Afrique map (BRGM, 2004). Feybesse and Milési (1994) undertook geological and geochronological investigations over the contact zone between the Archaean and Palaeoproterozoic Birimian terranes in West Africa. One of the areas studied was the Toulepleu-Ity area in Liberia and western Côte d'Ivoire, running north-east along the Cestos Shear Zone. Their work demonstrated the complex nature of the boundary in this region with extensive areas of Archaean and reworked Archaean basement located south-east of the Cestos Shear Zone and extending into Côte d'Ivoire. Within this zone a number of elongate, fault-bound tracts of Birimian sedimentary rocks intercalated with mafic volcanic rocks were also identified, together with Eburnean granitoid intrusions. More recently, Eburnean reworking has been recognised at the margins of the Kénéma-Man Domain in this region (Kouamelan et al., in press). The Archaean-Palaeoproterozoic boundary in Liberia is not, therefore, marked by a single fault, rather there is a broad complex boundary zone of folding, faulting and granitoid intrusion located to the east of its position on published geological maps of Liberia (Fig. 2).

Most rocks of the Baoulé-Mossi domain in Liberia, extending west from the Côte d'Ivoire border to Greenville, comprise tightly folded paragneiss, migmatite and amphibolite (Behrendt and Wotorson, 1974; Tysdal, 1975). These rocks have generally been considered to be part of the Birimian sequence (Milési et al., 1992; BRGM, 2004), but they are generally poorly known with little published modern research.

To the south-west of the Archaean basement, the southernmost extension of the NNW-trending Rokelide orogen forms much of Liberia's coastline. This belt comprises metasedimentary and mafic meta-igneous rocks. In Liberia these units are interpreted to be equivalent to the lower Rokelide metamorphic units of Archaean and Palaeoproterozoic age, deformed in the Pan African orogeny at about 550 Ma (Deynoux et al., 2006; De Waele et al., 2015). Phanerozoic rocks in Liberia include: numerous north-west-trending Jurassic-age dolerite dykes extending over much of the south-western part of the country (Wahl, 2007); kimberlites within the Kénéma-Man domain (Haggerty, 1982); and minor Palaeozoic and Cretaceous sandstones and unconsolidated Quaternary deposits (Wahl, 2007).

Multiple phases of deformation are present in the Archaean and Palaeoproterozoic rocks in Liberia. The predominant structural trend in the Archaean Kénéma-Man Domain is north-east to east-north-east (Feybesse and Milési, 1994). Close to the Sierra Leone border, there is very little evidence of Palaeoproterozoic reworking, but evidence of reworking during the Eburnean increases further to the south-east (Kouamelan et al., 1997). In the south-eastern part of the country, in the complex contact zone between the Kénéma-Man and Baoulé-Mossi domains, the most major structures are faults trending north-east which post-date the earliest Eburnean phase of deformation (D1). A number of major north-east-trending faults in this region are extensions of regional structures, which continue into Côte d'Ivoire. These structures include the Cestos, Dugbe, Dube and Juazohn shear zones which are associated with important occurrences of gold, iron ore and base metals over a wide area (see Figs. 2–4). In the elongate north-west-trending coastal zone the most common structural direction for rocks affected by the Pan African orogeny is north-west. The boundary of the Pan African deformation is the north-west-trending Todi Shear Zone, which comprises a series of south-west dipping faults associated with intense zones of mylonite.

## 4. Data sources

A major programme funded by the U.S. Agency for International Development (AID) and the then Liberian Ministry of Lands and Mines was carried out by the United States Geological Survey (USGS) and the Liberian Geological Survey (LGS) between 1965 and 1972. Aeromagnetic and total count gamma radiation surveys were carried out in 1967–68 over the entire country. A total of 140,000 km was flown, mostly along north–south lines, 0.8 km apart on land and 4 km apart over the continental shelf. The flight altitude was 150 m above terrain. Geological and geophysical maps for each of the ten quadrangles covering Liberia were compiled at a scale of 1:250,000 from interpretation of the airborne geophysical data and aerial photos, supplemented by field traverses along the major river courses. Airborne magnetic and radiometric maps and accompanying short descriptive reports were also prepared at that time. Subsequently, in 2007, the geological, geophysical and mineral occurrence data were compiled by the USGS into digital form and released as a series of four national maps at a scale of 1:350,000.

The United Nations Development Program (UNDP) conducted various mineral investigations in Liberia between 1968 and 1972. The programme entitled 'Mineral Survey in the Central and Western regions, Liberia', produced a series of technical reports on a range of commodities including gold and base metals. In general there has been little or no follow-up of these investigations.

All publications (maps, reports and data) derived from these early investigations and mentioned in this paper are available from the Liberian Geological Survey, Ministry of Lands, Mines and Energy in Monrovia.

The Peoples Republic of China began a geochemical survey programme throughout the country in early 2016. Low density geochemical data (one sample point/100 $km^2$) have been collected for the whole country with the exception of a 1,500 $km^2$ part of eastern Lofa county where higher density data (one sample point/1 $km^2$) have been collected. Regional geophysical surveys (1:100,000 scale aeromagnetic, 1 km line spacing) for the whole country and higher resolution geophysical surveys (1:25,000 scale aeromagnetic, 0.25 km line spacing) for part of Lofa County are expected to be flown in 2018. The data and interpreted results from this, the first systematic geoscience data collection programme in Liberia for 45 years, are scheduled to be delivered after 2018.

## 5. Metallic mineral resources and potential

### 5.1. Gold

There is a long history of artisanal gold mining in Liberia from alluvial placers with production peaking at more than 30,000 oz per annum in the 1940s. Between 2010 and 2015 annual production is estimated at about 18,500 oz per annum (BGS, 2017). Nearly 600 gold occurrences were recorded by the USGS in Liberia, with gold placer deposits accounting for almost 80 per cent of the total (Wahl, 2007). Gold remains the focus of most mineral exploration activity in Liberia today. Current licences are widely distributed over both the Archaean and Proterozoic terranes, focussed on major regional shear zones and belts of known alluvial gold.

#### 5.1.1. Placer gold deposits

Deep and intense weathering since the Pleistocene or earlier, together with persistent erosion in areas of moderate to low relief, favour the development of gold placers across Liberia although most are found in the eastern and western parts of the country. The deposits worked by artisanal miners are generally less than 2 m thick, and are narrow and discontinuous in form. A number of 'gold belts' have been defined based on the number and distribution of alluvial placer deposits recorded by the USGS (Fig. 3). Each of these includes a large number of alluvial

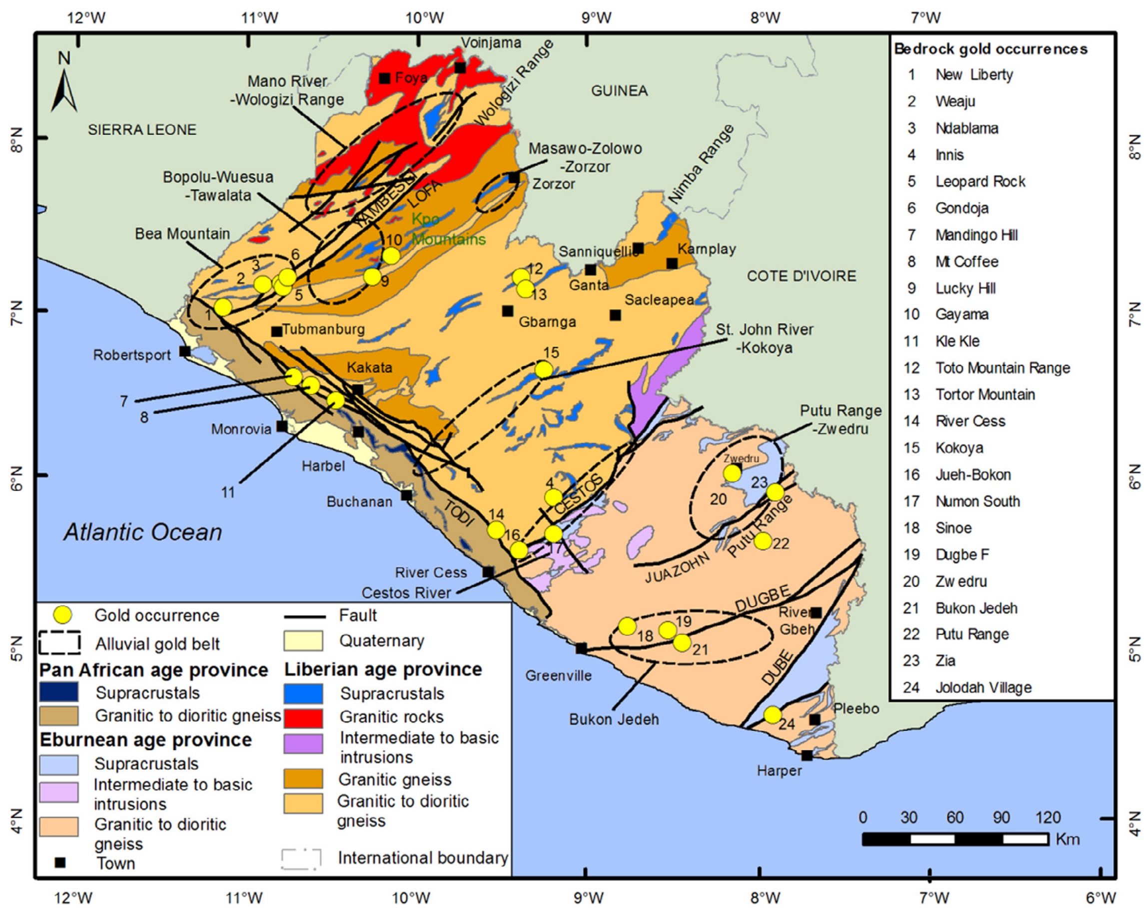


**Fig. 3.** The distribution of the principal bedrock gold occurrences and gold 'belts' in Liberia.

placer deposits, some of which have been worked in the past, and some where significant resources may remain. However, it is generally considered that large placers amenable to modern mechanised mining methods are unlikely to be found in Liberia. The widespread occurrence of placer gold deposits suggests significant potential for bedrock-hosted gold mineralisation and provides useful guidance for exploration targeting.

### 5.1.2. Bedrock gold deposits

*5.1.2.1. Archaean lode-gold deposits*. Lode gold deposits in Archaean rocks in Liberia are found in association with a wide variety of greenstone-belt lithologies with metamorphic grade ranging from lower greenschist to upper amphibolite facies (Fig. 3). The mineralisation, which may comprise quartz veins, breccia zones, stringers and disseminations, typically extends over widths of 10–20 m and may have a strike extent of more than a kilometre. Structure exerts a strong control on its distribution with north-east-trending zones of intense shearing being particularly important (Foster and Piper, 1993). Other favourable sites include zones of polyphase deformation, fold limbs and closures, and competency contrasts such as sheared lithological contacts. The mineralisation comprises free gold closely associated with a range of silicates, including quartz, tourmaline, chlorite and sericite, and various sulfide minerals. The gold-bearing mineralisation may be associated with local development of a range of alteration minerals including, most commonly, chlorite, carbonate and sericite. In some deposits, dependent on host rock lithology, the alteration assemblages may include phlogopite, talc, magnetite, hematite, iron sulfide, tourmaline and tremolite. A range of metals may be enriched in the gold-bearing ores including arsenic, tungsten, cadmium, copper, lead and zinc. Similar structurally-controlled gold mineralisation is found within the Archaean greenstone belts of Sierra Leone; the gold mineralisation appears to have formed at somewhat higher pressure than that in other greenstone belts worldwide (Barrie and Touret, 1999). The timing of gold mineralisation is not well known, but is generally considered to be late Archaean, potentially associated with the c. 2800 Ma granitoid intrusions that occur throughout the Kénéma-Man domain (Foster and Piper, 1993).

Perhaps the best known and economically most important gold occurrences in the Archaean greenstone belts are found in north-west Liberia associated with a series of major north-east-trending structural lineaments, principally shear zones. There has been very little research on the nature and origin of this Archaean gold mineralisation and so almost all of the available information is derived from company reports most of which provide little scientific information. New Liberty is a shear zone-hosted gold deposit owned by Avesoro Resources Inc (Avesoro Resources, 2018a). It is hosted by Archaean mafic and ultramafic rocks, representing a relict greenstone belt, surrounded by granites and granodiorites. The gold mineralisation at New Liberty is located in a structurally-controlled 100 m-wide steeply dipping silicified and sheared ultramafic unit trending between 097° and 105° (SRK Consulting, 2017). It comprises free gold associated with minor amounts, up to 1 volume per cent, of sulfides, chiefly pyrrhotite, arsenopyrite and gersdorffite. The mineralised zone varies in width up to 10–15 m and extends two km along strike and hundreds of metres down dip. In addition to silicification within the mineralised zone and the immediate hanging wall, phlogopite and chlorite are found within the ore zone and the immediate host rocks are bleached as a result of the destruction of magnetite. Geochemical analysis of drillcore has established a close association between gold and arsenic, sulfur, nickel and tungsten in the mineralised zones. Along the margins of the mineralisation high values of magnesium, sodium, potassium, rubidium and barium are commonly observed. Measured and indicated resources at New Liberty are 9.6 Mt @ 3.2 g/t with proven and probable reserves of 7.4 Mt @ 3.3 g/t Au (August 2017) (SRK Consulting, 2017). Gold production commenced in 2015 and the owners aim to produce approximately 120,000 oz per annum for the first 6 years of mine life (Aureus Mining Inc, 2016).

Many other major gold occurrences occur along a structural corridor extending north-east from New Liberty. Prominent examples include Weaju and Ndablama where Avesoro Resources continues to explore and has announced significant gold resources (Avesoro Resources, 2018b). At Ndablama, in an area of established alluvial gold mining activity about 40 km north-east of New Liberty, gold mineralisation is hosted in sheared ultramafic and mafic rocks intercalated in a gneiss sequence at the contact with a granite batholith. Gold is localised along sheared contacts between the ultramafic and mafic units that are intruded by granitic dykes and breccias. Phlogopite, tremolite, chlorite and talc alteration is associated with the mineralisation. A mineral resource (measured + inferred) containing 901,000 oz of gold at a grade of 1.6 g/t Au was reported at Ndablama in December 2014 (AMC Consultants, 2014). At Weaju, about 30 km north-east of New Liberty, a resource of 2680 kt @ 2.1 g/t Au was announced in November 2013 (AMC Consultants, 2014).

Exploration in the Kpo Range area of Gbarpolu County has identified gold-bearing quartz veins (Whiteaker, 2007). Mineralisation is thought to be related to shear zones at the margin of an Archaean greenstone belt consisting of banded iron formation, schist and amphibolite. To the north of the Kpo Range gold-bearing veins, hosted in granite and granitic gneiss, occur in the Lucky Hill (Gblita) area (Liberty, 2008). Mineralisation appears to be controlled by the lithological contact between granite and granitic gneiss.

Gold mineralisation comprising brecciated quartz stockworks in a shear zone within the Archaean gneisses has been located in the Mandingo Hill area in Bomi County, about 40 km from Monrovia (Whiteaker, 2007). This prospect is located close to the regional Todi Shear Zone that trends approximately 320° and dips to the west at 40–60°. A number of structurally-controlled, quartz-sulfide-bearing gold occurrences also occur in the Mt Coffee area of the Todi Shear Zone (Gem Rocks Mining Resources Inc, 2013). Further east along the shear zone at Kle Kle, now owned by MNG Gold, several broad zones of gold mineralisation have been defined (Amlib, 2012).

Quartz vein-hosted and disseminated gold mineralisation occurs in strongly sheared supracrustal rocks in the Toto Mountain Range area in Bong County. In the south of Bong County a mineral resource (indicated) containing 210,000 oz of gold at a grade of 3.5 g/t Au is reported at Kokoya (MNG Gold, 2015). The mineralisation is structurally controlled and hosted in a package of strongly deformed amphibolites and gneisses. In January 2015 MNG Gold was awarded a Class A gold mining licence at Kokoya valid until 2027. The company has announced its intentions to construct a new gold mine at Kokoya.

*5.1.2.2. Proterozoic lode-gold deposits*. Birimian-age greenstone belts host major gold deposits in a number of West African countries and most West African gold production has been derived from these rocks rather than the Archaean. Within the Baoulé-Mossi Domain, most gold deposits are focused along regional shear zones, with mineralisation styles including stockworks, veins, disseminations and breccias (Goldfarb et al., 2017). However, little systematic modern exploration has been undertaken over the Birimian terrane in south-east Liberia and the geology of the gold mineralisation has not been studied in detail.

As in the Archaean terrane, alluvial gold occurrences are numerous and widespread in the Birimian and significant mineralisation in bedrock is known at several localities (Fig. 3). Host rock lithologies are varied but the mineralisation may occur within metavolcanic and metasedimentary rocks and/or mafic and granitic intrusives; elsewhere in the Birimian, the contrasts between these metasedimentary and igneous lithologies have localised the ore bodies (Goldfarb et al., 2017). The mineralised bodies in Liberia have variable morphology, ranging from irregular sheets to quartz-carbonate sulfide-bearing veins, disseminated sulfides and sulfide stringer veins. As in the Archaean terrane, geological structure is the dominant control on the location of gold mineralisation (Hummingbird Resources, 2013, 2016). Particularly favourable sites include second-order structures to regional shear zones, structural intersections, lithological contacts, grain-size variations within sedimentary packages and zones of polyphase deformation. The gold occurs as free grains commonly closely associated with sulfide phases, chiefly pyrite, arsenopyrite and pyrrhotite. Hydrothermal alteration is present in some deposits, commonly with attendant enrichment in arsenic, bismuth and silver.

The most important known bedrock gold deposits in this terrane are spatially associated with major regional shear zones trending either north-east or east-north-east. Numerous gold occurrences (e.g. Jueh-Bukon, Numon South) have been identified in the environs of the Cestos Shear Zone, which marks the approximate limit of Eburnean deformation and reworking and represents a near vertical, crustal-scale structure that has been compared with the Ashanti Gold Belt in Ghana (Amlib, 2012). The Ity gold mine in Côte d'Ivoire is located on the north-eastern extension of this shear corridor (Béziat et al., 2016).

The Juazohn Shear Zone is another highly prospective target on account of known bedrock occurrences, extensive alluvial deposits and gold geochemical anomalies. BIF-hosted gold deposits are the principal target in the area. High grade mineralisation has been reported at several locations including Zia in the north, near Zwedru to the west and in the Putu Range area which straddles the Juazohn Shear Zone (Hummingbird Resources, 2013).

The regional Dugbe Shear Zone in south-east Liberia has been the focus of significant gold exploration in recent years. To date the most significant discoveries have been made by Hummingbird Resources plc and are located at Dugbe 1 about 40 km east of Greenville in Sinoe County. These foliation-parallel, disseminated gold deposits, known as Dugbe F, Tuzon and Sackor, are hosted in high-grade, migmatitic rocks. The gold is free milling and comprises fine grains along microfractures and at grain boundaries. The gold is associated with increased sulfide content, but alteration distal to the mineralisation is inconspicuous. The inferred resource at Dugbe F is 43 Mt @ 1.28 g/t Au and the indicated + inferred resource at Tuzon is 52.0 Mt @ 1.47 g/t Au (Hummingbird Resources, 2016). The company has signed a Mineral Development Agreement with the Government of Liberia and has completed a Preliminary Economic Assessment. It plans to build a mine that will produce 125,000 oz of gold per annum over a 20-year period. Approximately 12 km to the south-east drilling has intersected significant high-grade gold mineralisation at Bukon Jedeh. The intrusive contact of a granite body is a favoured site for high grade gold in this area. Along strike to the west of the Dugbe 1 Project gold mineralisation has been identified in the Sinoe area, which is characterised by biotite and garnet-biotite schists, intruded by sulfide-bearing quartz-feldspar-mica pegmatites and mafic and granitic intrusives. The highest gold concentrations appear to be associated with the pegmatitic zones.

### 5.1.3. Potential for new gold discoveries

The wide distribution of placer gold deposits across Liberia, together with the known presence of significant bedrock deposits of orogenic gold mineralisation, suggests potential for additional gold discoveries. The known bedrock deposits in the Kénéma-Man Domain of western Liberia are comparable with structurally-controlled lode gold mineralisation found in Sierra Leone and in other Archaean terranes worldwide (Markwitz et al., 2016). In eastern Liberia, the gold deposits at the margin of the Baoulé-Mossi Domain are considered to be part of the major Birimian gold province. They are characterised by gold-quartz veins and disseminated mineralisation in steeply dipping regional shear zones, commonly localised at bends, splay intersections and contact zones within the shear system. Significantly more work is needed to understand the nature of the Archaean-Palaeoproterozoic transition in Liberia and to develop better models for the gold mineralisation in this area.

Under-explored areas of alluvial mining activity are priority targets for future exploration. The distribution of BIF, considered to be the source of much of the placer gold in the Archaean of West Africa, is relatively well known in Liberia on account of the extensive exploration that has taken place for iron and the availability of national aeromagnetic data. The relationship between bedrock gold and BIF in Liberia is illustrated by the Innis prospect to the north of the Cestos Shear Zone, where gold is associated with disseminated and vein-hosted sulfides hosted by sericite-altered gneiss, BIF and garnet schist. Other areas with extensive BIF outcrop, coinciding with major structural corridors, are highly prospective. Targets of this type associated with alluvial gold occurrences are located in the Nimba, Putu and Wologizi ranges. In north-west Liberia the underexplored north-east extension of the Archaean Kénéma-Man domain, bounded by the Lofa and Yambesei shear corridors, is a priority target for gold exploration on account of the favourable geology and structure and the presence of alluvial placer deposits.

Other areas that merit further investigation include: the southern end of the Todi Shear Zone in the River Cess area where limited sampling has revealed elevated gold concentrations in the laterite (Whiteaker, 2007); the junction of the Dugbe Shear Zone with the north-east-trending Dube Shear Zone, in Grand Gedeh County where anomalous gold values in stream sediments have been reported (Hummingbird Resources, 2013); and the western end of the Dube Shear Zone in the Jolodah Village area of Grand Kru County where alluvial gold is widespread, although the bedrock source has not been identified (Whiteaker, 2007).

The distribution of known alluvial and bedrock gold in Liberia, together with the well-known geological and structural controls on gold mineralisation in Precambrian rocks worldwide, provides a useful starting point for gold exploration in Liberia. Accounts of recent gold exploration in Liberia suggest that a combination of structural analysis based on geological mapping and magnetic data (ground and airborne) together with drainage and soil geochemistry provide a sound basis for exploration for orogenic gold of this style. It is important to note that the gold content of surface geochemical samples may be diminished relative to gold values in bedrock as a result of leaching. Further, the gold mineralisation may be associated with enrichment in a suite of trace elements including arsenic, tungsten, copper, lead, zinc and nickel. Destruction of magnetite by mineralising fluids leading to bleaching and reduced magnetic susceptibility may be a useful local guide to mineralisation in some host lithologies.

### 5.2. Iron ore

Numerous iron ore occurrences and deposits are known in Liberia, with the most important being metamorphosed banded iron formation (BIF) within the greenstone belts of the Kénéma-Man Domain (Fig. 4). Such metamorphosed BIFs are also known as 'itabirite' where the metamorphism has made individual minerals indistinguishable in hand-specimen (Beukes, 1973). BIF-hosted deposits are responsible for the world's largest and highest grade iron ore districts, such as those in Western Australia, Brazil, USA, India and South Africa. In West Africa the largest deposit at Simandou in Guinea, which contains about 1120 Mt of iron, remains undeveloped (Hagemann et al., 2016). Sierra Leone is currently the largest producer of iron ore in the region with average annual production of approximately 8.4 million tonnes between 2011 and 2015, although there has been considerable variation year-on-year within that period (BGS, 2017).

Historically Liberia was a major global producer of iron ore, exporting about 20 million tonnes annually up to 1980 (Wright, 1985). Thereafter production levels declined until 1992 when the onset of civil war led to the closure of operations on the Nimba deposit at Yekepa and of Bong Mines in Bong County. After the cessation of hostilities and the establishment of a democratically-elected government in 2006 there was revival of commercial interest in Liberia's iron ore resources. China Union Investment (Liberia) Bong Mines Company Ltd. (hereafter China Union) and ArcelorMittal were the first companies to start production. Mining of 'direct shipping ore' (DSO) commenced in 2011 from the first of three deposits at Yekepa (Mount Tokadeh, Mount Gangra and Mount Yuelliton) in the 'Western Range Project' (WRP) operated by ArcelorMittal. In 2014 Liberia produced about 4.8 million tonnes and was ranked the 24th largest producer of iron ore in the world after just three years of production (BGS, 2016). However, following the collapse in the price of iron ore after 2013, mining operations were terminated at Bong in late 2015 and elsewhere production was curtailed significantly. Although uncertainties remain over future production levels, recent investment in the iron ore sector has boosted the development of infrastructure such as the refurbishment of the Buchanan to Yekepa railroad and the construction of a new iron ore berth at the Buchanan port. While iron ore is currently mined from only one deposit in the WRP, exploration activity for iron ore in most licence areas in Liberia is on hold because of global economic conditions.

Of the eight major iron ore districts and deposits in Liberia, six are located within the Archaean basement of the Kénéma-Man Domain in central and western Liberia, with less important deposits in the Baoulé-Mossi Domain and in the Pan African coastal belt. Kromah (1974) provides a descriptive summary of the geological setting, mineralisation and mining operations at some of the major iron ore deposits in the Liberian province, but the geology and controls on the mineralisation are generally not well known at the deposit scale. The Liberian BIFs are considered to be part of Archaean greenstone belts that have been metamorphosed to amphibolite- to granulite-facies, as in Sierra Leone and Guinea (Markwitz et al., 2016). Late supergene enrichment processes play an important role in the development of some high grade iron ores, notably at Mano River and Wologizi in the Archaean and at Goe in the coastal belt. These resulted in the formation of a cap-rock, known as 'canga', which forms a blanket over the exposed surfaces of the itabirite. Canga comprises a breccia of weathered BIF and iron ore clasts that are cemented by secondary Fe(III) oxides and hydroxides and is relatively resistant to weathering processes (Harder, 1914; Schuster et al., 2012).

Some minor components of iron ore, such as phosphorus, aluminium and manganese, may impact on the quality of the steel produced. In Liberia limited data suggest that the phosphorus content of some deposits is generally in the range of 0.05–0.10% which is higher than ideal ($< 0.01\%$ P) (Williams, 1986). However, as the iron ore deposits are generally of low- to medium-grade and suitable for blending, the phosphorus content can be readily managed to achieve acceptable concentrations.

#### 5.2.1. Iron ore deposits in Liberia

*5.2.1.1. The Nimba Range and deposits at Yekepa.* The Nimba and Simandou greenstone belts are significant structures within the Archaean basement in the Guinea-Liberia border area (Thiéblemont et al., 2004). The Nimba greenstone belt is a 1400 m-thick sequence of metavolcanic and metasedimentary rocks which extends for a total length of 45 km, with 25 km in Liberia and the remainder to the north-east along the border zone of Guinea and Côte d'Ivoire (Berge, 1974). Dating of detrital zircons in quartzite has placed the Nimba greenstone belt as latest Archaean to early Palaeoproterozoic (Billa et al., 1999), the same age as the Simandou belt in Guinea.

Historically iron ore has been exploited from both the Liberian and the Guinean sectors of the Nimba greenstone belt. In Liberia, the main Nimba ore body, now mined out, was located in one of two parallel bands of Archaean BIF with a north-east strike (Berge et al., 1977). The rocks in the Nimba belt are divided into two major units, the Yekepa Supergroup, comprising gneisses and orthoamphibolites with a dominant north–south structural trend, and the younger Nimba Supergroup, which consists of a basal conglomerate overlain by amphibole schists of

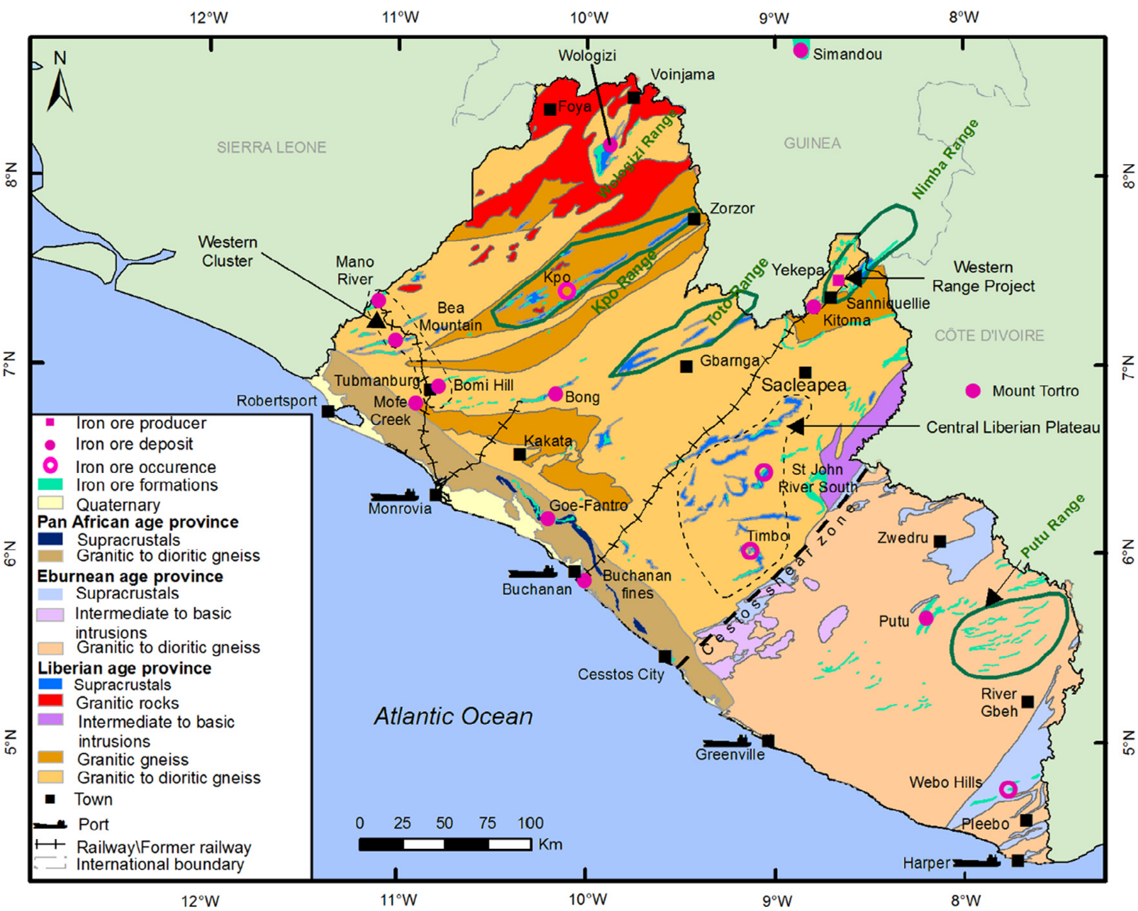


**Fig. 4.** The distribution of the principal iron ore deposits in Liberia and neighbouring countries.

volcanic origin, succeeded by metasedimentary formations comprising phyllites, the Nimba itabirite and the iron ores (Berge, 1974). The contact between the Nimba Supergroup and the underlying Yekepa Supergroup was interpreted as a regional unconformity, similar to that observed in the Simandou area of Guinea, located about 100 km to the north (Berge, 1972).

The main ore body at Nimba contained about 150 million tons of high grade iron ores, termed blue ores, with an iron content between 66 and 68% (Berge et al., 1977). Before mining the ore body was 250–300 m thick, 800 m long and known to a depth of 670 m. The ore was formed as a result of alteration of the enclosing grey itabirite during metamorphism, although the role of post-metamorphic meteoric fluids is unclear. Production commenced on the Nimba deposit in 1963 and peaked at 12 million tonnes in 1974 but subsequently declined due to market conditions. Production started at Mount Tokadeh in 1985 to extend the life of the Nimba mine but operations ceased in 1992 with the onset of the civil war.

In 2011 ArcelorMittal commenced mining of the Mount Tokadeh deposit at Yekepa, located about five km west of the now-exhausted Nimba Range deposit. Production from this deposit, which is part of the Western Range Project, is from high-grade oxidised ore, with an average iron content of 60–62%. This ore only requires crushing and screening to make it suitable for export. Total ore reserves at Yekepa are 501 million tonnes at 48.3% Fe (ArcelorMittal, 2015).

*5.2.1.2. Bong.* The Bong Mine, about 110 km north-east of Monrovia, is located at the south-western end of the north-east-trending Bong Range which comprises Archaean supracrustal rocks outcropping over a strike length of about 35 km (Kromah, 1974). The mine was operated by the Bong Mining Company between 1965 and 1990 when 158 million tonnes of medium to high grade iron ore were extracted (International Business Publications, 2013). It was most recently worked by China Union between 2011 and 2015. Further exploration has identified additional resources to the east of the Bong deposit at Goma and in adjacent ('Non-Goma') deposits. The 'Non-Goma' deposits within the Bong Range are estimated to contain 304 million tonnes ore at 36.5% Fe (Government of the Republic of Liberia, 2009).

*5.2.1.3. The Western Cluster (Mano River, Bomi Hills and Bea Mountain).* Historically a major iron ore producing region, these deposits in the west of Liberia, now generally referred to as the Western Cluster, are being developed by Vedanta Resources through its subsidiary Western Cluster Ltd. Early production in the 1950s took place first at Bomi Hills and subsequently at Mano River. At the same time, the railway between Monrovia and the Bomi Hills mine was constructed and the first port at Monrovia was established. The combined effects of the 1970s oil shock and the subsequent period of civil unrest led to the cessation of exploration and mining at the Bea Mountain deposit.

Recent exploration has focussed on the three deposits that constitute the Western Cluster and the company has acquired right of access to the old rail corridor to Monrovia port and two piers at the port. Drilling has been undertaken at all three deposits and in the licence areas surrounding them. Generally the itabirites of the Western Cluster deposits are weathered at surface to produce high grade canga above an unweathered magnetite-bearing primary ore. At Mano River and Bomi Hills this weathered cap has been exploited by previous mining ventures, yet much of it remains at Mano River. Bea Mountain has never been worked for iron ore. The future of this project is far from clear on account of the low and volatile iron ore price and geopolitical uncertainty (Vedanta Resources, 2017). The company has no immediate plans for any substantive expenditure on the Western Cluster.

The Mano River deposit, located about 140 km north of Monrovia, is the northernmost of the deposits in the Western Cluster. Kromah (1974) reported annual production of about 5 million tonnes of high grade fines. The BIF ores are associated with Archaean metasedimentary and metavolcanic rocks which have been intruded by mafic dykes of inferred Mesozoic and Palaeozoic age. High grade canga (c. 60% Fe) constituted a major part of the resource at Mano River. Recent exploration activities, including geological mapping, aeromagnetic surveys and diamond drilling, have led to the identification of an inferred resource of 95 million tonnes at 32.9% Fe (Vedanta Resources, 2015). The Bomi Hills mine, located 50 km north of Monrovia, was a historic producer of high-grade DSO magnetite in addition to magnetite concentrate beneficiated from itabirite. Currently exploration is ongoing in the area surrounding the Bomi Hills mine. A SAMREC resource of 291 million tonnes at 33.8% Fe, with probable reserves of 141.65 million tonnes at 35.67% Fe, has been reported in addition to the potential resources in fine tailings from previous operations that may be reworked for iron (Vedanta Resources, 2015). The Bea Mountain deposit, approximately 100 km north of Monrovia, has been explored by Vedanta Resources in recent years. The inferred resource, greater than 500 million tonnes at 33.2% Fe, has not yet been exploited (Vedanta Resources, 2015).

*5.2.1.4. Wologizi Range*. The large, low grade deposit in the Wologizi Range has a long history of exploration but is yet to be worked on an industrial scale. The Wologizi Range itself, located in north-western Liberia approximately 200 km north–north-east of Monrovia, extends over a total length of about 50 km and includes about 23 km of BIF located within an Archaean supracrustal belt (White, 1973). It has speculative resources of 1.271 billion tonnes at 30–45% Fe (Williams, 1986).

*5.2.1.5. Mofe Creek*. The Mofe Creek project is located within one of Liberia's historic iron ore mining districts in western Liberia, approximately 65 km from Monrovia and 10 km along strike to the west of the Bomi Hills deposit. It is currently being explored by Tawana Resources and has a maiden JORC resource estimate of 61.9 million tonnes at 33% Fe, including an indicated mineral resource of 16.2 million tonnes at 35.4% Fe (Tawana Resources, 2016) The deposit is characterised by coarse grained itabirite, with both haematite and magnetite mineralisation present.

*5.2.1.6. Putu*. The Putu deposit includes 12 km of BIF that form a series of mountains, including Mount Gedah, Mount Chea and Mount Taeley. These are located approximately 120 km north-east of Greenville in eastern Liberia and, unusually, they occur in rocks of presumed Palaeoproterozoic age rather than Archaean. The deposit is currently licensed to the Russian company, Severstal Resources, and has a SAMREC reserve of 102 million tonnes at 59.3% Fe, with low contents of phosphorus and aluminium (personal communication, Severstal Resources, 2014). A much larger resource of lower grade ore comprising 2.36 billion tons at 34.1% Fe was announced in February 2011 (Mining Technology, 2011). In early 2016 the government of Liberia announced that the company had shut down its operations in Liberia permanently (Front Page Africa, 2016).

*5.2.1.7. The Goe Range*. The Goe Range (or Goe Fantro) is located approximately 60 km south-east of Monrovia in a zone of northwest-southeast-trending metasedimentary rocks known as the Goe Range Series (Berge, 1971). These rocks are poorly known but may correlate with the Rokelide units recognised along strike in Sierra Leone (de Waele et al., 2015). The regional strike of the Goe Range Series, comprising metasedimentary schists, quartzites and BIFs, is north-west, which contrasts with the north-east orientation of all other iron ore deposits in Liberia. Exploration in the Goe Fantro area was first undertaken in the late 1950s, prior to the discovery and development of the Nimba deposits (Berge, 1971). The Liberian American Mining Company (LAMCO) identified two iron-rich bands, one silicate rich and the other oxide rich. However, the deposit is known to have elevated levels of some impurities such as phosphorus (0.27%), aluminium and manganese. Supergene enrichment has been important in upgrading the iron content at Goe Fantro and a canga cap is widely developed (Berge, 1971). The Goe-Fantro deposit is under licence to Cavalla Resources but there is no current activity because of the low iron ore price. Cavalla reports a JORC-compliant inferred resource of 568 Mt, which includes 101 Mt of DSO grading 57.2% Fe (Cavalla Resources, 2017).

*5.2.1.8. The Buchanan fines*. This is a 'deposit' of secondary material of fine grain size, located adjacent to Buchanan port and derived from the processing of iron ores originating from the Nimba Range mine between the 1960s and 1980s. It is currently owned by Cavalla Resources. The tailings from this process constitute a small but potentially easily-exploited JORC-compliant resource, which is estimated at 11 million tonnes (measured) of haematite fines with a grade of 45% Fe (Cavalla Resources, 2017). A definitive feasibility study was completed in 2014. This concluded that the project could produce 1.2 Mt per annum of concentrate grading 62% Fe over a five-year period, but production did not start in 2016 as planned.

*5.2.1.9. Other occurrences of iron ore*. Additional iron ore occurrences of potential economic importance are widespread in Liberia, especially in the Kénéma-Man Domain (Williams, 1986). Significant examples are found in the Kpo and Toto ranges of western Liberia, and in the Central Liberian Plateau. BIFs are also known from Webo Hills in south-eastern Liberia, hosted in Palaeoproterozoic metasedimentary rocks. This deposit is considered uneconomic on account of its reported high phosphorus content (c. 0.45%), although high iron grades are locally present in laterite and canga (Williams, 1986).

*5.2.2. Potential for new discoveries of iron ore*

Although considerable work has been carried out over a long period to assess the iron ore resources of Liberia, large tracts of the country are poorly known in detail and have not been systematically explored using modern techniques. The national digital geological and aeromagnetic datasets, available from the Liberian Geological Survey, provide an excellent basis for identification of areas prospective for new iron ore deposits. Certain under-explored areas are of particular interest on account of the known occurrence of extensive banded iron formation such as the Putu Mountain Range in the east of the country. Many areas, including the Wologizi Range, the Putu Range, the Toto Range, Webo Hills and the Central Liberian Plateau, would benefit from systematic mapping, sampling and evaluation of targets with modern exploration techniques. The results of the airborne geophysical survey over Liberia scheduled for 2018 will provide a large amount of new geological information especially with regard to delineating the BIF outcrop and elucidating geological structure. Modern geological and geochronological research on the known deposits would also help to develop genetic models for the iron ore mineralisation and thus to focus exploration for new resources.

## 6. Diamonds

The West African Craton is an area of thickened lithosphere (< 240 km; Jessell et al., 2016), and the Kénéma-Man Domain in particular is an area of Archaean crust with low geothermal heat flow (c. 40 mW/m$^2$) (Skinner et al., 2004), representing a favourable tectonic environment for economic kimberlites (Kjarsgaard, 2007). It is host to numerous kimberlite pipes and dykes, some of which are known to be diamondiferous (Haggerty, 1982). West African kimberlites are dominantly Mesozoic in age (Jurassic to Cretaceous) but some Precambrian kimberlites are also known (Skinner et al., 2004).

In Liberia, diamonds are produced solely by artisanal miners from alluvial placers located in the west and central parts of the country. Liberia has a long history of alluvial diamond production, with an aggregate output of about 14 million carats during the last 50 years. Output from small-scale operations peaked at about 600,000 carats per annum during the early part of the 1970s. Historic diamond production was tarnished by its association with conflict in the region. Export sanctions imposed by the United Nations in an attempt to end illicit diamond mining in Liberia depressed diamond production between 2002 and 2007. However, in 2007 Liberia became a Kimberley Process participant and, since then, diamond production has risen to approximately 74,000 carats in 2015 (Central Bank of Liberia, 2016). Reporting of diamond production is compulsory under the Kimberley Process. However, production figures are not guaranteed to represent the entire production of diamonds in the country due to the artisanal nature of the mining.

### 6.1. Diamond occurrences of Liberia

All the known kimberlites in Liberia fall within the Archaean Kénéma-Man Domain, close to the border with Sierra Leone. Kimberlites in Liberia and Sierra Leone occur predominantly as dykes with NNE to NE trends; a few kimberlite pipes have also been identified (Haggerty, 1982). New discoveries of kimberlite pipes and dykes have been made in recent years (Haggerty, 2017). The kimberlite dykes cross-cut an extensive swarm of north-west-trending dolerite dykes emplaced during a period of rift-related magmatism (180–200 Ma). Reactivation of north-east-trending Archaean basement structures, and the subsequent emplacement of kimberlites, occurred during later periods of rifting (c. 90 and c. 140–150 Ma; Skinner et al., 2004) that gave rise to swarms of dykes with slightly different trends. The Palaeoproterozoic Baoulé-Mossi Domain of eastern Liberia has generally been thought to be barren with respect to diamonds (Haggerty, 1992). However, relatively recent discoveries of alluvial diamonds in Sinoe County in south-eastern Liberia cast doubt on this assumption and highlight some uncertainty in the understanding of the tectonic evolution of the region.

Liberia has a lengthy history of diamond exploration, particularly in central and western Liberia. Between 1962 and 1966 the Diamond Mining Company (Liberia) identified a number of kimberlite dykes as part of a regional exploration programme. In 1972 the United Nations undertook a mineral indicator survey over western Liberia and discovered the small Mano Godua kimberlite pipe. In the late 1970s a number of companies were active along the Lofa River and Yambasi creek. Many of the early exploration campaigns concentrated on the discovery of alluvial diamond deposits. However, seasonal flooding, poor access and the erratic distribution of diamond-bearing gravels meant that many companies were ultimately unsuccessful in bringing Liberian alluvial diamond deposits into commercial production. Nevertheless, the discovery of alluvial diamonds highlighted the possibility of discovering buried kimberlites in central and western Liberia.

The USGS and LGS documented about 160 kimberlite occurrences in central and western Liberia (Wahl, 2007). However, due to lack of bedrock exposure, poor access and dense vegetation, this may not be an accurate reflection of the true number of occurrences. Since the 1980s, exploration for diamond-bearing kimberlites has increased significantly leading to the discovery of diamond-bearing kimberlites in western Liberia (Fig. 5). Three distinct clusters have been recognised, at Kumgbor, Mano Godua and Weasua, where current exploration licences are held by two companies. Other kimberlite occurrences, identified by the USGS, are found in Nimba County, central Liberia.

Seven new discoveries were made by Mano River Resources, near Weasua, between 2000 and 2006. In addition a series of kimberlite dykes, and a single pipe, were discovered in the Camp Alpha area by the Youssef Diamond Mining Company (YDMC) in 2013 (Haggerty, 2015, 2017). All of the Liberian occurrences are small pipes (with surface area less than 0.1 $km^2$) and thin dykes (up to a few metres thick) (Thorman and Hoal, 2007). Bulk sampling of the Mano Godua pipe, during a UN mineral survey in the 1970s, did not reveal any diamonds (Fairbairn, 1981). To date, Liberian kimberlites have not been commercially exploited for diamonds and the number of kimberlites with economic potential remains unknown. The recent increase in diamond production is linked to a rise in the number of alluvial diamond deposits being worked and the increased mechanisation of the production process. No modern estimates of diamond resources have been published for Liberia.

USGS and LGS regional surveys during the 1970s identified numerous alluvial placers and kimberlite indicator minerals in central and western Liberia. On the basis of these regional surveys, together with previous exploration and small-scale mining activity, extensive areas in central and western Liberia with significant alluvial diamond deposits have been defined (Fig. 5). Another area in south-eastern Liberia has recently been identified as an artisanal diamond mining area.

#### 6.1.1. Lofa River

The Lofa River is one of the largest rivers in the country draining over 350 km from the east of the Wologizi Range. The Lofa River area is host to significant alluvial diamond production, with numerous workings in the Lofa and Yambasi River basins and associated tributaries. Occurrences in these basins extend from Weasua to the coast at Bomboja. The distribution of diamonds in alluvial deposits in the Lofa River area is highly erratic, although early exploration reports suggest that lower terrace gravels, ancient alluvial river flats and deep-plunge pools within the active river channel are the most prospective areas for diamond recovery. The high diamond potential of the Lofa River area is attributed to a number of factors, including the known occurrence of kimberlitic source rocks and close proximity to the highly prospective eastern diamond region in Sierra Leone (Dorbor, 2010).

#### 6.1.2. Mano River

The Kumgbor and Morro-Gbeya River basins are areas of intense artisanal mining, with diamonds produced from many of the creeks in the area, particularly the Papaya Creek (Dorbor, 2010). Gem-quality diamonds, up to a maximum of 170 carats, and industrial diamonds were recovered from this area in the late 1970s.

#### 6.1.3. Du River

Historic alluvial workings have been identified in the Kakata area of the Du River basin. The diamonds recovered from this area are generally small but mostly of gem quality. Kimberlitic rocks have not been found in the Du River diamond area and, therefore, the source of the alluvial diamonds remains unknown, although it has been suggested that local conglomerates may be a potential source (Dorbor, 2010).

#### 6.1.4. Bee Creek River

The Gbapa-Bahn diamond area in Nimba County is relatively underexplored. It is largely confined to the margins of the Bee Creek River, where kimberlitic rocks were identified by the USGS and LGS in the early 1970s. The area has a history of small-scale alluvial diamond mining dating back to the 1950s. The diamonds are typically found in floodplain and river-terrace gravels flanking Bee Creek, although little is known about their distribution, morphology and grade. However, local reports suggest that diamonds up to 15 carats have been recovered from the area (Dorbor, 2010).

#### 6.1.5. Sinoe River

Alluvial diamond workings are found in the area around the Sinoe River in south-eastern Liberia, but no information about these operations is available (Dorbor, 2010). However, this is the first evidence of diamond occurrences in this part of the country, generally thought to be underlain by Proterozoic rocks of Eburnean age, which are considered to be barren.

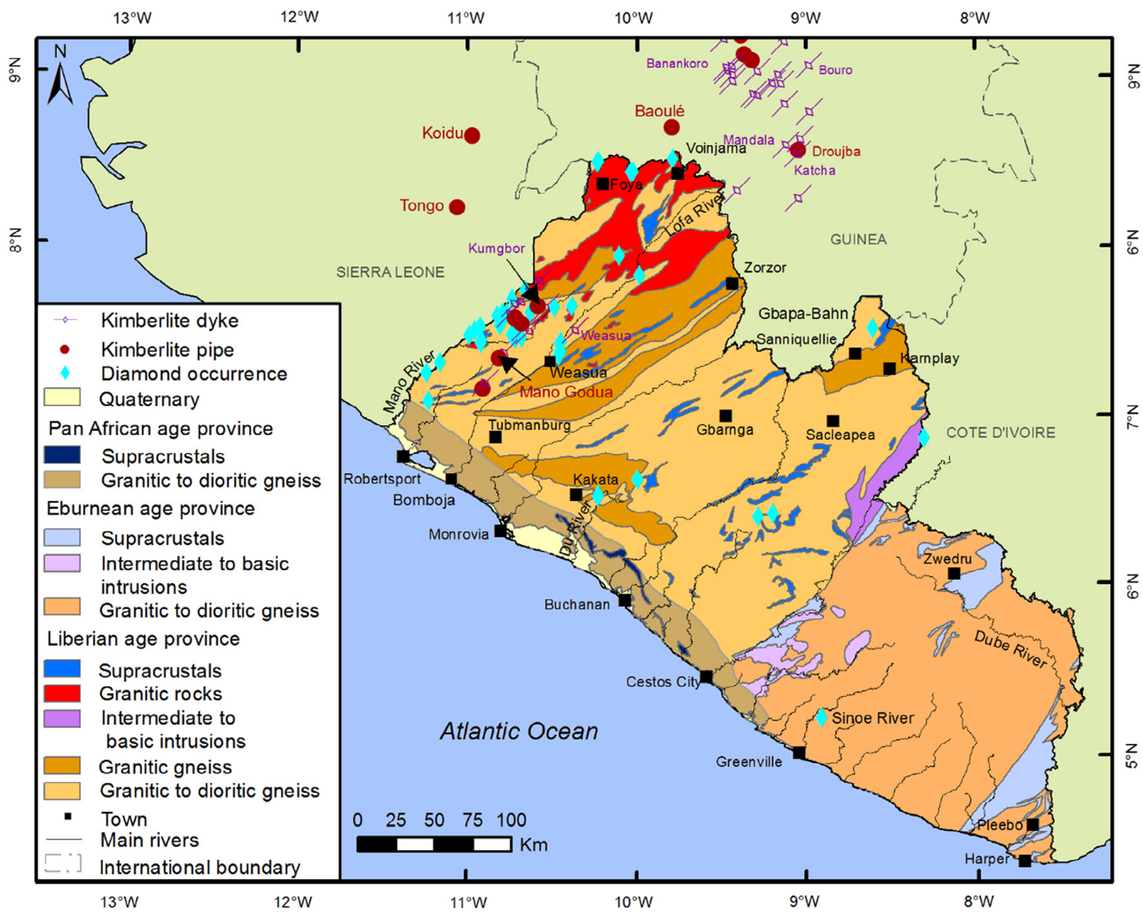


**Fig. 5.** The distribution of the principal diamond occurrences in Liberia and neighbouring countries.

### 6.1.6. *Kimberlite-hosted diamond deposits*

The majority of Man Shield kimberlites are geochemically classified as type-A, non-micaceous kimberlites (i.e. on-craton, basaltic kimberlites) and typically occur as small pipes and abundant dykes (Taylor et al., 1994). Liberian kimberlites have been described as occurring in three distinct clusters, two of which are Jurassic in age (Kumgbor and Mano Godua) and one older, Neoproterozoic-age, cluster (Weasua) (Skinner et al., 2004). The Jurassic kimberlites form part of a single kimberlite province that extends into neighbouring Sierra Leone and Guinea. Further evidence for the existence of a single kimberlite province is given by Taylor et al. (1994) who suggest, on geochemical grounds, that Jurassic kimberlites from Liberia, Sierra Leone and Guinea are all type-A, non-micaceous kimberlites.

A recent discovery of a kimberlite pipe (2.5 ha in area) in the Camp Alpha region in Kumgbor (Haggerty, 2015) highlights the potential for bedrock-hosted diamonds in Liberia. The associated dykes have significant micro-diamond populations, suggesting that the pipe may have economic potential.

## 6.2. *Kimberlite indicator minerals*

The identification of resistant kimberlite indicator minerals (KIMs), such as garnet, spinel, ilmenite, clinopyroxene, forsterite, orthopyroxene and zircon, in stream sediments and soil samples is a well-established exploration tool for kimberlites (Kjarsgaard, 2007). A number of these minerals have been widely identified in stream sediments, mostly in western Liberia. To date, indicator minerals have only been analysed from a small number of kimberlites in Liberia. For example, the composition of garnet (a chromium-rich, calcium-poor variety) and spinel (a chromium- and magnesium-rich variety) from the Neoproterozoic Weasua kimberlites suggest that these pipes may be prospective for diamonds (Skinner et al., 2004). Similarly, the chemistry of large ilmenite crystals recovered from kimberlites at Camp Alpha in Liberia (Haggerty, 2015) and from Koidu in Sierra Leone (Tompkins and Haggerty, 1984) suggests that these kimberlites are highly prospective for diamonds. The presence of micro-diamonds in a kimberlite is another strong indicator of the macro-diamond potential of a kimberlite. The significant population of micro-diamonds recovered from kimberlites at Camp Alpha in Liberia is, therefore, encouraging.

Comparative studies of kimberlites in eastern Sierra Leone and western Liberia focussed on the KIM picroilmenite (Haggerty et al., 1978). This research identified kimberlites in Sierra Leone trending east–west. These lack a distinct magnetic anomaly as do north–south trending kimberlites in Liberia. Similar east–west trending kimberlites with no clear magnetic signature may be present in Liberia.

## 6.3. *Potential for new diamond discoveries*

On the basis of favourable basement geology, the wide occurrence of alluvial diamonds and the known presence of kimberlites, there is considered to be significant potential for the discovery of additional diamond resources, both in bedrock and alluvium. The abundance of hypabyssal- (root-zone) kimberlites relative to diatreme-facies kimberlites in the Kénéma-Man domain is indicative of extensive erosion across the region.

River systems in western Liberia are strongly influenced by the underlying geology and structures. The river courses are irregular, commonly leading to sporadic sedimentation. In the case of the Lofa River this results in low overall volumes of gravel deposition but produces small pockets of gravel rich in heavy minerals (Leuria, 1966). Terraces along the river are frequently the site of re-concentration of heavy minerals, although these are generally difficult to identify as they are blanketed by thick lateritic overburden. Geomorphological mapping in the Koidu area of Sierra Leone (Thomas et al., 1985), the Birim area of Ghana (Hall et al., 1985) and the Tortiya and Séguéla areas of Côte d'Ivoire (Chirico and Malpeli, 2013) highlights the benefits of paleo-geomorphic studies for diamond exploration. This research emphasises the importance of understanding the Quaternary evolution and hence the depositional environments in the region and the influence that this has had on local diamond distribution. A similar approach could help to delineate the most prospective areas for alluvial diamond exploration in west and central Liberia.

The potential for placer diamonds along the Liberian coastline has not been evaluated. Although studies have suggested that the greatest quantity of alluvial diamonds is located proximal to the source, such as at Koidu in Sierra Leone (Thomas et al., 1985), where there has been extensive erosion, such as in Liberia, the potential for distal transport should not be overlooked. The estuary of the Lofa River at Bomboja is a possible target for the development of littoral or offshore marine diamond deposits.

Large areas of ground prospective for diamonds in Liberia have not been evaluated using modern methods. The most useful technique is likely to be high-resolution, stream-sediment and soil sampling for kimberlite indicator minerals. Ground-based electromagnetic and magnetic surveys, successfully employed in Sierra Leone and Guinea, should also be employed in conjunction with botanical surveys and KIM-chemistry. Localised swampy conditions are a possible guide to the presence of kimberlites. This is due to the clay-rich and hence impervious nature of the kimberlite bedrock. Furthermore it has been suggested that, a new species of palm, Pandanus candelabrum, may be restricted to the soils developed over kimberlite pipes but not kimberlite dykes (Haggerty, 2015), possibly diagnostic of coarsely-brecciated kimberlite pipe eluvium. If this relationship is substantiated, it has potentially important implications for improving future exploration for kimberlite pipes in Liberia and across West Africa.

## 7. Other metallic minerals

There has been very little systematic modern exploration for resources of other metallic minerals in Liberia. Limited studies by the LGS, USGS and industry, mostly undertaken in the 1960s and 1970s, identified a number of potentially significant occurrences of various metals (Fig. 6).

### 7.1. Barite

More than 40 barite veins are known in the vicinity of the Mount Gibi Ridge, located about 95 km north-east of Monrovia. Most of these were identified in the 1960s and 1970s and were evaluated by programmes of mapping, trenching and drilling by LGS, USGS and Dresser Minerals. The Mount Gibi Ridge comprises a large microgabbro dyke that trends about 300°, discordant to the regional strike which is north to north–north-east. This dyke, which extends at least 160 km to the Sierra Leone border, is considered to be of Jurassic age by analogy with mafic dykes of similar orientation in the region (Dalrymple et al., 1975). The Archaean country rocks comprise mainly granitic gneiss, with subordinate biotite gneiss and hornblende gneiss (Pomerene and Stewart, 1967). The larger barite veins are parallel to the Gibi dyke and a common origin, or at least some common control, has been suggested for the emplacement of both the dyke and the veins (Pomerene and Stewart, 1967). The largest veins are up to 5 m wide and have a strike extent up to 170 m. There are no modern estimates for the barite resources in the Mount Gibi area but it is considered that the district may contain 1–2 million tons of barite. The barite is reported to be of high purity (99% $BaSO_4$), suitable for chemical use and drilling mud. Dorbor (2010) reported a preliminary reserve estimate by Dresser Minerals in 1970 of 553,150 tons of barite in 19 veins to a depth of 500 feet (152 m). There has been a limited amount of recent exploration and extraction of barite from veins in the Mount Gibi district. Steinbock Minerals has produced barite and, up to April 2014, the company had exported 100,000 tonnes of barite through the port at Buchanan.

Another significant barite occurrence is found at Wouta, Grand Bassa County (Mason, 1980). Two veins were identified with a strike length of 350 feet (107 m) and widths of 4–8 feet (1.2–2.4 m), but only limited subsurface investigations were carried out.

Further work is required to evaluate the potential for economic resources of barite in the Mount Gibi area and at Wouta. If hydrocarbon exploration, both offshore Liberia and neighbouring countries, increases significantly then these easily-mined, high-grade vein deposits, located close to the coast, are a potential source of barite for use in drilling muds.

### 7.2. Bauxite

There has been a long interest in bauxite in Liberia going back to the 1950s and bauxite deposits are known in many of the neighbouring countries (Markwitz et al, 2016). Potentially significant resources have been identified in two districts: at the Kolahun deposit in Lofa County in the north-west of the country close to the border with Sierra Leone; and at the Karloke deposit in the extreme south-east in Maryland County close to the border with Côte D'Ivoire (Massah, 1985). Available geological information for these deposits is sparse. At Kolahun the bauxite occurs as patches on hill tops in dominantly granitic Liberian terrain, while at Karloke the country rocks comprise Eburnean granitic gneiss, dioritic gneiss and mica schist. Preliminary surface investigations, with limited shallow trenching at Karloke, suggest the presence of grades of potential economic significance over wide areas although detailed systematic assessment, including core drilling, is required to assess the resource potential in both areas. The USGS recorded several additional occurrences of bauxite in the area around Karloke, but no details are available.

### 7.3. Manganese

In Liberia the most important manganese deposit is located at Mount Dorthrow, 70 km east-south-east of Zwedru in Grand Gedeh County. The Cavalla River, which is the international boundary with Côte d'Ivoire, forms the eastern boundary of the deposit. Two types of mineralisation are present, sedimentary-metamorphic comprising banded manganiferous iron formations (Eburnean) and supergene iron-manganese enrichment. The manganiferous iron formations (itabirite), which are finely layered on a millimetre scale, locally grade into quartzite and elsewhere into higher grade, enriched ore types. The secondary mineralisation is derived from chemical and physical weathering processes under lateritic conditions in Tertiary to recent times. It comprises eluvial deposits on the hill tops and slopes together with an iron-manganese capping, referred to as canga, which is confined to a limited area on the crest of Mount Dorthrow. The LGS investigated the deposit by mapping and a limited programme of pitting and shallow drilling in 1980–81 (Sangmor et al., 1982). The deposit is characterised by a generally high Fe/Mn ratio, but sporadic high values, up to a maximum of 53% MnO, were reported in the surficial float and canga. The deposit was not considered to be economic at that time, but considerable additional work is required to evaluate the resources present.

Other indications of similar manganese enrichment associated with BIF in the supracrustal sequences of the Eburnean terrane were recorded by the USGS and LGS but no systematic assessments have been carried out (e.g. see Mason and Shannon, 1980). There has been no assessment of the potential in Liberia for the occurrence of carbonate ores of manganese, comparable with the Nsuta deposit in Ghana.

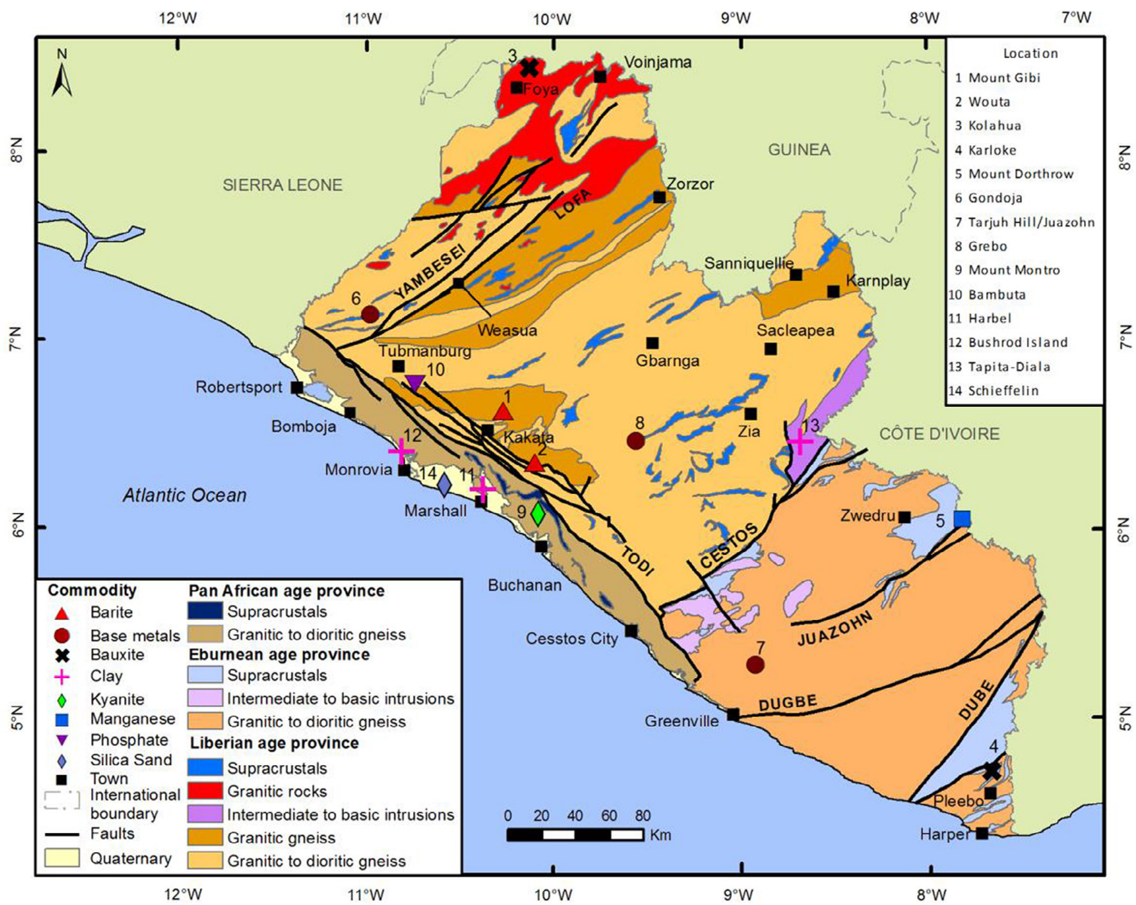


**Fig. 6.** The location of selected deposits of metals and industrial minerals in Liberia (deposits of gold, iron ore and diamonds are not shown).

### *7.4. Heavy mineral sands*

Heavy mineral sand deposits on beaches, in estuaries and offshore are an important global source of a range of metals including titanium, zirconium, thorium, rare earth elements and, locally, tin, tungsten and precious/semi-precious stones.

In Liberia preliminary surveys for heavy minerals were carried out by the UNDP in 1972 and 1973 along 300 km of the Liberian coastline. Heavy mineral concentrations, comprising chiefly ilmenite with subordinate amounts of rutile and zircon and minor monazite, were found at several localities. Hancox and Brandt (2000) reviewed the heavy mineral potential of Liberia and summarised the historic investigations carried out, most of which were undertaken in coastal beach sands. They concluded that there are heavy mineral 'reserves' amounting to 744 700 tons along the entire coastline, with the most promising area being the 188-kilometre stretch of coastline between Buchanan and the Sierra Leone border. However, the known deposits are small and, due to the low quality of the ilmenite, the economic value lies mainly in the contained rutile and zircon which comprise about 6 per cent and 11 per cent of the total heavy mineral content, respectively. It should be noted that the exploration undertaken to date has not been exhaustive and modern techniques have not been used with most work carried out by pitting with limited banka drilling.

It is recommended that a systematic evaluation of the most promising zones involving radiometric and magnetic surveys, pitting/trenching and mineralogical analysis should be undertaken. No work has been done to search for relict beach systems that potentially could host larger and higher quality heavy mineral deposits.

### *7.5. Base metals (copper, lead, zinc, nickel, tungsten, tin)*

By analogy with Archaean greenstone belts elsewhere, there is potential for polymetallic base metal and gold mineralisation in these terranes in Liberia. However, little exploration for base metals has been carried out and few occurrences are known in Liberia.

There are some promising indications of tungsten-bearing mineralisation in Liberia. The most well known is in the Sam Davis Creek near Gondoja in Grand Cape Mount County (Sangmor and Dorbor, 1982; Dorbor, 2010). In this area the LGS identified enrichments in pegmatitic quartz of 1–5% scheelite associated with 1–2% Pb, Zn, Cu and up to 31 g/t Au + Ag. The mineralisation is located in fracture zones in mafic and ultramafic country rocks of the Liberian terrane. Another significant base metal occurrence is found at Tarjuh Hill, about 10 km south-west of Juazohn in Sinoe County, south-east Liberia (Dorbor, 2010). Here low tenor enrichments in copper, zinc and nickel have been identified in and around an ultramafic intrusive body that forms Tarjuh Hill, which is located in the Eburnean terrane. Nickel values up to 1% were reported in lateritic soils at Tarjuh Hill (Richardson, 1980). Dorbor (2010) also notes some evidence of base metal potential in Cape Mount County, Gbarpolu County and Bong County, but no work has been carried out to evaluate the potential in these areas.

Minor occurrences of low grade tin mineralisation have been reported from a few localities (Richardson, 1980). Most of these appear to be related to pegmatites found within Eburnean supracrustal rocks of the St John River Shear Zone, located about 95 km inland from Buchanan along the LAMCO railroad, and its extension around Zia. UNDP (1972a) reported on investigations for tin over an area of 22 km$^2$ near Grebo where elevated cassiterite and columbite were identified in heavy mineral concentrates with values in rock up to 0.1% Sn. No systematic work has been done to evaluate the tin mineralisation in this belt and further investigations are required to determine the resource potential at Grebo. In addition more detailed mapping and sampling of the greenstone belts is needed to identify targets, especially for rare/minor metals associated with pegmatites.

### 7.6. Nickel, copper, PGM and chromite in mafic–ultramafic rocks

Potential exists for nickel-copper-platinum-group metals (PGM) in a variety of settings in association with mafic–ultramafic rocks in the basement. By analogy with known deposits worldwide, prospective targets include PGM in layered complexes, nickel-copper sulfide deposits ± PGM in marginal, contaminated or deformed zones in mafic–ultramafic intrusive bodies, nickel ± PGM in komatiitic rocks, and hydrothermal PGM in structurally-controlled settings in serpentinites. There is also potential for supergene nickel ± cobalt in laterites developed over ultramafic rocks and for the development of PGM-bearing placer deposits derived from ultramafic source rocks.

Although there have been no studies of these targets, the presence of a wide range of mafic and ultramafic rocks, commonly deformed and altered, suggests that further investigation is merited. Of particular note are the Juazohn intrusive complex (serpentinite, dunite, pyroxenite) in Sinoe County, south-east Liberia located within the Eburnean terrane (Tysdal, 1975) and the Gohn Zulu ultrabasic body in Cape Mount County, north-west Liberia (UNDP, 1972b; White and Leo, 1969). The norite body at Cape Mount, near Robertsport, which is considered likely to be part of the Central Atlantic Magmatic Province, is also worthy of investigation (Dorbor, 2010). In addition the published geological maps indicate the widespread occurrence of ultramafic rocks in western Liberia, particularly in the Bopulu map quadrangle. It is considered likely that additional ultramafic bodies are present in this region that were not recognised during the reconnaissance mapping carried out by USGS.

Potential also exists for chromite mineralisation in association with layered mafic–ultramafic intrusive complexes and as podiform deposits in serpentinites. USGS recorded about 500 chromite occurrences, either in alluvium or by chemical analysis, but no association with bedrock mineralisation has been demonstrated. Richardson (1980) noted that massive chromite was formerly mined in the North Kambui schist belt in eastern Sierra Leone. Given that these rocks extend into western Liberia in the Kumgbor forest region it was suggested that this area should be investigated for similar chromite mineralisation.

The prospectivity of Archaean terranes for magmatic nickel-copper-PGM and chromite mineralisation in West Africa is further highlighted by the occurrence of deposits of these types in the Samapleu area of western Côte d'Ivoire close to the border with Guinea (WSP, 2015). Substantial enrichment of nickel and cobalt in laterites has been demonstrated in the same area.

Significant PGM mineralisation (primary and alluvial) is known in the early Jurassic Freetown Igneous Complex located along the Atlantic coast in Sierra Leone (Bowles et al., 2000). Basic dykes of this age are known to occur in the coastal zone of Liberia and these should be examined for magmatic nickel-copper-PGM mineralisation.

### 7.7. Technology metals (niobium, tantalum, rare earth elements, lithium, beryllium)

A range of minor metals used chiefly for new and green technologies is of great interest to governments in the West because of the possibility of supply disruption. Many of these are by-products of the extraction of major metals such as copper, nickel or zinc, while others are derived from deposits in which they are the main commodity produced.

Granitic pegmatites are potential sources of many minor metals including lithium, rubidium, caesium, beryllium, gallium, scandium, yttrium, rare earth elements, tin, niobium, tantalum, uranium, thorium, zirconium and hafnium. The coarse grain size and high purity of their non-metallic (industrial) mineral components also makes them attractive exploration targets that might support small-scale extraction of both ore and industrial minerals. They also have potential as sources of semi-precious stones, such as rose quartz, aquamarine and tourmaline.

Most tantalum deposits are hosted by peraluminous pegmatites and granites with columbotantalite group minerals (commonly referred to as ‘coltan’) the most important hosts for tantalum. Major sources of tantalum from pegmatites are found in Canada, Western Australia and Brazil. In Africa there has been production from pegmatites over long periods, notably in DRC, Ethiopia, Namibia and Mozambique. In many cases the extraction is from shallow, small-scale workings and related eluvial and alluvial deposits derived from pegmatite sources. Significant niobium-tantalum deposits, sometimes associated with tin and tungsten ores, are also found in peraluminous granites in China, USA, Egypt, France, Russia and the Czech Republic.

Dorbor (2010) reported the presence of columbite-tantalite in concentrates from soils and stream sediments, mostly in western Liberia. USGS also reported columbite-tantalite at more than 440 localities, either in alluvium or by chemical analysis (Wahl, 2007). These are widely distributed and are found both in the eastern part of the Archaean terrane and in the Proterozoic terrane in the east with many occurrences close to the border with Côte d'Ivoire. These coltan occurrences may owe their origin to concentration through superficial processes during prolonged tropical weathering. Exploration for coltan-bearing pegmatites in Liberia would present a formidable challenge. Although pegmatites are widespread, especially in proximity to granite bodies, they are commonly thin and discontinuous in form and few are recorded on the 1:250,000 scale geological maps of Liberia.

Alkaline rocks are not well known in Liberia, although syenite is present at Tarjuh Hill and trachyte dykes have also been more widely recorded in the Juazohn region. Given that alkaline and peralkaline granites and syenites are potential sources of niobium, tantalum, zirconium and rare earth mineralisation, these rocks merit further investigation in Liberia.

## 8. Industrial mineral resources

The distribution of the main deposits and occurrences of industrial minerals is shown in Fig. 6.

### 8.1. Kyanite

Kyanite-bearing gneisses and schists are developed in an elongate belt about 14 km long and 1.6 km wide within the Archaean terrane located about 20 km north of Buchanan, Grand Bassa County. The kyanite resources at Mount Montro, the most prominent hill in this belt, were studied initially by USGS and LGS (Stanin and Cooper, 1968), with later more detailed investigations including drilling and resistivity surveys (UNDP, 1972c). Preliminary estimates suggested the presence of up to 10 million tonnes of kyanite-bearing rock containing approximately 2.5 million tonnes of kyanite. Considerably more work is required to quantify this resource and to determine the grain size and homogeneity of the contained kyanite. The proximity of the deposit to a paved road and to a sea port may confer significant economic advantages and make this a viable mining proposition.

### 8.2. Phosphate

A phosphate deposit of potential economic significance is located near the town of Bambuta, about 70 km north–north-east of Monrovia and 25 km east of the former Bomi Hills iron ore mine. High-grade phosphate rock, identified in this area by the LGS and USGS in 1969, was soon after investigated by the Liberia Mining Company Ltd who undertook a programme of core drilling (25 boreholes total, average depth 28.9 m) and mapping (Rosenblum and Srivastava, 1979). The mineralisation comprises a layer of phosphate rock up to 38 m thick underlying banded iron formation and resting on older granitic gneiss. The drilling data indicated a tentative “minimum reserve” of 1.5 million tonnes of phosphate rock grading 28% $P_2O_5$ or 1 million tonnes at 32% $P_2O_5$. Furthermore, Van Rooijen (1971) noted that the ‘ore’ is highly heterogeneous in texture and that the phosphate grade varies greatly both laterally and vertically. Mineralogical study of drillcore shows the phosphatic layer to range from iron to aluminium phosphates with the predominant mineral being aluminium strengite, an orthorhombic iron phosphate containing some aluminium ($FePO_4{\cdot}2H_2O$) (Rosenblum and Srivastava, 1979). Further investigations are required to determine the suitability of this deposit as an economic source of phosphate for use as fertiliser or for other purposes.

### 8.3. Clay

Dorbor (2010) noted that kaolin-rich clay deposits are known at three localities: (1) Bushrod Island – New Georgia, located near Monrovia; (2) the Harbel Firestone plantations; and (3) Tapital-Diala. Only the first has been investigated (Blade, 1969) where they are suitable for ceramic, high quality bricks and pottery. A reserve of 8 million tonnes was estimated for the readily accessible part of the deposit. The small Harbel deposit was previously used by the Firestone Plantations Company for making bricks. Shannon (1979) reported that the clay in the Tapita-Diala deposit is very pure kaolin, although no other information is available.

These sources of clay remain of potential economic value to local industry, although they have not been properly mapped and no systematic geological assessment has been carried out.

### 8.4. Silica sand

Silica sand is an important commodity used mainly in glassmaking. It is valued for a combination of chemical and physical properties including high silica content and low levels of deleterious impurities, such as clay, iron oxides and heavy minerals. Silica sands typically have a narrow grain size distribution in the range 0.5–1 mm.

Silica sand deposits have long been known along the coast, mainly between Monrovia and Marshall, a distance of about 45 km, extending inland up to 20 km (Rosenblum and Srivastava, 1970; Sangmor, 1976). Other deposits found along rivers in the interior have not been evaluated.

Pitting and drilling, with supporting mineralogical studies, conducted in the late 1960s and 1970s on the coastal deposits suggested a ‘reserve’, based on an average thickness of one metre, of about 136 million tonnes of good quality sand suitable for glass manufacture (Sangmor, 1976). A small programme of additional drilling focussed on an area near Schiefflin identified at least 2.7 million tonnes of high grade silica sand (Shannon and Richardson, 1979), while Dorbor (2010) suggested that a total of about 4 million tonnes of high quality silica sand may be available. Before the civil unrest, the deposits in the Schiefflin area were used by the Pan African Glass Factory to manufacture glass bottles, but it has been reported that some of the resources in this area have effectively been sterilised by recent urban development.

## 9. Construction mineral resources

Liberia’s only cement plant is operated by Cemenco (a subsidiary of Heidelberg Cement). Located in Monrovia, cement is manufactured at the plant from imported materials. In 2014, cement output was 295,363 tonnes following the commissioning in 2013 of a new cement grinder with an annual capacity of 500,000 tonnes (Bermúdez-Lugo, 2016).

### 9.1. Construction aggregates

In Liberia, potential sources of aggregates exist in river terraces and flood plains. Terrace deposits along major rivers comprise sands and gravels which are generally well graded and well stratified but which also may contain deleterious materials such as iron oxides. Flood plain material is often fine to very-fine grained with a high clay content. River-sand mining in active river channels is the primary source of sand and gravel in Liberia. Such mining is extensive in and around Monrovia, in particular on and adjacent to the Saint Paul River. Beach-sand mining is now prohibited, although it was commonly undertaken along the Liberian coastline in the past (Hasselmann and Wiles, 1988). The government now has a policy of encouraging river-sand mining as an alternative (MAC-Africa, 2015).

The best materials to produce crushed rock for aggregate in Liberia include resistant granites and migmatites together with younger basic dykes and sills. Primarily utilised for road building, such construction materials, are currently extracted from small quarries located throughout the country with several larger quarries operating in the vicinity of Monrovia.

### 9.2. Dimension stone

The term ‘dimension stone’ covers a wide variety of naturally occurring stones used for the external cladding, structure and internal decorations of buildings. The potential for dimension stone in Liberian rocks has not been established and there is no commercial extraction of rock for this purpose. Several types of granite and granite-gneiss found in Liberia may be suitable for making dimension stone. The principal dimension stone resources of the country are in the large exposures of granitic rock in Lofa County. These anatectic granites are massive, coarse-grained granite-granodiorites (Dorbor, 1982) which have been a focus for evaluation in the past (Rosenblum, 1971).

Areas with potential for dimension stone include: the inselbergs in the vicinity of Kolahun, Lofa County; pink granitic gneiss north of Zorzor, Lofa County; medium grey gneiss from Green Hill Quarry, south-east of Palala, Bong County [owned and operated by Arcelor Mittal for the extraction of crushed rock]; and the white granitic gneisses and black granitic gneisses located north-east of Buchanan, Grand Bassa County (Rosenblum, 1971). Further study of any potential source is required to determine its suitability for use as dimension stone.

## 10. Discussion and conclusions

By analogy with Precambrian terranes elsewhere, Liberia is considered to be highly prospective for a wide range of metallic and industrial mineral deposits. Elsewhere in West Africa world-class resources of gold and iron ore are widely known and high levels of exploration for non-ferrous metals, especially gold, have been sustained for long periods. The region also has a long history of mining bauxite and manganese, while the base metal potential has only been appreciated more recently with the discovery of significant deposits of zinc and nickel-copper.

By comparison with other countries in West Africa the geology of Liberia is poorly known and there has been very little systematic modern exploration carried out for most commodities, with the exception of gold. The available digital data on geology, airborne geophysics and mineral occurrences for the whole country provide an excellent basis for the identification of additional exploration targets but more detailed investigations are required to characterise these more closely. In particular, modern mapping and geochronological studies are critical to resolving the position and nature of the complex boundary zone between the Archaean and Palaeoproterozoic rocks in the south-east of the country. Improved understanding of the geological history of this region would help to focus exploration and identify areas prospective for Birimian orogenic gold deposits. Further, the location, nature and extent of mafic–ultramafic rocks in Liberia need to be better resolved in order to identify potential targets for magmatic nickel-copper-PGM and chromite deposits. Re-processing of the legacy aeromagnetic data using modern software would provide a highly cost-effective way of elucidating the bedrock geology and structure of Liberia. However, this requirement will be reduced when the results of the national airborne geophysical survey to be flown in 2018 are released.

In general there has been very little modern published research related to the origin of the known mineral deposits in Liberia. While models for the formation of, for example, orogenic gold deposits and diamond deposits developed elsewhere have been successfully applied in Liberia, there is a paucity of modern research specific to Liberia, most notably related to the genesis of the iron ores. Detailed geological, isotopic and geochronological studies would allow the development of genetic models for these deposits thereby elucidating the importance of stratigraphical, structural, geochemical and other controls on the mineralisation and thus facilitating the identification of new exploration targets. Exploration and resource assessment of most of the known mineral occurrences described in this review were investigated during the late 1960s and 1970s in a cursory manner using mainly low-cost methods. Detailed multi-disciplinary field surveys using modern techniques, combined with diamond drilling, are required to evaluate their economic potential.

In addition to the major industrial metals, such as iron, aluminium, copper, nickel and zinc, it is also important to consider the potential for a range of minor metals and industrial minerals, often now referred to as critical raw materials, which are of increasing importance for new and green technologies. For example, available information on metals such as antimony, chromium, cobalt, gallium, germanium, indium, lithium, niobium, the platinum-group metals and the rare earth elements is largely unavailable in Liberia and yet modern analytical methods mean that high quality data for most of these are available routinely and at low cost. Similarly, a range of industrial minerals, such as fluorspar, graphite and phosphate rock, are also much sought after by many advanced, manufacturing economies in the West.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.oregeorev.2018.07.021.

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