Full Length Research Paper

Identification of iron ores in Sierra Leone, Africa by using remote sensing techniques

G. Diaz¹* and R.M. Prol-Ledesma²

¹Department of Bible Studies, Archaeology and the Ancient Near East, Faculty of Humanities and Social Sciences, Ben-Gurion University of the Negev, Be’er Sheva, Israel.
²Instituto de Geofísica, Universidad Nacional Autónoma de México, Cd. Universitaria, Cd. de México, México.

Received 25 November, 2022; Accepted 14 June, 2023

Remote sensing is used in this work as a geological reconnaissance technique, demonstrating that it is profitable and effective in providing valuable information for distant regions of mining interest. Due to the Civil War that affected Sierra Leone from 1991 to 2002, Sierra Leone’s mining resurgence has focused only on restoring closed mines and the exploitation of previously proven reserves. Thus, the main objective of this work is to locate new iron ores in the districts of Marampa and Tonkolili, located in areas outside the mining licensee sites where previous exploratory studies have not been carried out. To do this, Landsat 5 TM multispectral satellite images were used. Two different spectral enhancement methodologies were applied: Colour composition with band ratios and principal component analysis (PCA) applied to band ratios. The results were integrated to generate a map that delimits areas with exposed mineralization of iron oxides, which allowed us to associate them with the regional geology. Finally, access roads are included for field checking and detailed exploration.

Key words: Remote sensing, iron ores, PCA, spectral signature, Landsat 5 TM.

INTRODUCTION

Sierra Leone became an independent republic in 1961 after being a British protectorate since 1896 and a nation under British administration since 1787. It is a country rich in natural resources and characterised by its tropical environment, including plateaus, plains, savannah, forests, deserts, and tropical forests (Jalloh et al., 2013). The Sierra Leone Geological Survey quickly recognised its broad mineral resource base in the 1920s and 1930s, which has supported a strong mining sector since then. After Sierra Leone’s independence, diamonds and iron deposits were the economy’s mainstays, and subsequently, bauxite and rutile were also added to the list (Ellis, 2003). The main minerals extracted are diamonds, rutile, and gold, as well as rocks of economic interest such as bauxites, limonites, and iron deposits.

Organised mining in Sierra Leone began in 1927, after the Mining Act was written and adopted. During the 1930s and 1940s, significant mining discoveries were made by the Sierra Leone Geological Survey (Jalloh et al., 2013). Then, from 1991 to 2002, Sierra Leone was devastated by a brutal civil war, resulting in catastrophic impacts on lives, human rights, property, and the economy (Jalloh et al., 2013). Before the Civil War, the production or mining extraction of resources such as...
diamonds, rutile, gold, bauxite, and iron deposits contributed 20% of the GDP, up to 15% of fiscal income, and represented more than 90% of the exports. Mining and extraction provided a livelihood for more than 250,000 people and employed around 14% of direct and indirect labour. Although this sector operated at only a fraction of its potential, its contribution was sufficient to make Sierra Leone a resource-rich country (Jalloh et al., 2013). The return of political stability in 2002, accompanied by positive global developments in the mining sector, has generated the rejuvenation of the domestic mining sector. This rejuvenated sector is expected to sustain the economy once again and support government development goals (Jalloh et al., 2013). While the resurgence of Sierra Leone’s mining sector has been impressive since the Civil War, so far it has solely focused on re-establishing closed mines and exploiting previously proven reserves. However, the greatest challenge in the immediate conflict situation is still based on maintaining foreign investments in the mineral and mining sectors (Jalloh et al., 2013). Being a region rich in minerals of high commercial interest, coupled with the scarcity of information available in Sierra Leone regarding iron deposits, remote sensing techniques will allow us to locate and identify sites where these deposits are abundant.

In spite of its geological wealth, the country is still on the margins of the economy (Mabey et al., 2020). With an approximate estimated population of 8.6 million people in 2022 (World Bank, 2021), by the end of June 2022, Sierra Leone’s GDP was US $3.76 billion (Vandi, 2022). This places it among the poorest countries in Africa in terms of per capita income. According to the Sierra Leone Integrated Household Survey elaborated in 2018, the overall poverty of the country is 57%, while the population in extreme poverty is 10.8% (SLURC, 2019). Sierra Leone’s economic growth has been driven by export-led, capital-intensive mining during the last decade (SLURC, 2019) and is expected to grow at 3.8% on average during 2023–2025 (World Bank, 2021). Among Sierra Leone’s main large-scale iron ore projects are Marampa and Tonkolili. These two regions accounted for 86% of the mining sector’s contribution to GDP, 67% of mineral exports, and 55% of government revenues from mining (SLURC, 2019). Remote sensing application to ore deposit exploration is well established, as it has proven to be very successful in locating undiscovered deposits with a minimum cost during reconnaissance and advanced exploration stages (Sabins, 1999). In terms of remote sensing applications for iron oxide exploration, the latest studies focused on mineral mapping of iron oxides are found in India (Al-Quraishi et al., 2020; Gopinathan et al., 2020), where band ratios and PCA analyses were employed. In Western Africa, some studies have been done as well, adding false colour compositions to the same approaches (Ciampalini et al., 2013); another example is found in southwestern Algeria (Bersi et al., 2016), where iron ore deposits were also detected by adding airborne gravity data analysis and iron ore indexes to the remote sensing techniques previously mentioned. Previous remote sensing exploration in Sierra Leone was restricted to the leased mining areas and proved the effectiveness of the use of TM images to identify iron ore outcrops (Mansaray et al., 2013, 2014). Satellite remote sensing techniques are used because of their cost-effectiveness, their ability to study hard-to-reach areas, and because information can be collected frequently and quickly on a large scale. For this reason, the objective of this work is to apply image satellite processing techniques to identify areas with suitable surface characteristics for the presence of iron deposits in Sierra Leone and define new exploration targets in the Marampa and Tonkolili districts that, given the geological setting, are very likely to contain iron deposits. In this research, a combined methodology has been employed, utilising band ratios and false colour composition as well as PCA of band rationing.

**STUDY AREA**

Sierra Leone is a West African country bordered by Guinea, Liberia, and the Atlantic Ocean. This nation is subdivided into four administrative divisions: the Western Area, the Northern, Eastern, and Southern Provinces. These sections are further divided into sixteen administrative districts plus the capital city of Freetown, located in the Western Area. Marampa and Tonkolili are both located in the Northern Province. Marampa is located in the Port Loko district, while Tonkolili is part of the district bearing the same name. These two regions (Figure 1) were selected because they are confirmed areas with the highest actual amounts of iron ores. Table 1 shows its limiting bounds of this study area. Since 1933, the Sierra Leone Development Company (DELCO) began to exploit the Marampa iron until 1975, when it ended work as a result of liquidation. In 2005, the London Mining Company (LMC) took over the Marampa concession and developed a mining project. The tailings abandoned by DELCO were reported to be in the range of 40 million to 45 million metric tons with an average grade of 27.7% Fe, and the primary iron deposits were reported to be from 92 million to one billion metric tons with an average grade of 37.7% Fe (Jalloh et al., 2013). The Tonkolili iron deposit occurs in the greenstone belt of the Sula-Kangari Mountains, near Ferengbeya, in the northern part of the country. Iron occurs as banded iron formations belonging to the Precambrian. Iron ore calculations are at least 720 million tons with an average grade of 56.3% Fe (Jalloh et al., 2013). Tonkolili has been exploited by African Minerals Limited (AML) and Shandong Iron and Steel Company, mining a total of 30.2 metric tons of iron ore during 2011-2018 (Bank of Sierra Leone, 2016; Bedder, 2019). Marampa and Tonkolili are
characterised by their abundant rainfall during the year and high vegetation density, which makes it extremely difficult to access them for exploration and surveying iron ores. That is why the use of remote sensing is ideal and convenient because, with satellite imagery provided by the United States Geological Survey (USGS) and image data processing, it is possible to obtain complete and reliable information in a reasonably affordable way without the need to travel to the study area or to require government permits to access the sites. Previous exploration work in both districts used Landsat images to define favourable areas for iron oxide deposits within the licenced field (Mansaray et al., 2013, 2014), and the results obtained indicated that multispectral image processing provided successful identification of iron oxide outcrops that revealed the presence of magnetite and hematite ore prospects. Therefore, the wider application of this methodology in this work is expected to deliver results that will serve as support for the completion of further detailed exploration to define the location of new prospects.

**GEOLOGICAL SETTING**

The Republic of Sierra Leone is located between latitudes 7° and 10° north and longitudes 10.5° and 13° west. Sierra Leone covers a total area of 71,740 km². The study areas with mining potential are Tonkolili and Marampa, located at coordinates 8°44'20" N, 11°47'53" W, and 8°41'32" N, 12°28'10" W, respectively (Figure 2). Figures 1 and 2 are shown in geographic coordinates because they include both study areas, and the western side of Sierra Leone corresponds to Zone 28N

---

**Table 1. Limiting coordinates for the study area.**

<table>
<thead>
<tr>
<th>UTM zone 29N (WGS 84)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum X coordinate</td>
<td>113055</td>
</tr>
<tr>
<td>Maximum X coordinate</td>
<td>276735</td>
</tr>
<tr>
<td>Minimum Y coordinate</td>
<td>899835</td>
</tr>
<tr>
<td>Maximum Y coordinate</td>
<td>1028955</td>
</tr>
</tbody>
</table>

Source: Author, 2023
(Marampa), while the eastern side (Tonkolili) corresponds to Zone 29N in the UTM WGS84 projection; the rest of the maps are presented in UTM coordinates. Tonkolili is located NE of Makeni; Marampa is situated between the districts of Lunsar and Rokup Rokup. The geology of Sierra Leone is divided into two main tectono-stratigraphic units. The eastern part corresponds to the West African Precambrian Craton, which belongs to the Archaic Aeon. This eastern cratonic fragment extends from the Western Sahara and the Anti-Atlas Mountains eastward to the Hoggar Mountains and southward into the regions of Mauritania, Senegal, Guinea, Sierra Leone, Liberia, Ivory Coast, and Ghana and has a heading foliation in the NE-SW direction. The western portion of the craton is currently forming the Shield of Guyana, which includes the countries of Venezuela, French Guyana, and Brazil, with an NNW-SSE strike being oblique to the central highlands. The craton is made up of rocks with a high degree of metamorphism and granite gneisses. The western part contains elements of an orogenic belt known as “Rokelides” or “Rokel River Group” (Figure 2), which was formed during the Pan-African thermo-tectonic event, 560 Ma ago. A smaller part, covering 20 to 40 km of the coastal strip, is composed of marine sediments dating from the Pleistocene to the present day (Warnsloh, 2011). In Sierra Leone, the greenstone belts emerge as four prominent, elongated mountainous areas in the eastern part of the country. Two of them are known as the Sula-Kangari belt (Wilson and Marmo, 1958; Marmo, 1962); the other is called the Kambui belt (Andrews-Jones, 1966); and the last two are called the Nimini and Gori belts. A geological map of Sierra Leone is shown in Figure 2, displaying the location of the main greenstone belts. Iron ores are found in banded iron formations and are characteristic of transitional zones between sedimentary and volcanic units. These deposits are present in each of the greenstone belts (Umeji, 1983).

Tonkolili is located on a basement (Figures 2 and 3) formed by granitoids (Leonean and Liberian). On top of this basement lies a discordant sequence with regional meta-sedimentary, meta-volcanic metamorphism, and volcano-sedimentary and ultramafic lithological units belonging to the Kambui Super Group. Tonkolili is dominated by lithological units belonging to the Sula Group, which is part of the Kambui Supergroup (Armitage, 2010). The Sula Group (Figure 3) is comprised of the Sonfon Formation and the Tonkolili Formation. The Sonfon Formation (Figure 3) is composed of amphibolites with palled lavas and ultramafic rocks, as well as amphibolite and hornblende shale. To a lesser extent, there are BIF deposits, which are interstratified

Source: Author, 2023
with amphibolites. On this formation, the Tonkolili Formation rests in a concordant way, in which the upper part hosts most of the BIF deposits (characterised by an alternation of thin layers of magnetite and silica) as well as a composition of fine, well-stratified alternating layers of mica-quartz shale, pelitic to semi-pelitic sediments, and possibly tuffs. The lower part is composed mainly of coarse-grained quartz mica-shale, which graduates into quartzites towards the south of the study area. In the tuffs, there are two types of mineralization in the form of bands and lenses: the primary mineralization of magnetite and the secondary one of hematite/goethite (Armitage, 2010). These mineralizations have a ferric percentage of approximately 55% (Adjimah and Asamoah, 2010). Magnetite is the main mineral found in this formation and is classified as an Algoma type of banded iron formation (Mansaray et al., 2013). The supracortical sequence of the Marampa group corresponds to the archaic aeon, which was affected by the Eburnian Paleoproterozoic metamorphism (Morel 1979; Wright et al. 1985). This group is divided into two formations (Figure 3), the Matoto metavolcanic formation and the meta-sedimentary formation Rotokolon that overlies it. In both of them, there is an iron ore occurrence. The Matoto formation is composed of basaltic lavas with padded lava zones up to 25 m thick, interspersed by serpentinites and andesites (Williams, 1978); it also contains amphibolites with magnetite, serpentinitised ultramafic units, and talc serpentinites (De Waele et al., 2014), as well as volcanic tuffs that vary from mafic to felsic composition; volcanicogenic sediments are also present (Adjimah and Asamoah, 2010); this formation is limited by faults and thrusts. The estimated thickness varies from 200 m to 750 m. On the other hand, the Rotokolon formation (Figure 3) is a meta-sedimentary succession dominated by semipelites, psammites, quartzites (rich in hematite), paragneises, chlorite shales, muscovite shales, sericite, specular magnetite shales, and banded iron formations (De Waele et al., 2014). The Marampa group (Figure 3) contains iron minerals, rocks of volcanic origin that vary from felsic to mafic composition, and volcanicogenic sediments. The Marampa rocks date from about 2,100 Ma (Warnslo, 2011).

### Table 2. Spectral characteristics of Landsat 5 TM.

<table>
<thead>
<tr>
<th>Landsat 5 TM Bands</th>
<th>λ Min (nm)</th>
<th>λ Max (nm)</th>
<th>Bandwidth (nm)</th>
<th>Spatial Res. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM1 - Blue</td>
<td>450</td>
<td>520</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>TM2 - Green</td>
<td>520</td>
<td>600</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>TM3 - Red</td>
<td>630</td>
<td>690</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>TM4 - Near Infrared (NIR)</td>
<td>760</td>
<td>900</td>
<td>140</td>
<td>30</td>
</tr>
<tr>
<td>TM5 - Shortwave Infrared (SWIR) 1</td>
<td>1230</td>
<td>1250</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>TM6 - Thermal</td>
<td>1570</td>
<td>1650</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>TM7 - Shortwave Infrared (SWIR) 2</td>
<td>2080</td>
<td>2350</td>
<td>270</td>
<td>30</td>
</tr>
</tbody>
</table>

Source: Author, 2023

### MATERIALS AND METHODS

#### Satellite imagery

The satellite used for this work was Landsat 5, sensor TM (Thematic Mapper). The images were obtained from the USGS Earth Explorer webpage. This and other imagery can be obtained for free at http://earthexplorer.usgs.gov/. The spectral characteristics of this satellite are found in Table 2. The preference of this sensor over most updated ones was due to its effectiveness in iron ore exploration and because new sensors such as Landsat 8 do not provide any improvement in the spectral resolution in the bands used in this study (Table 2): bands 1, 3, 5, and 7 in Landsat 5 TM that correspond to bands 2, 4, 6, and 8 in Landsat 8 and have similar spectral resolution and identical spatial resolution. From the seven bands provided by Landsat 5 TM, only band TM6 was excluded because it belongs to the thermal infrared spectral region and was not needed for the purpose of this work. The acquired images already have radiometric and geometric corrections; therefore, the first step of the pre-processing stage consists of cropping the image considering the study area (Table 1 and Figure 2). Next, the relative atmospheric correction was done through the darkest pixel subtraction method. A full methodology flow chart is shown in Figure 4.

#### Spectral characterisation of materials

Since this research aims to identify iron oxides (present in BIF ores), spectral signatures of these materials are necessary. Aside from iron oxides, vegetation and hydroxy-bearing minerals (e.g., clay and mica minerals) were also considered due to their relative abundance within the study area. Figure 5 shows the spectral signatures of these materials: Iron oxides (such as hematite and goethite) present a higher reflectance in TM3 (0.63–0.69 µm), while absorbance is higher in TM1 (0.45–0.52 µm). Magnetite, although not presented in Figure 5, also has a reflectance peak in this range (proof of this can be found by analysing its spectral signature on the USGS spectral library). Vegetation has its highest reflectance peak in TM4 (0.76–0.90 µm). In TM3, vegetation finds its absorbance peak. Lastly, a typical hydroxyl mineral is kaolinite which has its reflectance peak in TM5 (1.55–1.75 µm) and one of its absorbance peaks in TM7 (2.08–2.35 µm). Hydrate sulphates and carbonate minerals (calcite and dolomite) also share a similar spectral behaviour as hydroxyls and are therefore included in that group (Ducart et al., 2016).

#### Spectral enhancement of multispectral data

Image processing was performed to enhance the iron oxide's
**Figure 4.** Methodology employed for this research.
Source: Author, 2023

**Figure 5.** Reflectance spectra of iron oxides, hydroxyl-bearing mineral and vegetation (modified after Ducart, 2016).
Source: Author, 2023
spectral response. Processing included band ratios (Gibson and Clare, 2000) and principal component analysis (Crosta and Moore, 1989); these methods have proved to be very useful in ore deposit exploration by enhancing the spectral response of iron oxides and hydroxyl minerals using multispectral images as Landsat TM (Sabins, 1999). The bands used to identify oxides are TM1 and TM3, and for hydroxyl minerals, TM5 and TM7 (Tables 1 and 3).

In areas with dense vegetation cover, the bands typical of the vegetation spectral signature are also included in the band ratio analysis to subdue the vegetation spectral response influence in the results (Fraser and Green, 1987): TM3 and TM4 (Figure 5 and Table 3). The band ratio results are displayed in a false colour image, with the primary colours assigned as shown in Table 3. This procedure is the standard remote sensing methodology for hydrothermal mineral deposits exploration; however, in the iron oxide ore exploration, the process involves preferentially the use of the oxides and vegetation spectral response, and the hydroxyl minerals that are the main product of hydrothermal alteration are not relevant and therefore are not included in the Band-Ratio-PCA but are used for display purposes in the false colour image of the band ratios, as they are abundant in soil. The band ratio method provides better results if the band ratios TM3/TM1 and TM4/TM3 are used as input bands in a Principal Component Analysis (PCA) (Fraser, 1991) and the load matrix that results of the process validates the reliability of the process with the relative variance of each component and the load of each band ratio.

RESULTS

Band ratio colour composition

The false colour composition (RGB) of the three band ratios (Figure 6): R-TM3/TM1, G-TM4/TM3, and B-TM5/TM7, shows the predominance of vegetation, and the areas clear of vegetation present a mixture of soil (hydroxyl minerals) and oxides that yields a brownish colour with a predominance of oxides in selected areas.

PCA of band ratios

The results of the band ratio PCA is shown in Table 4, where it is pointed out that most variance (>99%) is represented by the first component with the load of each ratio concentrated with a high positive load for TM4/TM3 ratio, representing vegetation, and a high negative load for the TM3/TM1 ratio, representing oxides. The image that represents the first component is shown in (Figure 7). As the oxide representation has a negative load the high values of the TM3/TM1 ratio are represented by dark pixels and vegetation by bright pixels, it is necessary to reverse the palette for C1, that is, component C1 is multiplied by -1 in order to represent TM3/TM1 as the brightest pixels and will be evident the iron oxides location, and the dark pixels will indicate vegetation.

DISCUSSION

The false colour composition (Figure 6), shows in bright red the pixels where iron oxides predominate, some of them are surrounded by vegetation (blue colour), and some include hydroxyls. In the Northeast of Tonkolili, there are two small areas of very bright red colour, which indicates a very high spectral response typical of iron oxides, and this can be corroborated with the results of the PCA. The principal components were created from a ratio of bands; they do not contain information on albedo. In the case of C1, it contains 99.70% of the variance with a high negative load of the TM3/TM1 ratio. The percentage of the variance shows that the separation of both components was attained in the process, and most information is contained in PC1, with the bright pixels denoting vegetation, and the dark pixels characterising the areas with a predominance of oxides. By reversing the palette, the image (Figure 7) shows the pixels where iron oxides predominate as very bright. The comparison of both resulting images (Figures 6 and 7) reveals that the areas with the highest concentration of iron oxides that result from both processes coincide, and define two favourable areas to the NW, or our study area, where detailed field exploration is recommended to define the extension of the mineralised areas. The false colour image and the PCA-C1 image indicate that some pixels on the western side of the study area, aligned with a NW-SE direction, show a minor content of iron oxide mixed with hydroxyl minerals that would make them a secondary target for exploration. As a validation of the results, two approaches were followed. First training polygons were elaborated inside and outside of the main areas dominated by the presence of iron oxides to define the characteristic spectra of the pixels within these areas, each pixel or set of pixels must comply with very high tones in red in Figure 6 and very bright pixels in Figure 7. The obtained signatures are shown in Figure 8. The reflectance and absorbance peaks for iron oxides and vegetation match perfectly with the laboratory signatures shown in Figure 5. Hydroxyl minerals spectral signatures are very subdued, possibly because of the presence of high humidity in the soil, but the high-low reflectance pattern in bands 5 and 7 is evident. Secondly, from these training polygons, a supervised classification was performed. The outcome was then compared with field data reported by the West African Minerals Corporation (Figure 9a). The map was georeferenced, and stratified random sampling was applied. Since the materials of interest are solely iron oxides and the number of

Table 3. Associated colours for each band ratio for oxides, vegetation and hydroxyls identification.

<table>
<thead>
<tr>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM3/TM1</td>
<td>TM5/TM7</td>
<td>TM4/TM3</td>
</tr>
<tr>
<td>Oxides</td>
<td>Hydroxyls</td>
<td>Vegetation</td>
</tr>
</tbody>
</table>

Source: Author, 2023
classified hydroxyls is minimal, this class was combined with vegetation, and an error matrix was produced as shown in Table 5. Note that many points falling into the category of ‘iron oxides’ in Figure 9c do not match those from Figure 9b, making it seem like a poor classification (Table 5). As a matter of fact, due to the absence of thorough exploration and surveying outside of the licenced zones, Sierra Leone necessitates an enhanced and comprehensive mapping approach (Goodenough et al., 2018). The polygons elaborated from Figures 6 and 7

**Figure 6.** Band ratio colour composition. Red tones indicate the presence of iron oxides; in blue, we find vegetation; in cyan tones hydroxyl minerals in coexistence with vegetation and in brown tones iron oxides and hydroxyl minerals coexist, being the former greater in contribution. Regions marked with white indicate purer shades of red. UTM Zone 29N (WGS 84).
Source: Author, 2023

**Table 4.** Load matrix for PCA of band ratios for oxides and vegetation identification. In grey the dominant component is highlighted.

<table>
<thead>
<tr>
<th>Component</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance (%)</td>
<td>99.699305</td>
<td>0.300694</td>
</tr>
<tr>
<td>TM3/TM1</td>
<td>-0.734203</td>
<td>0.678930</td>
</tr>
<tr>
<td>TM4/TM3</td>
<td>0.999995</td>
<td>0.003262</td>
</tr>
</tbody>
</table>

Source: Author, 2023
Figure 7. PCA of band ratios. \((-C1)\) is displayed with a linear histogram stretch of 2%. Bright pixels indicate the presence of oxides; dark pixels indicate presence of vegetation. Regions outlined in blue show digital numbers very close to 255, hence, mainly oxides. Zone 29N UTM WGS84.
Source: Author, 2023

Figure 8. Spectral signatures for vegetation, hydroxyls and iron oxides obtained when making the training polygons.
Source: Author, 2023
Figure 9. Validation map: a) West African Minerals Corporation map showing iron ore current project (Innet, 2017); b) closer examination of the studied area displaying stratified point; c) map of classes produced from previous data.
Source: Author, 2023

Table 5. Confusion matrix, producer’s and user’s accuracy iron oxides and vegetation/hydroxyls.

<table>
<thead>
<tr>
<th>Classified data</th>
<th>Reference Data</th>
<th>Iron Oxides</th>
<th>Vegetation/Hydroxyls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron oxides</td>
<td></td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Vegetation/Hydroxyls</td>
<td></td>
<td>50</td>
<td>41</td>
</tr>
<tr>
<td>Overall accuracy (%)</td>
<td></td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Producer’s accuracy (%)</td>
<td></td>
<td>10.7</td>
<td>93.18</td>
</tr>
<tr>
<td>User’s accuracy (%)</td>
<td></td>
<td>66.7</td>
<td>45.05</td>
</tr>
</tbody>
</table>

Source: Author, 2023
were superimposed on the geology of the study area, and presented along with active mining areas (Figure 10). Following these two zones are described.

Zone 1

This zone is located in the town of Bumbuna, which belongs to the Tonkolili district. In Figure 10, it can be seen that the enclosed area coincides with the Sula Group, in which the Sonfon and Tonkolili Formations are found (Figure 2). This area is part of the Sula-Kangari greenstone belt; the banded iron formations in this region are interstratified with amphibolites, so the BIF deposits are probably found in the Sonfon Formation (Figure 10). Therefore, it is essential to carry out exploration brigades since it is located approximately 42 km northwest of the Tonkolili mining district, which is currently operating. The recommended route to reach this site by car is from Makeni, as this is the largest and most populated city in the Northern Province of Sierra Leone. From Makeni, it is necessary to head northwest towards the Kabala highway and take the Binkolo-Bumbuna highway. This leaves us right in the southwest part of the delimited area shown in Figure 9.

Zone 2

This zone is located on Mount Bintumani, which belongs to the Loma Mountains, with its lower slopes covered with tropical forests. The results indicate that the deposits rest on Liberian granite of considerable dimensions (Figure 10); however, according to the compiled geological information, the iron deposits found in this area are theoretically of sedimentary origin, contradicting the presented results (Figure 10). A possible explanation for this can be that the geological maps (Figures 2 and 10) were made by digitising maps previously done by authors like Williams (1978), Culver and Williams (1979), Umeji (1983), Sierra Leone Mining Review (2003), Keyser (2004), Keyser and Mansaray (2004), Kröner (2004), Warnsloh (2011), De Waele et al. (2014), and the Ministry of Water Resources of Sierra Leone (2015). The problem is that some of them differ in terms of lithological units, dimensions, and locations as well as some area
have not been mapped in detail, lacking modern descriptions of geological structures (Goodenough et al., 2018). For this reason, the probability that this site has not been mapped meticulously and carefully is possible; therefore, there is a high likelihood that sedimentary units also rest on top of the Liberian granite. If this is true, BIF formations might be in the zone, which could belong to either the Tonkolili or Sonfon Formation. It should also be noted that, while analysing Figures 6 and 7, they both show a high vegetation density in this region, which could be another factor that explains why Sula Group deposits have not been previously mapped. Although this has potential mineral interest, the Loman Mountains are part of a national park (LMNP) in Sierra Leone and are also the habitat of West African chimpanzees (Pan troglodytes verus), which unfortunately were listed as critically endangered on the IUCN Red List in 2016. According to model predictions, chimpanzee nests are even more abundant in a crown surrounding Mount Bintumani. In addition, this area harbours two more species, Pan troglodytes troglodytes and Pan troglodytes schweinfurthi, with varying densities that range from 0.05 to 10 individuals/km² (Molina-Vacas et al., 2023). Also, at least 49 species of large mammals, 257 bird species, and more than 41 species of amphibians are found in the LMNP (Kortenhoven, 2008; Forestry Division, 2012). Due to my ethical concerns, no access routes have been included, and I do not recommend carrying out any mineral exploration or exploitation campaigns that can permanently affect the endangered species living in this zone. Lastly, based on the stratigraphic data (Figure 3), the metallogenic period of the units does correspond to a favourable period (Archean aeon) of deposition of iron ores. The results presented here indicate that the iron deposits of Zone 1 and Zone 2 are present in the Tonkolili Formation of the Sula Group and were deposited during the Archean aeon.

Conclusion

In this study, Landsat 5 TM satellite imagery was employed to map new iron ore deposits in the Northern Province of Sierra Leone. The results show that the use of band ratios and principal component analysis using band ratios as input bands yields similar results and positively identifies the same two zones in the northeastern part of the study area, where iron oxides are predominant in the spectral response of the land cover. The two interest zones are 50 km apart from each other. The western zone (Zone 1) is suggested to be explored through in situ campaigns and geochemical analyses. However, for the eastern zone, or Zone 2, I do stress and strongly advocate against exploring or exploiting due to the presence of endangered species, including chimpanzees under high levels of threat, among some other mammals, birds, and amphibians. Further research using this methodology and testing other satellite sensors is recommended. For instance, it would be of high interest to analyse the other greenstone belts, such as the Kambui and Gori, which are also part of the Sula Group. This group in particular is of special interest for its high likelihood of hosting BIFs. Lastly, another region of interest would be the Marampa Group (located NW of Marampa), which is outside the study area.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES
