DOI: https://doi.org/10.20372/star.v8i2.03
ISSN: 2226-7522 (Print) and 2305-3372 (Online)
Science, Technology and Arts Research Journal
Sci. Technol. Arts Res. J., April-June 2019, 8(2), 37-50
Journal Homepage: https://journals.wgu.edu.et

Original Research

Mapping and Characterization of iron ore deposits in Bikilal area, West Wollega Zone, Oromia, Ethiopia

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Abstract

The ground magnetic survey and 2D electrical resistivity imaging methods were carried out to map and characterise the iron ore deposits in the Bikilal area, West Wollega Zone, Ethiopia. The magnetic data were collected using a proton-precession magnetometer and the 2D electrical resistivity imaging with the SYSCAL R1 PLUS Switch-72, respectively. The magnetic data points have a spacing of 50m along each of the five profiles. The Wenner electrode configuration was applied to collect the 2D electrical resistivity imaging data points along the same profiles. The magnetic field data were processed and analysed by Oasis Montaji software, while the electrical resistivity data were filtered, analysed, and processed by Prosys-II and RES2DINV software. The results of the magnetic analysis mapped the mineralized zones and indicated the iron ore deposits in the south-west, north-east, and central parts of the study area. The results of the ERT showed that the depth of iron ore deposits ranges from 7m to 16 m, with an average depth of 9m on the survey profiles and a thickness of 8m to 30.8m. The integrated results of magnetic and 2D resistivity methods mapped and characterised the potential occurrence of iron ore deposits as the response of high magnetic intensity and low resistivity in the study area. Finally, the depth and thickness of the iron ore deposits were delineated and mapped.

Article Information

Article History:
Received : 25-04-2019
Revised : 17-05-2019
Accepted : 26-06-2019

Keywords:
Magnetic method, Iron Ore; Magnetic Anomaly; 2D ERT, resistivity

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INTRODUCTION

Iron is the fourth most common element in the earth's crust after oxygen, silicon, and aluminum and is the second most abundant metal next to aluminum in the earth's crust (Satyendra, 2015). It is found in nature in the form of compounds with oxygen-forming iron oxide minerals, such as magnetite (Fe_3O_4), hematite (Fe_2O_3), siderite ($FeCO_3$), pyrite (FeS_2), goethite ($Fe_2O_3H_2O$), and other compounds (Rosli S., 2012; Lawan A.M., 2018). The most economical iron ore deposits belong to magnetite, hematite, and limonite, respectively. Magnetite occurs in igneous, metamorphic, and sedimentary rocks, while hematite is associated with vein deposits as a product of the weathering of magnetite. Iron ore can be in the form of rocks or minerals from which metallic iron can be extracted for economical purposes (Gordon, 1996).

In Ethiopia, the three different types of iron deposits include magmatic iron (Fe-Ti type) of Precambrian age from Bikilal and Melka Arba areas; banded iron formation (BIF type) of Precambrian age from Kore, Gordoma, and Chago areas; and lateritic iron deposits (residual type) from Melka Sedi, Garo, Gato, Billa, Gambo, and Gammalucho areas. Among these, Garo, Dombova, and Melka Sedi (in Kaffa) are the biggest of about 12.5 million tonnes each in terms of reserve. Metals associated with iron in these deposits are mainly Mn, Au, Pt, Ni, and Co (Tadesse, 2006). Mostly, the Bikilal, Sirba, and Kore iron ore deposits and mineralization in the Western and Southwest Belts of Ethiopia were identified. The Bikilal deposit is dominated by apatite, followed by magnetite, and consists of a layered hornblende gabbro with massive and disseminated ilmenite-magnetite (Ghebre W.M., 2010). Besides the Bikilal deposit, the Geological Survey of Ethiopia (GSE) has identified many iron occurrences in the areas of Wollega (Gordana, Worakalu, Chago, Yubdo, Nejo, Kata, Tsoli, Sirba-Korkandi, Kiltu Kara, and Wobera Kiltu), Bale (Melka Arba), Kefa (Mai Gudo and Ghimira), Hararghie (Cherecher), and Jijiga. Mamo Ghebre (2010) described the Petrogenesis of Bikilal-Ghimbi Gabbros, geology, mineralogy, and whole rock analysis with their grade implications. It was also correlated with gabbro intrusion occurrences in the West Wollega Zone of Ghimbi District (Didisa Bikilal) area with those of the East Africa region, such as the Phalaborwa and Schiel igneous complexes of South Africa and Sukulu (Uganda) carbonatite and the Villa-Nora (South Africa) basic-layered gabbros.

The studies conducted by Ghebre, W.M. (2010) disclose that there were no detailed geophysical data incorporated, particularly magnetic and 2D electrical resistivity tomography (ERT) methods, during the geological study conducted at the Bikilalal iron deposits. Thus, the most widely used geophysical techniques in mineral exploration work included the magnetic, gravity, electrical, and electromagnetic methods. Electrical resistivity is routinely used for a wide range of applications, ranging from lithological variation, hydrology, and environmental pollution to mineral exploration (Al Dulaymi et al., 2012; Fon et al., 2012; Teikeu et al., 2012). Among the techniques, magnetic and 2D electrical resistivity tomography methods were used to map and characterise the detailed iron ore deposits in the subsurface information. For this purpose, magnetic and 2D electrical resistivity imaging methods were used in this study to reduce the uncertainty innate in the geophysical data combined with the geological knowledge of the study area.

Location and accessibility of the study area

The Bikilal study area (Figure 1) is located in Oromia Regional State, Ghimbi District, Western Ethiopia, about 441 km west of Addis Ababa. It is located at a geographical coordinate of 1021000 mN to 103600 mN latitudes and 80600 mE longitudes. The area is accessible by a four-wheel vehicle drive through the asphalted road of 441 km from

Addis Ababa to Ghimbi town and then to Bikilal through a 24km dry weather road. Bikilal village covers the area of the iron ore deposit located in the northern part of the study area and includes Sijo, Abo, and Figa, Jare, and Garjo villages. The inhabitants of the area are Oromo people, who lead their lives through agriculture (Figure 1).

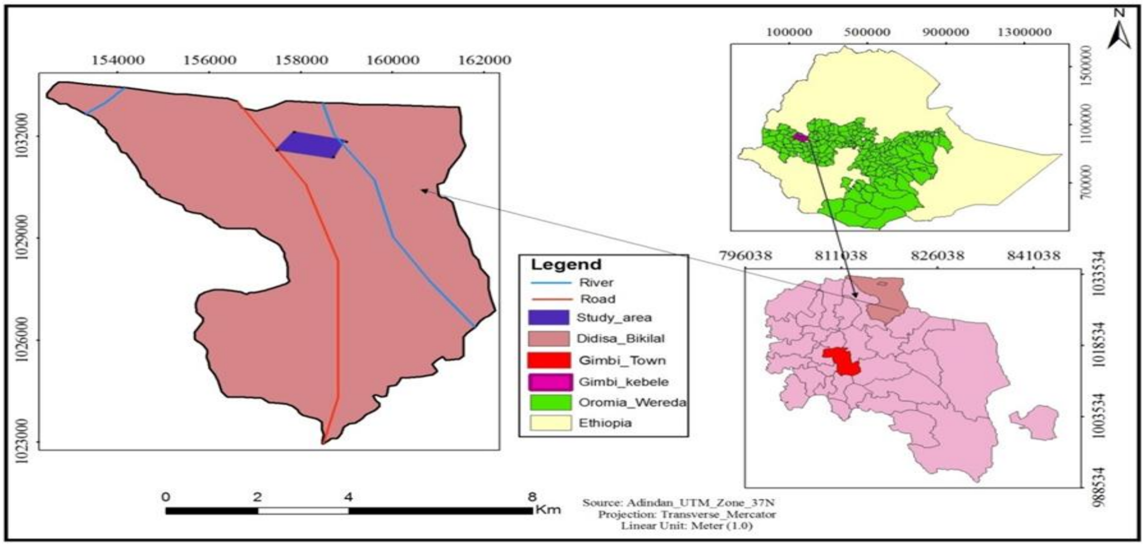

Figure 1 *Map of the study areas*

Geological Setting

Regional Geology

Iron ore deposits are distributed in different regions of the world under varied geological conditions and in different geological formations. The largest ore concentration is found in banded sedimentary iron formations of the Precambrian age. These formations constitute the bulk of the iron ore resources in the world (Satyendra, 2015). Iron ores have a wide range of formations in geologic time as well as a wide geographic distribution. Iron ores occur in a wide variety of geological environments, in igneous, metamorphic, or sedimentary rocks, or as weathering products of various primary iron-bearing materials. The geological formations in Ethiopia range in age from Precambrian to recent. The Phanerozoic sedimentary and volcanic rocks cover most of the central highlands, rift valley, and eastern lowlands of Ethiopia. The Precambrian metamorphic rocks, which consist of low-grade volcano sedimentary metamorphic rocks and high-grade gneiss and schist, outcrop only in the northern, western, and southern parts of the country. The most important economic minerals that are found in Ethiopia can be grouped into metallic minerals, industrial minerals, and energy resources. The metallic minerals hosted mainly in the basement rocks include various occurrences of gold (Adola), platinum (Yubdo), rare earth elements, columbo-tantalite, copper, lead, zinc, iron, and nickel. Several gabbroic intrusions occur within the Western Ethiopian Shield.

The Bikilal-Ghimbi gabbric intrusion is one of the largest intrusions in the region and is considered to be a syn- to post-tectonic type based on its apparently intrusive relationships with the surrounding gneiss (Allen and Tedese, 2003). As part of a syn- to post-tectonic intrusion, the Bikilal gabbro complex intrudes the Precambrian gneiss, low-grade metamorphic rocks, and minor ultramafic (Ghebre W.M., 2010). The Bikilal Ghimbi gabbro is the largest and best documented, and hence it is used as a comparison for the other bodies. It consists of olivine gabbro in its centre and hornblende gabbro and hornblendite at the perimeter (Binyam Woldemariam, 2008).

Local Geology of the Study Area

Based on surficial and subsurface (pitting and trenching) information, field phosphate tests, and visual examination of apatite mineralization, three major and three minor favourable lithological units were identified in the northern extreme curvature of the Bikilal gabbroic complex. The major lithological units are olivine/pyroxene gabbro, hornblende gabbro, and hornblendite (Figure 2). The minor lithological units are pegmatites, anorthosite, and metasediment (Ghebre, 2010). The Sijo Bikila area is underlain by the major lithological units, olivine/pyroxene gabbro, hornblende gabbro, and hornblendite . The local geological map of the study area revealed that the area was underlain mainly by hornblende and olivine/pyroxene gabbro (Figure 2).

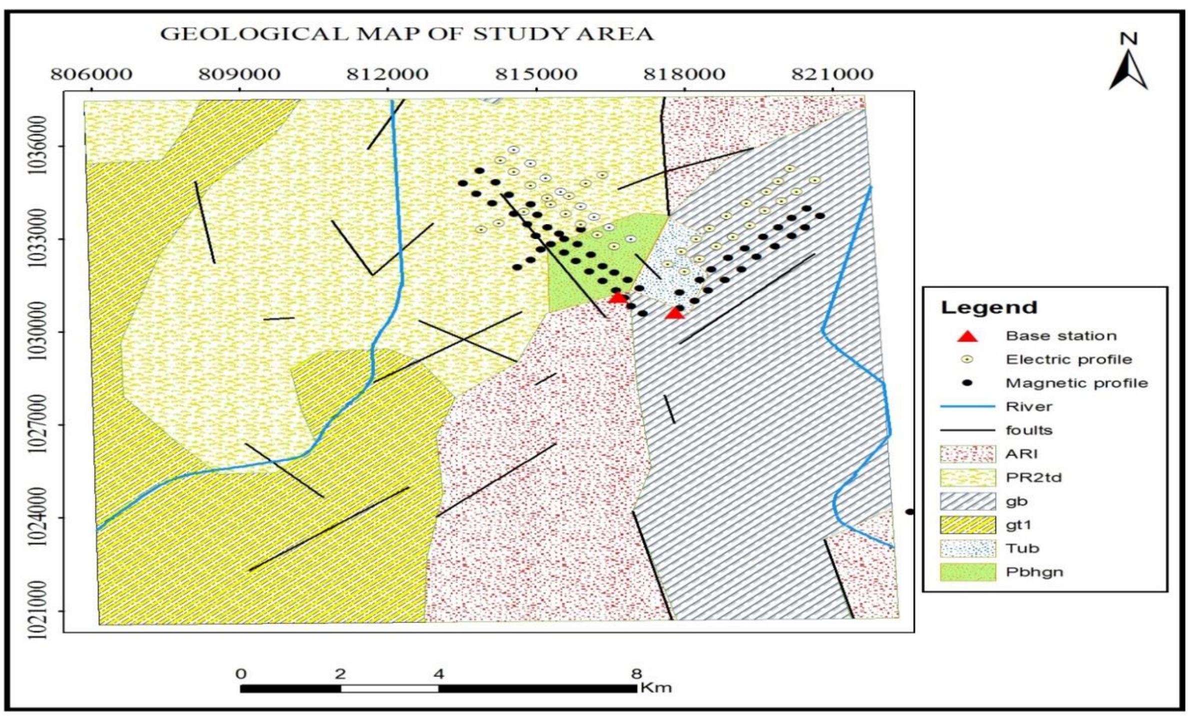

Figure 2 *Geological map of Bikilal area*

Materials and Methods

In this study, magnetic and 2D electrical resistivity tomography geophysical methods were used to map and characterise the deposits of iron ore in the Bikilal area. Five separate profiles were selected for each magnetic and 2D electrical resistivity imaging method to cover the survey area (Figure 3).

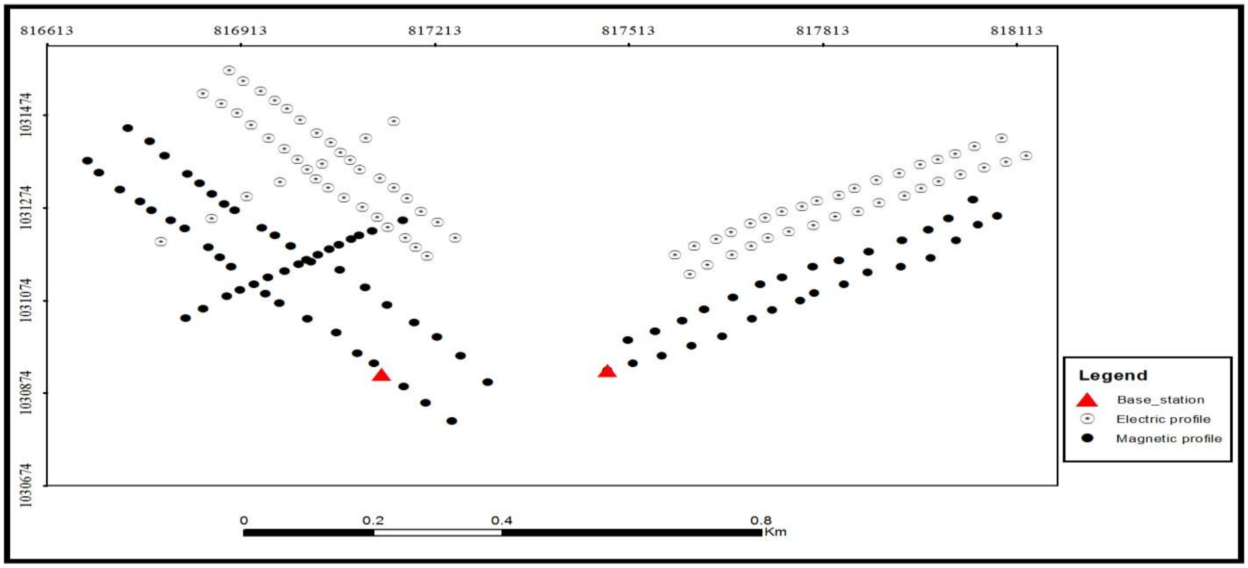

Figure 3 *Magnetic and Electric survey lines in the study area*

Magnetic Method and Its Instrumentation

The magnetic data points were measured along five profiles using a Proton Precession Magnetometer-600 model at spacing intervals of every 50m. These profiles were selected based on the topography and accessibility of the study area. Prior to the magnetic field data measurement, the survey was started with the establishment of a base station within the study area that was easily accessible and free from magnetic noise. The total magnetic field data points were collected from all the profiles with 100-m spacing in between each profile. The station position and elevation measurements were made using a Garmin 72.

2D Electrical Resistivity Imaging Method and Its Instrumentation

The 2D electrical resistivity surveys were performed using the IRIS instrument SYSCAL R1 PLUS Switch-72. It was used to measure the apparent resistivity in ohms. The 2D electrical resistivity imaging technique is a fast and cost-effective technique that covers both vertical and horizontal changes in the surface and subsurface of the geological formations of the study area. The Wenner array configuration was selected for this study due to non-invasive measurements and simple correlations between the results. This configuration is able to provide better resolution and horizontal coverage of the subsurface.

RESULTS AND DISCUSSIONS

In this section, the data collected was interpreted in order to investigate the iron ore deposit in the Bikilal-Ghimbi area using magnetic and 2D electrical resistivity imaging methods. The magnetic and 2D resistivity imaging techniques were applied along five selected profiles in the study area to delineate and determine the extensions of the depth, width, and thickness of the locations of the underlying iron deposits. Furthermore, a correlation between the magnetic anomaly profile plot and the inverse model electrical resistivity section was done. The qualitative interpretation of the 2D resistivity models in geophysical terms is carried out in order to locate the presence of a suspected mineral ore zone using electrical profiling, as revealed by Ratnakumari et al. (2012). The results, discussions, and interpretation of different magnetic anomalies and 2D electrical resistivity maps were discussed separately.

Magnetic Anomaly Map

Meaningful geophysical results, discussions, and interpretations for magnetic data were done by integrating the magnetic anomaly maps with local geological information in the Bikilal area. The magnetic data were processed through the Oasis Montaji software package to locate iron ore deposits and map their zones and extensions through the interpretation process. From various techniques of analysis, the total magnetic intensity map, residual magnetic intensity map, and analytical signal map were generated.

Total Magnetic Intensity (TMI) Map

The total magnetic field anomaly map was produced after the diurnal corrections were applied to the collected data. The TMI map of the study area shows that the magnetic intensity distribution and variation of the subsurface are categorised as low, moderate, and high magnetic anomaly zones, represented by zones A, B, and C, respectively. The magnetic anomaly value of zone A is relatively low and varies from 32970.6 nT to 33492 nT, and this zone dominates the central and south-eastern part of the surveyed area, which is the response of the subsurface rock units probably associated with weak zones filled with weathered material. The magnetic anomaly value of zone B is relatively moderate and varies from 33492.7 nT to 35098 nT. Zone B is mainly concentrated in the central part and designated as the intermediate magnetic anomaly responses, which are related to the subsurface rock units of granite and basalt. The magnetic anomaly in zone C is relatively high and varies from 35098 nT to 37127 nT. It covers a large portion of the study area that is characterised by a very high magnetic anomaly response. It is a considerably high value since the area consists of magnetite, where the high anomalous values are acceptable. The distribution manifested particularly at the end parts of the north-western, north-eastern, south-western, and southern parts of the study area as a result of shallower-depth deposits of the iron ore (Figure 4).

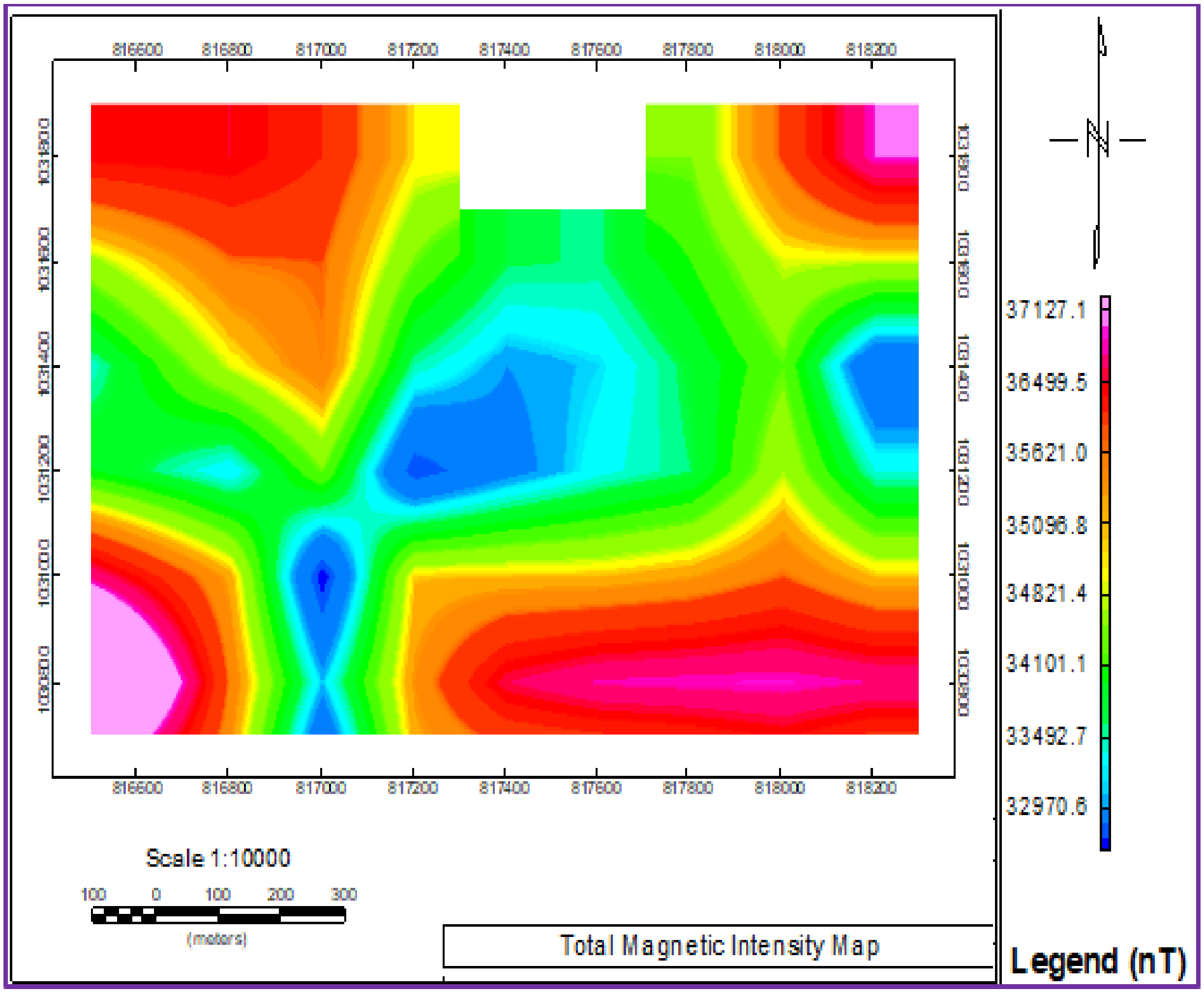

Figure 4 *Total magnetic field intensity map*

Analytical Signal Magnetic Map

An analytical signal map was produced to enhance shallow sources and contact zones by removing the dipolar nature of Earth's magnetic field observed in the total magnetic field. Analytic signal values are generally coincident with the total magnetic anomaly peaks observed in the residual map of Figure 5, and geological boundaries are evident. The south-west, north-east, and central parts of the area are characterised by a high magnetic response, which is the effect of magnetite iron ore (Ghebre, 2010). The rocks in the Bikilal area are classified as olivine/pyroxene gabbro, hornblende gabbro, and hornblendite, which were the major lithological units, and pegmatites, anorthosite, and meta-sediment were the minor lithological units (Ghebre, 2010).

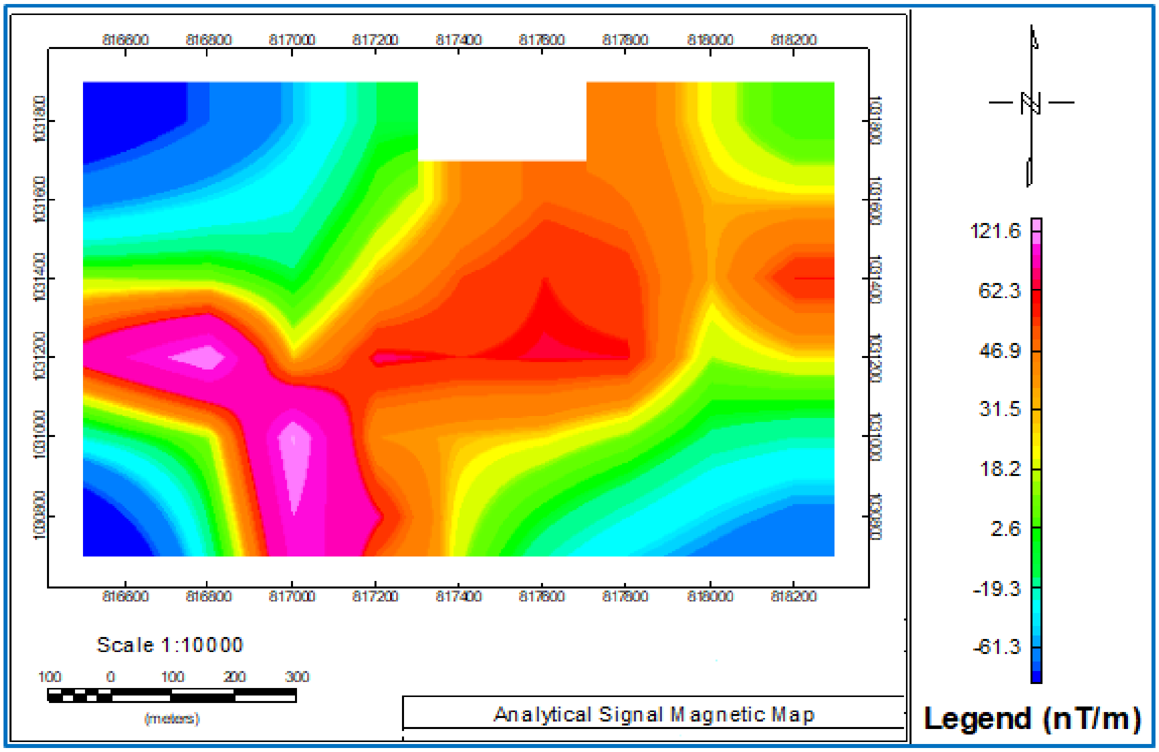

Figure 5 *Analytical signal magnetic map*

The Horizontal Gradient Magnetic Map

The amplitude of the horizontal gradient of the magnetic data in the study area was calculated in the frequency domain and is illustrated in Figure 6. It shows the qualitative interpretation of the horizontal gradient data. The area may be dissected by major faults striking in the south-west, south-east, north-east, and central parts of the study area. This indicates that the iron ore bodies in the area are structurally controlled, especially for the shallower sources. This result is important, as a selection of new areas for mineral exploration can be made based on the horizontal gradient map. The high amplitude magnetic anomaly and the associated maximum value of the analytical signal anomaly of the magnetic map gave the signature of subsurface structure in the same location as the assumed iron ore bodies. Since the magnetic method observes the relief and structures of the ore bodies, the amplitude of the magnetic anomaly associated with the expected iron mineralization is high enough to map and characterise the iron ore in the basement.

Thus, the interpretation of the analytical signal and the horizontal gradient of the magnetic data indicated that the area is characterised by existing iron mineralization and manifestations that enabled the tracing of several subsurface geological structures (the iron mineralization zone) trending in the south-west, north-east, and central parts of the study area. Therefore, the maximum magnetic anomaly value was assumed to be olivine/pyroxene gabbro, whereas the minimum magnetic anomaly value is metasediment (Figure 6).

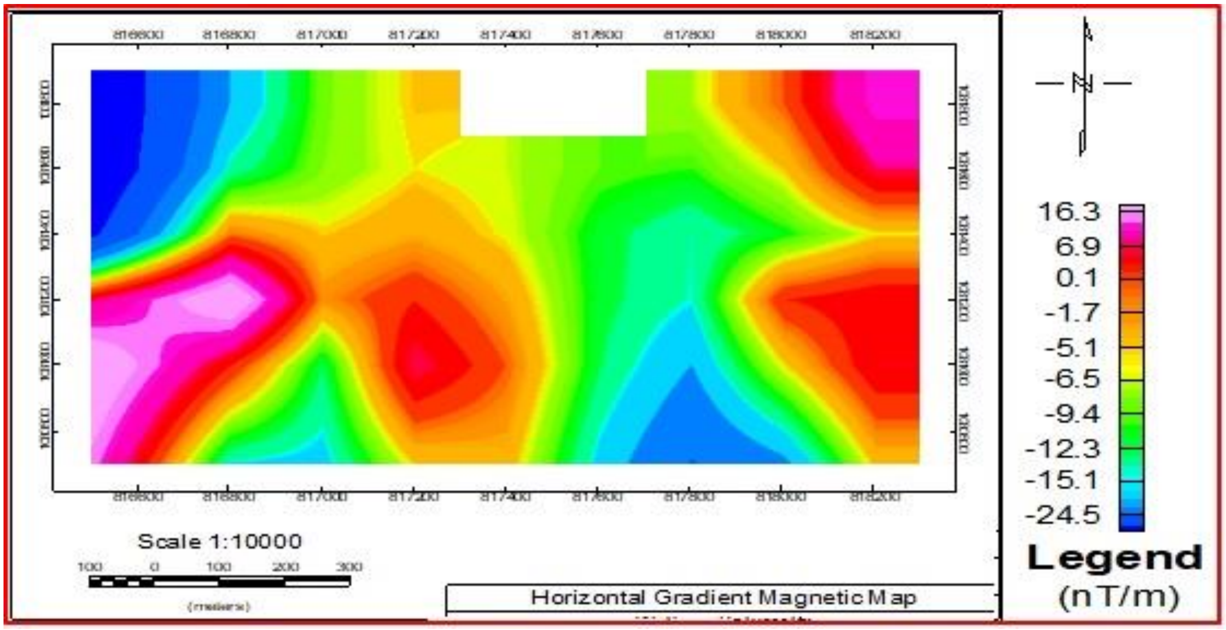

Figure 6 *The Horizontal Gradient magnetic map of the study area*

Results, Discussions, and Interpretations of 2D Resistivity Map

The geological interpretations for the five electrical resistivity-imaging profiles were done by integrating the range of resistivity values from the 2D electrical resistivity-imaging sections and the electrical properties of earth materials given in the table appendix (Rosli, S. et al., 2012) with local geological information of the study area. The resistivity values of several industrial metals, such as iron, have extremely low resistivity values (Loke, 2000). The resistivity imaging technique was applied along five selected profiles in the study area to delineate the locations of the underlying mineral deposits. The measured data were subjected to intense filtering by Prosys II software before the interpretation process. Then, the filtered data were analysed through the inversion processes using the RES2DINV ver.3.53g software package to locate iron ore deposits and determine their extensions and depth through the interpretation process.

Profile One

Profile one runs across the North-West to South-East directions, covering a total length of 355m. Figure 7 shows that the electrical resistivity model of profile one reveals variations in subsurface resistivity ranging from 149 Ωm to 2145 Ωm. Based on the 2D electrical resistivity model, the variation of subsurface resistivity can be categorised as three zones, namely: Zone A, Zone B, and Zone C.

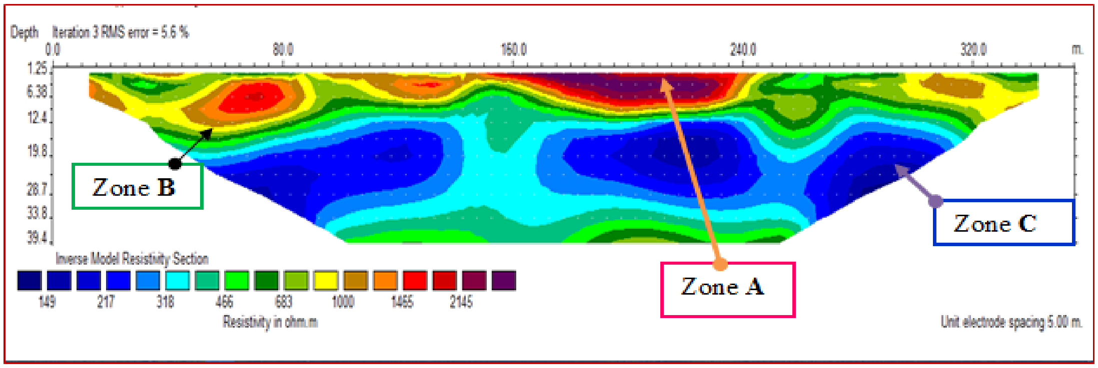

Figure 7 *Inverted 2D electrical resistivity imaging along profile one*

Zone A could be the response of the loose sand in the top part. Zone B is a soil part in the form of granite, and zone C is designated to be magnetite and hematite, which are major constituents of the iron ore type occurring within the study area (Lindgren and Waldemar, 1933; Rosli, S. et al., 2012). Based on the local geological map of the study area, this could be the response of gabbro intrusive rock, particularly olivine or pyroxene. The 2D electrical resistivity imaging of profile one in Figure 8 clearly shows the depth of the iron ore deposit is about 12m below the ground surface and has a 260m width and 17m thickness. Zone B, with its broad low resistive zones, seems to be the response of the olivine/pyroxene unit, which is the dominant lithology of the study area.

Profile Two

The electrical resistivity model of profile two in Figure 8 is viewed as different geological stratifications based on the inverse model electrical resistivity section, the electrical properties of earth materials as shown in Figure 8, and the local geological information of the study area. Based on the resistivity value shown in the model, the variation of subsurface resistivity is zoned into high, moderate, and low electrical resistivity zones, which are named, respectively, zone A, zone B, and zone C.

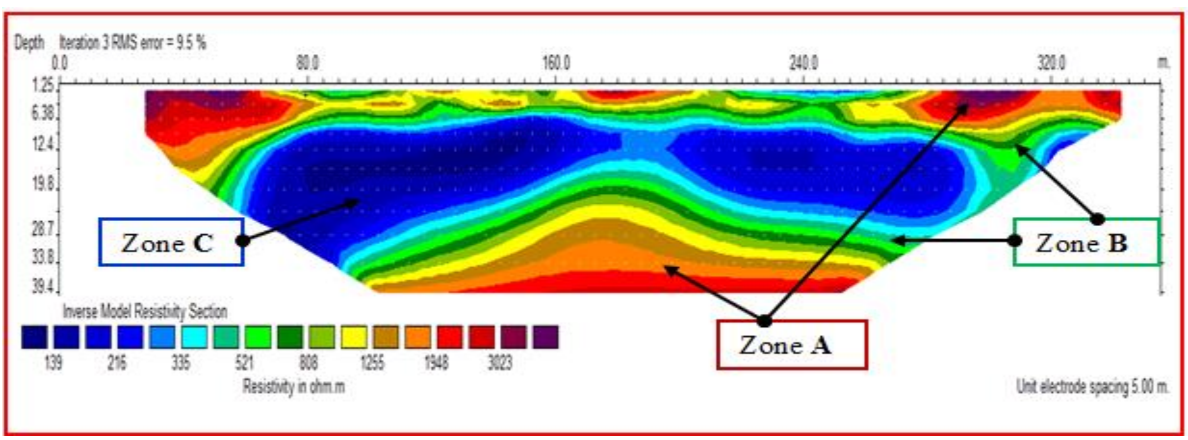

Figure 8 *Inverted 2D electrical resistivity imaging along profile two*

The upper shallow depth of the high resistivity zone (Zone A) was observed to be the slates and loose sand lithologies units. Zone B has a thin layer with a relatively moderate resistivity value varying from 521 Ωm to 1255 Ωm and is interpreted as granite and basalt in the top and bottom parts. Zone C (in the middle part) is relatively thick, very low, and varies from 139Ωm to 335Ωm. This range falls within the electrical resistivity range of magnetite and hematite, which are major constituents of the iron ore type occurring within the study area (Lindgren and Waldemar, 1933). Based on the local geological map of the study area, this could be the response of gabbro intrusive rock, particularly olivine/pyroxene, as also described on profile one. The inverted 2D electrical resistivity imaging of profile two in Figure 9 clearly shows the depth of the iron ore deposit is about 6m below the ground surface and has a width of 240 m and a thickness of 21 m.

Profile Three

Profile three runs across a south-west to north-east direction in transverse to profiles one and two, with a total length of 355m. Figure 9 shows the model with different subsurface resistivity values ranging from 76.7 Ωm to 1820 Ωm. Zone A, described in Figure 9, reveals a relatively high resistivity that varies from 1158 Ωm to 1820 Ωm, and it could be the response of the loose sand, greenstone, and slates in the top and bottom parts whereas zone B has a moderate resistivity varying from 298 Ωm to 736 Ωm and is lithologically interpreted as granite and basalt (Figure 9)

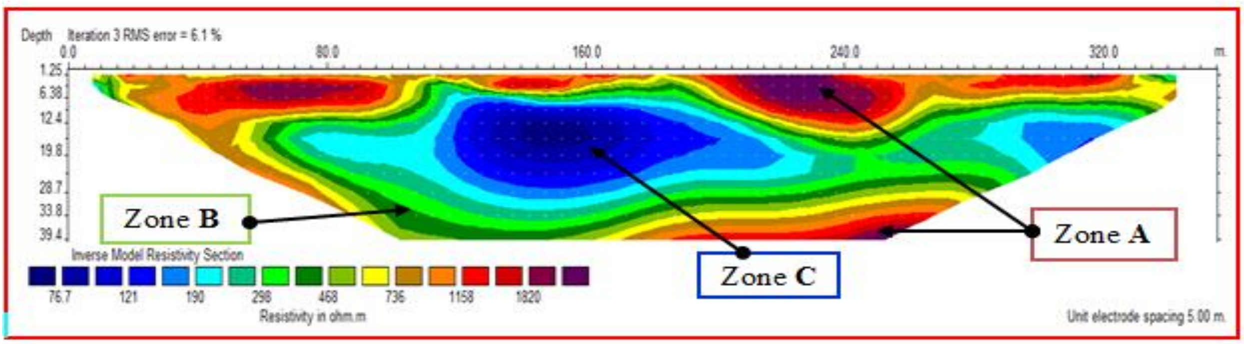

Figure 9 *Inverted 2D electrical resistivity imaging along profile three*

The electrical resistivity value of zone C (in the middle part only) falls within the electrical resistivity range of magnetite and hematite, which are major constituents of the iron ore type occurring within the study area. Based on the local geological map of the study area and the 2D electrical imaging model, it could be the response of gabbro intrusive rock, particularly olivine or pyroxene, and the depth of the iron ore deposit is approximately 8m below the ground surface with a width of 150m and an 8m thickness

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Profile Four

Figure 10 shows the 2D resistivity imaging of profile 4 along the south-west to north-east directions. The information obtained revealed Zone A is the response of the green stone and slates at shallow depth of the top part and signature of appearance at the bottom layer of the model; Zone B is the response of a thin layer of gabbro intrusion, granite, and basalt rocks in the area; whereas Zone C is regarded as the magnetite and hematite, which are major constituents of the iron ore type occurring within the study area. The occurrence of iron mineralization along this profile is at a depth of 12 m, a distance of 170m to 300 m, a lateral width of 130 m, and a thickness of almost 30.4m.

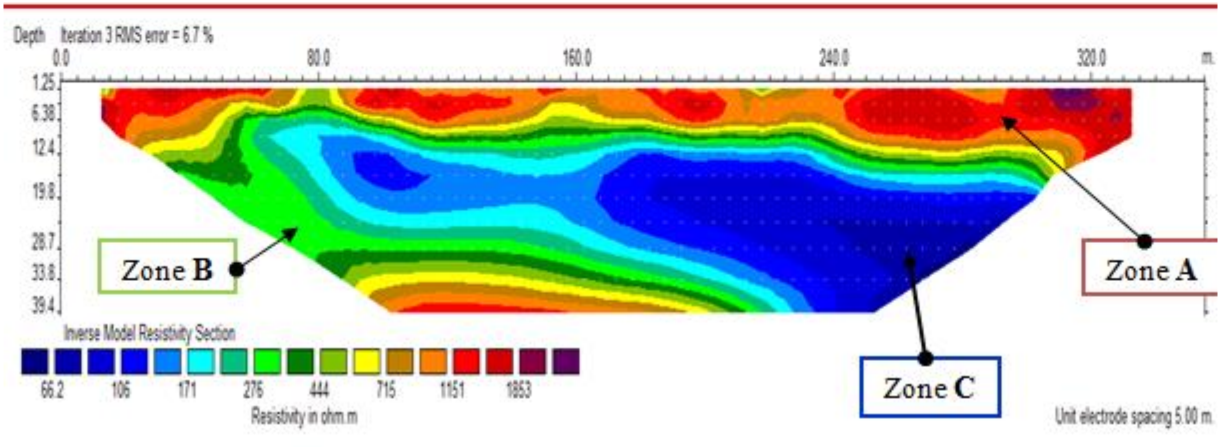

Figure 10 *Inverted 2D electrical resistivity imaging along profile four*

Profile Five

Profile five runs in parallel to Profile 4, which is oriented in a south-west to north-east direction, covering a total length of 355m. Zone A is the region considered to be the result of the response of green stone and slates, while Zone B is the consequence of granite and basalt occurrences in the central and partially in the bottom parts, as shown in Figure 11. However, not all hematite rocks containing iron minerals occupy this profile due to the discontinuous nature of iron mineralization (Octova & Yulhendra, 2017).

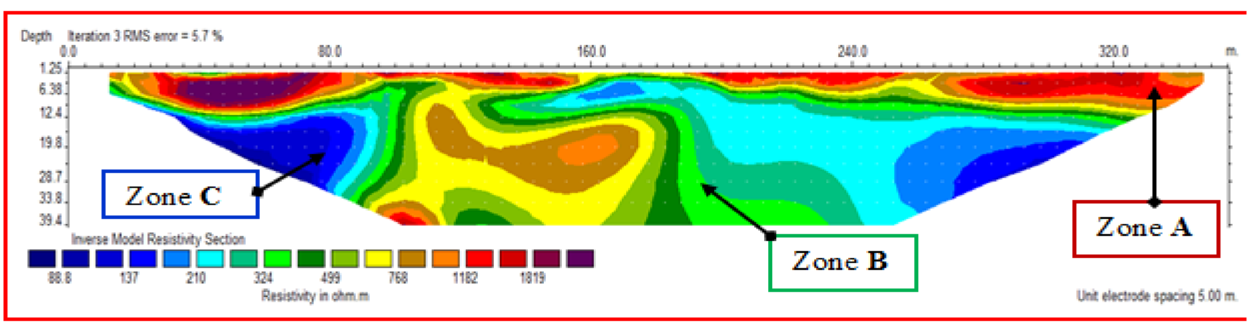

Figure 11 *Inverted 2D electrical resistivity imaging along profile five*

CONCLUSIONS

The purpose of this research is to map and characterise the iron ore deposit using magnetic and ERT geophysical methods in the Bikilal-Ghimbi area, West Wollega Zone, Oromia, Ethiopia. Based on the results of the magnetic and ERT methods, which were constrained by the previous geological surveys and local geological map of the study area, the researcher pointed out the following conclusions:

The analytical magnetic signal map revealed numerous prominent wavelength anomalies, mostly in the south-west and northeast, and the central part, characterised by the highest anomaly values, showed the occurrence of potential iron ore deposits in the area. The area with high magnetic intensity in the analytical signal map and low resistivity values from the electrical resistivity model obtained revealed potential iron ore deposits starting at an average depth of 9m below the ground with an average thickness of about 20m. The 2D electrical resistivity tomography model characterised the area into three subsurface zones: high-resistivity rock units identified as loose sand, green stone, and slates; moderate-resistivity rock units as gabbro, granite, and basalt rocks; and low-resistivity rock units as magnetite and hematite ores. The results from the ERT clearly showed that the potential occurrence of iron deposits varies in depth, ranging from 7m to 16 m, with corresponding thickness in the range of 8m to 30.8 m.

The magnetic and ERT methods employed in this work have mapped and characterised the potential iron mineralization zones associated with the gabbro lithologic unit at a shallow depth favourable for exploitation.

Acknowledgments

The researchers acknowledge Wollega University's Department of Earth Sciences for allowing the research fund to carry out their work.

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