Vol. 19, n.° 2, pp. 77-84, 2020
Revista UIS Ingenierías
Página de la revista: revistas.uis.edu.co/index.php/revistauisingenierias

Gilsonite exploration by using electrical resistivity tomography with multi-electrode gradient array: A case study in Rionegro (Colombia)

Exploración de gilsonita usando tomografías de resistividad eléctrica con geometría tipo gradiente: Caso de estudio en Rionegro (Colombia)

Yesid Paul Goyes-Peñafiel [1a], Sait Khurama-Velasquez [2], Oleg Nikolaevich-Kovin[1b]

[1]Geological Faculty, Perm State University, Russian Federation. Orcid: [a] 0000-0003-3224-3747, [b] 0000-0003-1156-2802. Emails: [a] goyes.yesid@gmail.com, [b] onk2004@netscape.net
[2] Energy and and other non-renewable resources research group, School of Geology, Universidad Industrial de Santander. Orcid: 0000-0003-4324-9546. E-mail: skhurama@uis.edu.co

Received: 12 September 2019. Accepted: 28 November 2019. Final version: 10 March 2020.

Abstract

Subsurface exploration using geophysical methods has increased the prospective economic possibilities for new non-metallic minerals and other raw materials such as solid hydrocarbons. In this paper, we show results of electrical resistivity tomography (ERT) carried out by using the multi-electrode gradient array, and conducted with the main purpose of mapping the high resistivity anomalies related to the presence of solid hydrocarbons bodies. ERT profiles were interpreted trough considering the gilsonite evidence on rocky outcrops in the La Luna Formation (Ksl) and their respective lithological contact with the Bocas Formation (Jb). This study concludes that, both on the surface and in the subsurface, in the stratification plane of La Luna Formation, the gilsonite is a tabular and oblique shape, and the contact Ksl-Jb is faulty with an almost vertical inclination. However, different structural processes have contributed to the irregular formation and massive body of gilsonite. Finally, the study concludes that resistivity tomographies represent a reliable alternative for preliminary exploration stages. Since the cost of the method is relatively low in Colombia, it also serves as an economically viable alternative for small exploratory projects.

Keywords: gilsonite; asphaltite; electrical resistivity tomography; electrical prospecting; geophysical exploration; shallow geophysical method.

Resumen

La exploración del subsuelo usando métodos geofísicos ha incrementado las posibilidades económicas de prospección para nuevos minerales no metálicos y otros materiales tales como hidrocarburos sólidos. En este artículo, se muestran los resultados de la tomografía de resistividad eléctrica (ERT) llevada a cabo usando el arreglo multi-electrodo tipo gradiente, los cuales fueron usados para delimitar las anomalías principalmente de alta resistividad asociadas a la presencia de hidrocarburos sólidos. La interpretación de los perfiles en profundidad fue realizada teniendo en cuenta la evidencia de gilsonita en afloramientos de la Formación La Luna (Ksl) y su contacto con la Formación Bocas (Jb). Se concluyó que, en superficie y en profundidad, la gilsonita presenta forma tabular y oblicua respecto al plano de estratificación de Ksl, y que el contacto Ksl-Jb está fallado con inclinación casi vertical. No obstante, diferentes

ISSN Printed: 1657 - 4583, ISSN Online: 2145 - 8456,
How to cite: P. Goyes, S. Khurama-Velasquez, O. N. Kovin, “Gilsonite exploration by using electrical resistivity tomography with multi-electrode gradient array: A case study in Rionegro (Colombia),” *Rev. UIS Ing*., vol. 19, no. 2, pp. 77-84, 2020. doi: 10.18273/revuin.v19n2-2020008

procesos tectónicos han contribuido también a la formación de gilsonita en cuerpos masivos e irregulares. Finalmente, se pudo establecer que las tomografías de resistividad representan una buena alternativa para la exploración preliminar, y ya que los costos de este método son relativamente bajos en Colombia, representa también una alternativa económicamente viable que permite mejorar los proyectos exploratorios pequeños.

Palabras clave: gilsonita; asfaltita; tomografía de resistividad eléctrica; prospección eléctrica; exploración geofísica; método geofísico superficial.

1. Introduction

Gilsonite is a solid hydrocarbon, which along with the glance pinch and grahamite, are part of the asphaltite group ([7]) and differ mainly by their specific gravity and ranges of their softening point (above the 270 Celsius). Gilsonite has been documented by [3] in tabular and vertical forms, as well as being aligned with local fractures and regional faults. One of the most studied areas with gilsonite has been discovered in the Uinta basin in Utah (USA), where, according to [16], geochemical and geophysical methods are proposed to explore the gilsonite dykes covered by alluvial deposits with a thickness of less than 5 meters.

A gilsonite deposit in Rionegro (Colombia), with the same classification characteristics as those found in the Uinta basin, was described and characterized with geochemistry, vertical electric soundings, and parametric electrical tomography in [14], which revealed a correlation between an increase in apparent resistivity and the occurrence of gilsonite in geometric and massive bodies. The contrast of the resistivity between the host rock and the gilsonite was widely studied by [6], although it was analyzed only for perfectly tabular forms of gilsonite embedded in a sedimentary rock with little deformation. By considering the recent and current use of the electrical resistivity method for different studies and/or characterization of gilsonite and other types of bitumen [10], [11], [12], [1], the use of electrical resistivity tomography (ERT) with the multi-electrode gradient array was proposed for the deposit located in Rionegro. This study aims to evaluate the lateral and in-depth distribution of the veins and massive bodies associated with the gilsonite.

2. Geological setting

The deposit is located in the department of Santander, coinciding with the delimitation of the sedimentary basins ([2]). Figure 1 shows that study area (ZE) is located in northeastern Colombia exactly above the northeast boundary between the middle Magdalena Valley basin (VMM) and the Eastern Cordillera (CO).

According to [9], due to the general influence of a high structural control by the Lebrija Fault in this sector, this area has been identified as a complicated compressional margin where deformation increases continuously. In the area of geophysical exploration, Jurassic and Cretaceous rocks comprised of shales and weathered siltstones come from Bocas Formation (Jb), hard limestone shales and phosphate layers of La Luna Formation (Ksl), old Quaternary deposits (Qal) of Magdalena River, and recent alluvial deposits (Qtf) of La Julia creek.

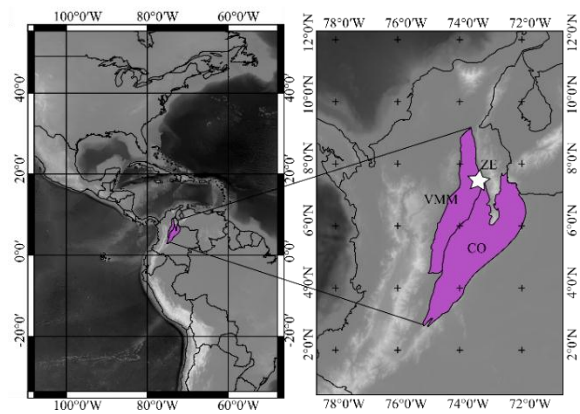

Figure 1. Location of the study area (ZE) in the northeast limit of the sedimentary basin of the Middle Magdalena Valley (VMM) and the Eastern Cordillera (CO). Source. The authors.

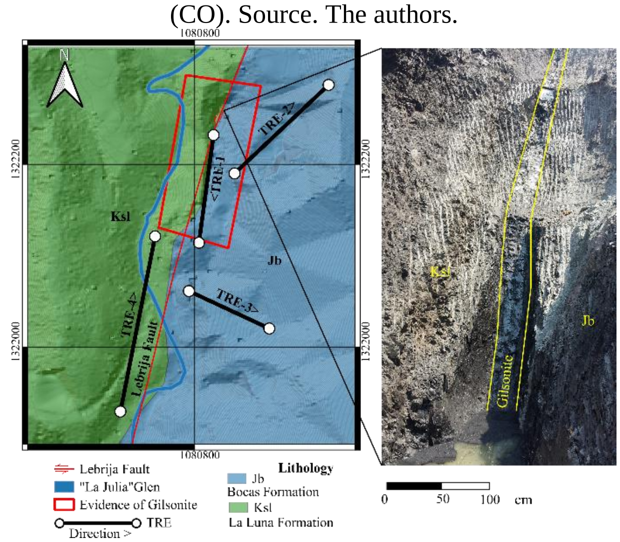

Figure 2. (Left) Geological map and polygon with confirmed occurrence of gilsonite and TRE localization. (Right) Gilsonite dike in vertical tabular form at the geological contact Ksl-Jb. Source. The authors.

The mining of gilsonite is carried out on the lithological contact between the La Luna Formation and the Bocas Formation (see Figure 2). In this zone, the dip of La Luna Formation is almost vertical and abundant calcareous nodules and local deformation in small areas are attributable to the Lebrija Fault. Figure 3 shows the bedding of La Luna Formation and its deformation in areas adjacent to the gilsonite dyke.

3. Methodology

Previous and related works in gilsonite exploration and characterization are shown in [15], [5], and [6], which describe the conditions of formation and use of geophysical methods to explore the occurrence and to optimize the development of natural bitumen deposits. In [6], by using the gish-rooney method, found that there is a range of resistivity of 25000 - 100000 Ω-m-cm between the solid bitumen and host rock. [12] through useing a wenner array and drilling holes found a relationship between the solid bitumen and a maximum resistivity of approximately 153 Ω-m. In addition, [12] associated gilsonite ore bodies with the highest resistivity values. However, geological conditions cause the range of resistivities to be variable.

The parameters used in this work for the electrical resistivity tomography were chosen considering the geological conditions of the study area (mentioned in Geological Settings). The multi-electrode gradient array was used for the tomography, and shows an increase in resolution and lateral continuity [13], thus evidencing anomalies associated with the massive bodies that cut the stratification or fracture planes. Four ERT profiles with a maximum depth of 33 meters were carried out over the study area. The equipment used for the geoelectrical data acquisition was a TERRAMETER ABEM LS, which deployed 72 electrodes, a set of LUND cables (4 cables with 21 outputs at the interval of 10 meters), connectors and 75 cable-electrode jumpers. Geoelectrical profiles had a length between 100 and 200 meters (depending on their location) with electrode spacing between 1.5 and 2.5 meters respectively. Therefore, the design of the survey (location, extension and separation between electrodes) was made considering the objective of the study and the terrain limitations at the land area.

Table 1. Geometry of electrical tomography profiles. L is the total length of the tomography lines and dx is the separation between electrodes

	East-1	North-1	East-2	North-2
ERT-1	1080823	1322231	1080807	1322113
ERT-2	1080846	1322189	1080949	1322286
ERT-3	1080796	1322060	1080884	1322019
ERT-4	1080721	1321928	1080759	1322120
	L (m)		dx (m)	
ERT-1	120		1.5	
ERT-2	144		1.8	
ERT-3	100		2.5	
ERT-4	200		2.5	

Source. The Authors.

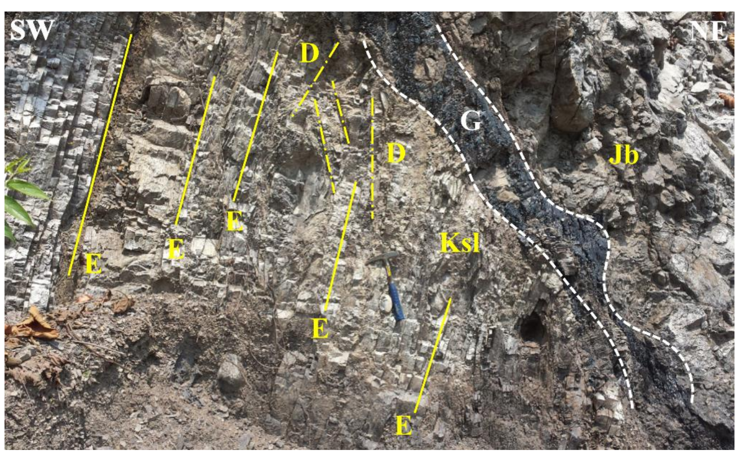

Figure 3. Dyke of gilsonite (G) in massive form with the northeast oblique inclination. Bedding plane (E) of La Luna Formation (Ksl) and deformed bedding planes (D). Bocas Formation (Jb) without distinct bedding.
Source: The authors

Table 1 shows length (L), x-axis sampling (dx) and coordinates (in the MAGNA SIRGAS coordinate system: EPSG 3116) of beginning (East-1, North-1) and final (East-2, North-2) points of each ERT profile. Electrical resistivity tomography observations were carried out using the multi-electrode gradient array. Previously, this method showed good results in vein prospecting ([5]), where the resistivity changes between materials are very similar to those studied in this work. According to the study conducted by [4], the gradient electrode array was developed for multichannel resistivity systems. The measurements were carried out by using a separation of *(s+2)/a* for the electrode current, and simultaneously or sequentially measuring all potential differences between the two electrodes with spacing *a* (see Figure 4). Here, the separation factor *s*, an integer value, is the maximum number of potential readings for an injected current. The factor *n* can be defined as the smallest relative spacing between a current electrode and a potential electrode. The factor *m* (midpoint factor, eq. (1)) can be defined as the average position of the potential electrodes with respect to the average position of the current electrodes [4]:

$$m = \frac{(x_N + x_M)/2 - (x_A + x_B)/2}{x_N - x_M} = \frac{x_{MN} - x_{AB}}{a} \qquad (1)$$

Where, x_B, x_A, x_N, x_M are the potential and current electrode positions ($x_B > x_A$, $x_N > x_M$), and x_{AB}, x_{MN} are the potential and current middle point electrodes respectively.

Once the factor *m* has been calculated, the values of the factor *n* can be found with the following equations:

$$m = n - \frac{s+1}{2} \; for \; x_{MN} \leq x_{AB} \; (m \leq 0) \qquad (2)$$

$$m = n + \frac{s-1}{2} \; for \; x_{MN} > x_{AB} \; (m > 0) \qquad (3)$$

Where *n* and *m* can be positive or negative numbers.

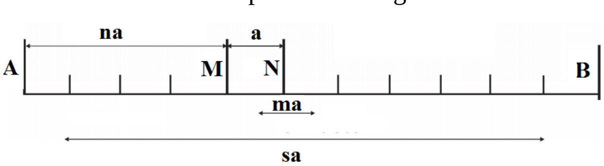

Figure 4. Diagram of the gradient array showing the position of the electrodes for a typical measurement with the current-potential electrode spacing of *(s + 2) / a*, where *s = 7*, *n = 2* and the midpoint factor *m = -2*. Source: Modified from [4].

The resistivity data inversion was carried out with the commercial software RES2DINV, which offers two inversion option: robust inversion and smoothness-constrained least square inversion [8]. According to others related works [5], [11], [12], [14], [15], [17], true resistivity of the subsurface was determined through the smoothness-constrained least-squares optimization algorithm that is normally used for data inversion. The Finite Element method was used for the forward model method and Cholesky decomposition for the solver (inverse problem). The main inversion settings were initial and minimum damping factor 0.1500 and 0.0300 respectively.

4. Results

Results of data inversion obtained to determine the true resistivity distribution in the tomography cross-sections are shown in Figure 5. The Root mean square (RMS) error for each inverted ERT-profile is well below 10% (Table 2) which are reliable results according to the complex subsoil studied. ERT-4 has the highest RMS error value, which corresponds to the profiles with high anomalies in both horizontal and vertical directions. The initial absolute error shows high values for ERT-1 and ERT-4, where lateral resistivity changes and there are ore-associated anomalies. In this study, the electrical resistivity tomographies were interpreted considering the lithostratigraphic units within the study area. Several irregularly shaped anomalies are observed in the resistivity sections. In Figure 5a, La Luna Formation is identified with an average resistivity of 71 Ω-m. The high resistivity anomaly is most likely related to the gilsonite body, which is located at the central part of the profile and has a resistivity up to 5000 Ω-m, a depth of 4.5 meters, and is approximately of 12 meters thick. There are some concretions of high resistivity that have smaller and more angular forms.

Table 2. RMS error for each inverted ERT-profile

Profile	RMS error	Iterations	Initial absolute error
ERT-1	9.99 %	9	42.447 %
ERT-2	6.04 %	10	14.029 %
ERT-3	4.47 %	16	11.890 %
ERT-4	10.94 %	7	51.857 %

Source. The Authors.

The profile in Figure 5b is characterized by the abundance of alluvial deposits and completely saturated zones that strongly reduce the average resistivity value in La Luna Formation (Ksl) (71 - 80 Ω-m for areas of alluvium distribution and 8.4 - 25 Ω-m for water saturated areas). No anomalies associated with gilsonite were detected in this profile. The boundary between La Luna (Ksl) and Bocas Formation (Jb) in terms of the geological unconformity can be determined at resistivity value of 135-180 Ω-m. The zone of the weathered bedrock (the areas of low resistivity) may poses some uncertainty in the interpretation of ERT results, because its resistivity is similar to that of the water saturated unconsolidated rock.

In Figure 5c, the Bocas Formation (resistivity range 125-210 Ω-m) is overlain by 78 m of unconsolidated sedimentary deposits that make the delimitation difficult of La Luna Formation, which has a resistivity range of 15 - 35 Ω-m (saturated rock) and 68 - 83 Ω-m (less saturated rock). In Figure 5c, the Ksl-Jb boundary between formations is shown according to the unconformity boundary.

ERT Profile in Figure 5d shows weathering clay soils with an average resistivity of 37.9 Ω-m. The first layer is underlain by the La Luna Formation (Ksl) which has vertical saturated zones (8.5 Ω-m). High resistivity anomalies observed in the middle of the ERT profile are most likely associated with the gilsonite body (the average resistivity 1438 Ω-m) and an almost circular shape elongated horizontally. Additionally, a wide anomaly with values in a range of resistivity from 8.58 Ω-m to 40.25 Ω-m was found in the resistivity section. This zone corresponds to a tabular body 20 meters wide and completely vertical, which is associated with fractured, saturated gilsonite deposits.

5. Conclusions and discussions

The electrical resistivity tomography method was applied as a valuable alternative for the exploration of gilsonite in the Rionegro municipality (Colombia).

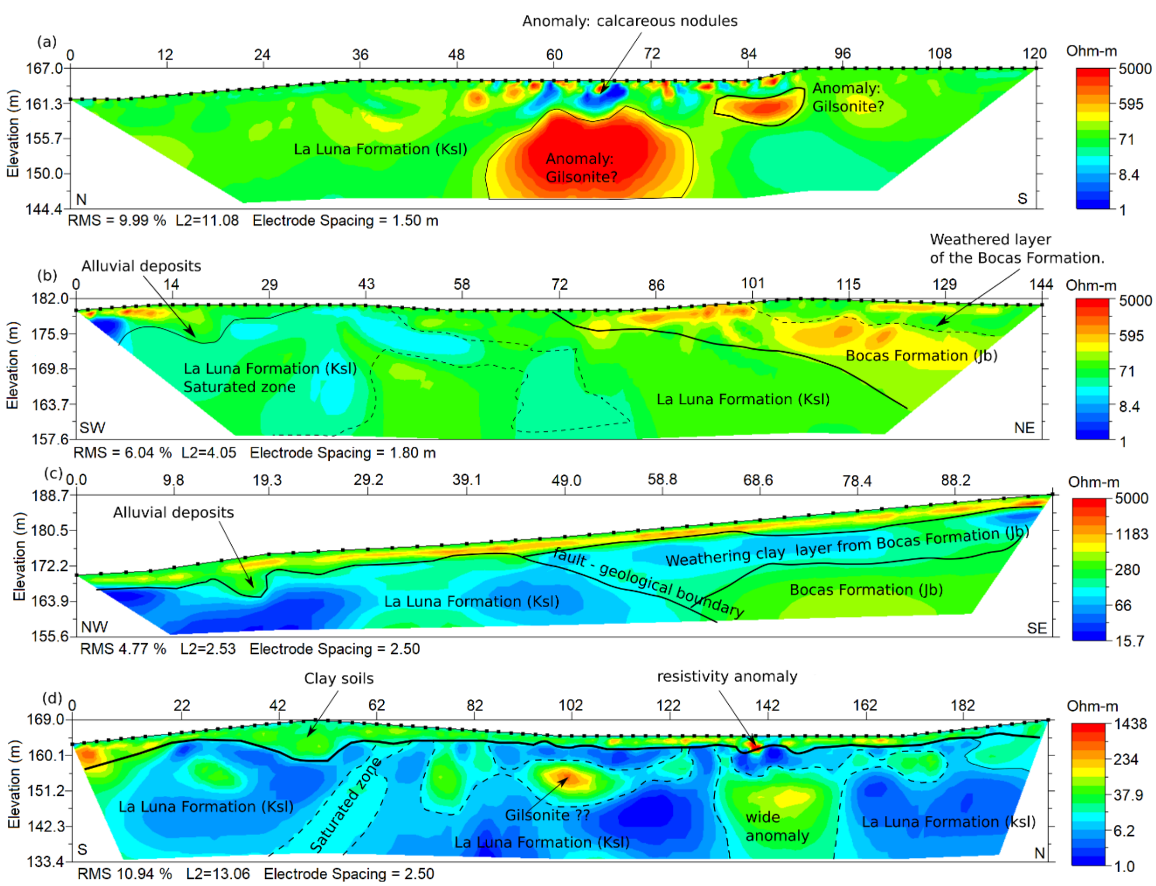

Figure 5. Interpretation of the electrical tomography data identifying main high resistivity anomalies corresponding to gilsonite occurrence. (a) ERT-1, (b) ERT-2, (c) ERT-3 and (d) ERT-4. Low resistivity anomalies are mainly associated with water saturated zones and characterize the moisture content of Ksl and Jb, and the highest resistivity anomaly is related to gilsonite bodies. Source: The authors. Image modified with the authorization of the company LAVGR SAS.

Results from the preliminary studies had shown that the method could have a direct application for surveying this material, which opens new possibilities to explore unconventional resources. This method has important economic implications because of the location of solid hydrocarbons at shallow depths. In this work, the gradient geometrical array and the equipment adapted to the geological and logistic conditions of the Middle Magdalena Valley (VMM) Basin and succesfully explored the solid hydrocarbons.

The gradient array generates valuable results in gilsonite veins survey and can be effectively applied for the resistivity contrasts of the lithologies present in La Luna Formation. Due to the complicated topography of the study areas at the open pit mine, the electric tomography method with the gradient array was adjusted to the geometrical restrictions, because it allows measurements with 1 current injector electrode to be collected. The separation between the current's electrodes should be fixed at up to seven times the distance between the potential electrodes. In addition, the observation grid for the prospection of solid hydrocarbons must have the minimum distance between electrodes allowed by the geophysical equipment, because it is expected that the anomalies caused by the presence of asphaltite usually have an irregular and complex distribution. The visual evidence of asphaltite in outcrops suggests that the majority of them are found in small tabular bodies surrounded by massive oblique bodies of the host rock.

The authors propose to continue the geophysical prospecting of areas, where the presence of solid hydrocarbons is known and, preferably, to combine with other methods that characterize the contrast between the geological objects and identify them. Techniques such as resistivity are relatively inexpensive geophysical tools compared to others used in the hydrocarbon industry, which would allow researchers to apply methodologies that could effectively contribute to expanding energy reserves both regionally and nationally.

Acknowledgment

The authors thank the company LAVGR SAS. for providing us with the geophysical data and the necessary information on the study area for the comprehensive analysis carried out in this work. We thank the anonymous reviewers whose comments have greatly improved this manuscript.

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