INNSPUB

Journal of Biodiversity and Environmental Sciences (JBES)
ISSN: 2220-6663 (Print), 2222-3045 (Online)
http://www.innspub.net
Vol. 6, No. 2, p. 479-487, 2015

RESEARCH PAPER

Application of electrical resistivity method in sodium sulfate deposits exploration, case study: Garmab, Iran

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Key words: Sodium sulfate exploration, Electrical resistivity method, CRSP array, Garmab, Iran.

Abstract

This paper is devoted to application of resistivity method in sodium sulfate mineral bodies exploration. Garmab area in central of Iran was selected as a pilot area for this research. Geological studies and preliminary explorations indicate that there are potential anomalies of sodium sulfate in the studied area, and there are some outcrops include marl with sodium sulfate as inter-bed in the alluvial plain. Therefore, Geophysical surveying was carried out in two steps. The first step was considered as testing ability of the applied method in order to assess its ability to detect the sodium sulfate bodies, and the second step has been devoted to estimate resistivity properties to explore the hidden bodies. In the first step, three profiles were designed and surveyed, as testing profiles. These profiles were located on some outcrops and/or over some sulfide bodies detected in a few trenches. The testing data was processed and interpreted and the results have led to a very satisfying contrast between resistivity of the sodium sulfate bodies and the host rocks. In the second step, 12 profiles with different lengths were designed and surveyed in Garmab based on geological and topographical results. Geoelectrical, resistivity, surveying was performed with an innovative array so called CRSP (Combined Resistivity Sounding and Profiling). The obtained data was processed and interpreted and some locations were proposed for drilling based on the highlighted outlines. Drilling results confirmed the resistivity results as well as its efficiency to explore sodium sulfate deposits.

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Introduction

Sodium sulfate is used in pulp and paper, glass, detergents, ceramic glazes, tanning, textile dyes, nickel smelting, animal feed supplements, and as a feedstock for a range of chemicals. Most sodium sulfates consumed annually are used to make soaps and detergents. It is especially an important ingredient in powdered soaps. There are a lot of sodium sulfate minerals.

Sodium sulfate is the sodium salt of sulfuric acid. When anhydrous, it is a white crystalline solid of formula, Na_2SO_4, known as thenardite mineral; the decahydrate $Na_2SO_4.10H_2O$ is found naturally as the mineral mirabilite. Thenardite and mirabilite are relatively common salts precipitated in evaporated settings. Thenardite is a colorless to white mineral with a specific gravity of 2.67 and a hardness of 2.5-3. Thenardite contains about 56% water of crystallization and forms opaque to colorless needle-like crystals referred to as Glauber'ssalt (Na_2So_4,$CaSo_4$) (Warren, 1999).

Sodium sulfate is commercially important, natural sources of sodium - sulfate makes up more than 70% of total world production (Warren, 1999).

Sodium sulfate is used in pulp and paper, glass, detergents, ceramic glazes, tanning, textile dyes, nickel smelting, animal feed supplements, and as a feedstock for a range of chemicals. Most sodium sulfates consumed annually are used to make soaps and detergents. It is especially an important ingredient in powdered soaps. There are a lot of sodium sulfate minerals. Some of them which are more important in industries are shown in table1. Eugsterite and Glauberite are the main minerals in the study deposit. Eugsterite and Glauberite are the main minerals in the study area. This fact has been realized by XRD and chemical analyze for more than 100 samples but in this manuscript because of simplify we used sodium sulfate term.

Table 1. Main sodium sulfate minerals (McIlveen and Cheek, 1994).

Mineral	**Formula**	**% Na_2CO_4**
Thenardite	Na_2SO_4	100
Hanksite	$2Na_2CO_3.9Na_2SO_4.KCl$	81.7
Burkeite	$Na_2CO_3.2Na_2SO_4$	72.8
Eugsterite	$2Na_2SO_4.CaSO_4.H2O$	*62.3*
Glauberite	$Na_2SO_4.CaSO_4$	*51.1*
Loweite	$MgSO_4.Na_2SO_4.2.5H_2O$	46.2
Mirabilite	$Na_2SO_4.10H_2O$	44.1
Bloedite	$MgSO_4.Na_2SO_4.H2O$	42.5

Glauberite is a sodium calcium sulfate mineral with the formula $Na_2Ca\ (SO_4)_2$ formed in an evaporated deposits. It occurs in continental and marine evaporated deposits; as mineral sublimates deposits near fumaroles; in amygdules in basalt and in nitrate deposits in arid climates. It associates with halite, polyhalite, anhydrite, gypsum, thenardite, mirabilite, sassolite andblodite (Anthony *et al.*, 1990). Eugsterite, $Na_2Ca\ (SO_4)_3\ .2H_2O$ is a very common salt mineral formed during evaporation of non-alkaline waters (Vergouwen, 1981).

Geological, mineralogical and geochemical methods are the most common methods which have been used to explore sodium sulfate deposits for many years. (Vergouwen, 1981; Khalili and Torabi, 2003; Merry and Fitzpatrick, 2005; Audra and Nobécourt, 2013).

Generally in sodium sulfate mineral bodies exploration, geophysical exploration methods have not been applied widely, and it could be said that, these methods are not common methods for exploration of sodium sulfate deposits. In this research, the resistivity method application was tested for sodium sulfate minerals exploration. Garmab area selected as pilot and in this area resistivity method efficiency was investigated. The purpose of this study is devoted to application of resistivity method in sodium sulfate mineral bodies exploration in the Garmab, Iran.

Material and methods

Electrical Resistivity method

The science of geophysics applies the principles of physics to the study of the Earth. Geophysical investigations of the interior of the Earth involve taking measurements at or near the earth's surface that are influenced by the internal distribution of physical properties. Analysis of these measurements can reveal how the physical properties of the earth's interior vary vertically and laterally (Kearey, Brooks and Hill, 2002).

Exploration geophysics is the practical application of physical methods (such as seismic, gravitational, magnetic, electrical and electromagnetic) to measure the physical properties of rocks, and in particular, to detect the measurable physical differences between rocks that contain ore deposits or hydrocarbons and those without. Exploration geophysics can be used to directly detect the target style of mineralization, via measuring its physical properties directly (Gadallah, Fisher, 2009). In the mineral exploration investigation, because of optimization in cost and time application of geophysical exploration methods are increasing. Integrated geophysical methods are commonly used in mineral exploration to obtain qualified results (Gautneb and Tveten, 2000). Uncertainties of the occurrence, association depth, shape, and quality which are usual with deposits have led to the application of geophysical methods (Murthy *et al.*, 2009).

Selection of geophysical method(s) to be applied in a mineral deposit exploration depends on the physical properties of the target and its accompanied rocks geological setting, and even its topography. Integration of a few methods is necessary in many cases in order to achieve more certain result (Ramazi and Mostafaie, 2013). The resistivity survey method is one of the oldest and most commonly used geophysical exploration methods (Reynolds, 2011). The Direct Current (DC) resistivity of geophysical prospecting was introduced almost at the same time (Schlumberger, 1920). Electrical methods have broad application to mineral exploration (Singh *et al.*, 2004; Legault *et al.* 2008; Ramazi *et al.* 2009; Magnusson *et al.*, 2010; Mohanty *et al.*, 2011; Chambers *et al.*, 2012).

The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock (Loke and Barker, 1996 a, b). The resistivity method is based on measuring the potentials between one electrode pair while transmitting DC between another electrode pair. The depth of penetration is proportional to the separation between the electrodes, in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground. The measured quantity is called apparent resistivity. Interpreting the resistivity data consists of two steps: a physical interpretation of the measured data, resulting in a physical model, and a geological interpretation of the resulting physical parameters (Dahlin, 2001). Electrical resistivity surveys are generally carried out by two methods; Resistivity Profiling and Resistivity Depth-sounding.

Resistivity Profiling

Resistivity traversing is used to detect lateral changes. Array parameters are kept constant and the depth of penetration therefore varies only with changes in subsurface layering.

Resistivity Depth-sounding

Resistivity depth-soundings investigate layering, using arrays in which the distances between some or all of the electrodes are increased systematically (Milsom, 2003).

An electrical array has significant influence on accuracy of interpreting and various depth studies can be obtained according to various arrays [White *et al.*, 2003; Oldenburg and Li 1999]. Although, the conventional arrays (e.g. Dipole-Dipole, Pole-Dipole and Wenner) have successfully been used in many mineral deposits exploration, but, in some topographical and geological conditions especially in thin and high dip-angle mineralized vines, these arrays may not lead to satisfying results (Ramazi and Mostafaie, 2013). Hence, Ramazi (2005) designed a new array so called "CRSP" (Combined Resistivity Sounding and Profiling). This array is a combination of geoelectrical profiling and sounding which can lead to useful results in the mentioned geological conditions. CRSP has successfully been applied in many exploration and/or site investigation projects using Resistivity and/or induced polarization methods (Ramazi and Mostafaie, 2013, Ramazi and Jalali, 2014). The CRSP array has been used for detecting sulfate bodies in the studied area.

Study area

As mentioned, sodium sulfate is one of the nonmetal mineral that has many industrial applications. The Garmab mine is the feed of a big detergent factory in Iran. Garmab area was selected as a pilot area for application of electrical resistivity method to sodium sulfate exploration. This area is located about 30Km west of Semnan province, Iran. An open pit is operated in this area.

Geological setting

From geological point of view the study area is located in an alluvium plain which some sedimentary rocks have outcrops as small hills. Some of the hills include marls with sodium sulfate bodies as inter-bed. The north of the area is surrounded by mountains having complicated topography. It seems that most of the sulfate bodies have formed in boundary of the plain and the mountains.

Regional geology showed that sedimentary rock outcrops in Garmab area are related to Dozahir marl of upper Eocene. Dozahir marl and gypsum unites with Eocene volcanic unites has a good contrast with a clear fault, in the northwest of Garmab mine. Generally it can be said that all of the marl and gypsum sediments are a part of upper Eocene Dozahair. In the north of Garmab, Eocene volcanic rocks are located under the Dozahir formation, and in the south of Garmab tuff and limestone of Razaghi formation are located above the Dozahir. Tectonic condition of this place is very complex and separation of the formations is difficult. As mentioned sodium sulfate has been formed as sedimentary lenses associated by marl layers and usually it is covered by gypsum unite (Aghanabati and Hamedi, 1994).

Electrical resistivity surveying in Garmab

Electrical resistivity surveying was carried out in two steps. The first step was considered as pilot surveying to test the ability and efficiency of application of resistivity method in detecting sodium sulfate bodies.

The second step was application of the method to explore the hidden bodies.

In the first step, three profiles were designed and surveyed, as testing profiles. These profiles were located on some outcrops and/or over some sulfide bodies detected in a few trenches. The test measurements data were processed and interpreted. The results lead to a very sharp contrast between resistivity of the sodium sulfate bodies and the host rocks and confirmed the applicability of resistivity method in sulfate the bodies detection. Resistivity of the sodium sulfate was more than 100Ωm while, the host rocks showed more conductive. And the sulfate bodies were clearly detected by the resistivity measurements.

In the second step, 12 profiles with a different length of 15 to 200 meters were designed and surveyed in the study area. Location of these profiles is presented in fig. 1.

These profiles were designed base on geological, topographic, and expectable features. From topographical point of view, the study area is suitable for electrical resistivity surveys. Optimization condition of geology and topography was chosen for electrical resistivity surveying.

Most of the profiles are somehow perpendicular to the geological structures and all of them were surveyed by CRSP array. Designing of these profile were performed by means of:

- A full coverage of the obtained data along the profiles;

- The stable potential electrode distance [Distances between measuring points along profiles were 5 or 10 meters];

- Distance of measurement points along depth was between 5 to 10 meters;

- RS sections could be continuously prepared;
- Data accuracy is sufficient for detecting 50 Ωm. This point realized the applicability of resistivity method for the mineral bodies exploration.

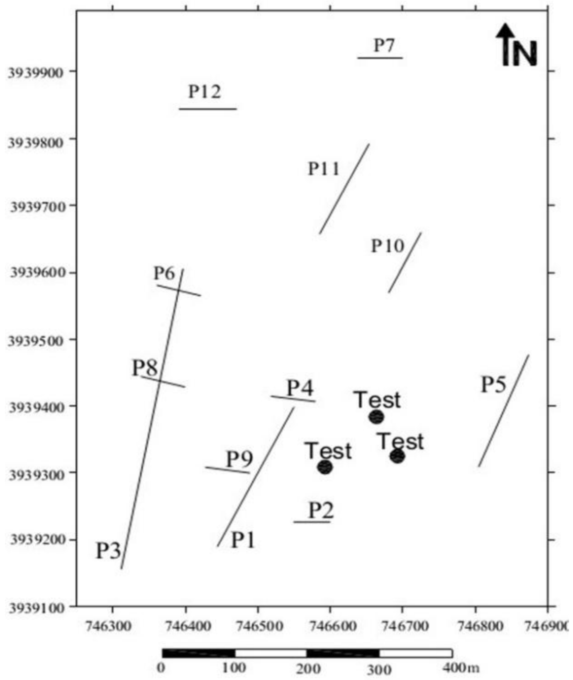

Fig. 1. Location map of surveyed profiles.

Results and discussion

As it was mentioned, electrical resistivity method was applied to get some information about existence, depth and shape of the probable ore bodies. The results of testing surveys show that resistivity of the sulfate bodies is more than 100Ωm while resistivity of the host and the associate rocks decrease to less than 50 Ωm. This point realized the applicability of resistivity method for the mineral bodies exploration.

As it was mentioned above, CRSP array is a combining of sounding and profiling, so the curves of vertical electrical sounding could be prepared for each one of the measurement points. Real resistivity of the geological bodies was determined. It helps to increased accuracy of resistivity and depth of the desired bodies. So we can compile more reliable sections. According this procedure, resistivity sections along the profiles were compiled. Some of the sections are described as fallow.

Resistivity section II

This section was prepared along profile2 having a length of 50m. Its strike was nearly E-W, the maximum current line length (distance between current electrodes) was 150m and measuring point interval (in fact distance between the soundings) was 5m. As it is shown in fig.2, tow high resistivity anomalies could be recognized in the middle part of the profile. The first one appears from depth of 27 and the second one appears in depth of nearly 45 meters and the both one are extend toward the more depths. We offered a bore hole to be drilled in location of the first anomaly. The drilling results confirmed the resistivity result and a sulfate body was detected in this location, in the motioned depth.

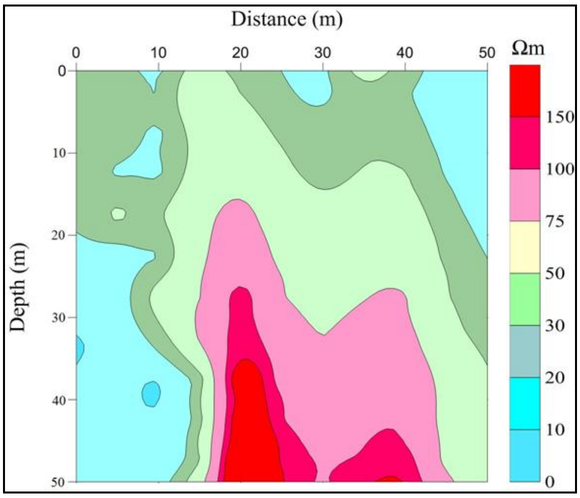

Fig. 2. Electrical resistivity section prepared along profile 2.

Resistivity section III

Profile no.3 was the longest surveyed profiles in the studied area by 400 meters (Fig 1). According to resistivity section (Fig4) there are two notable anomalies. The first anomaly was located 250m from the start point of the profile, anomaly A, and it is a shallow anomaly. Its resistivity is 100 Ωm up to more than 150 Ωm (Fig4); this anomaly could be indicating a good surface mineral body. Anomaly B, in the distance of 350 to 380m, a deep anomaly has been detected. This anomaly can be indicative of the mineral body in the depth of more than 50m. There is a poorly deep, anomaly C, anomaly in the distance of 150 to 175m. This anomaly may be related to impure mineral body.

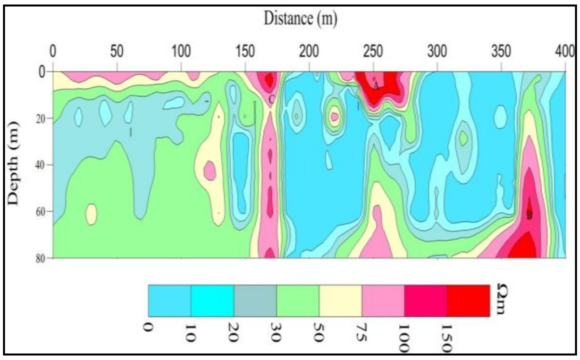

Fig. 3. Electrical resistivity section prepared along profile 3.

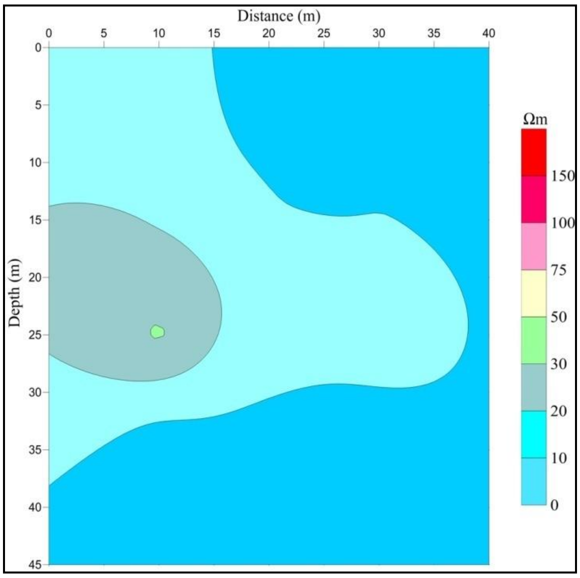

Fig. 4. Electrical resistivity section prepared along profile 4.

Resistivity section IV

Resistivity section of profile4: this profile-P4- was surveyed toward profile 1 and the almost perpendicular to it with the strike of W-E in the middle of study area and length of 40m. Resistivity section along this profile was prepared, and according to fig.5 there is no anomaly and naturally there are no mineral bodies. According to this section the high cost of drilling was avoided, as it was removed from exploration and mining priorities.

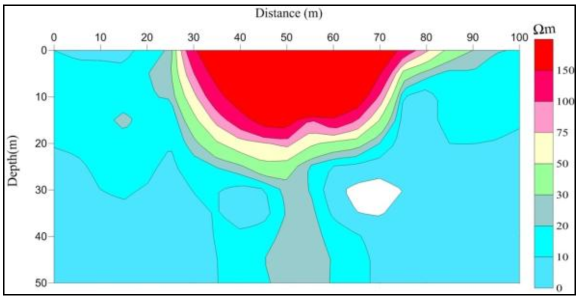

Fig. 5. Electrical resistivity section prepared along profile 10.

Resistivity section X

Resistivity section of profile no.10 was prepared (fig.6). The length of the profile is 100m and its strike is NE- SW. There are some mineralization symptoms in this profile; in order to studying of mineralization depth and separation this profile was surveyed. The good anomaly was determined in this profile, and this anomaly can be indicative of the appropriate mineral body. The resistivity is very high, more than 150 Ωm, and there is no notable overburden.

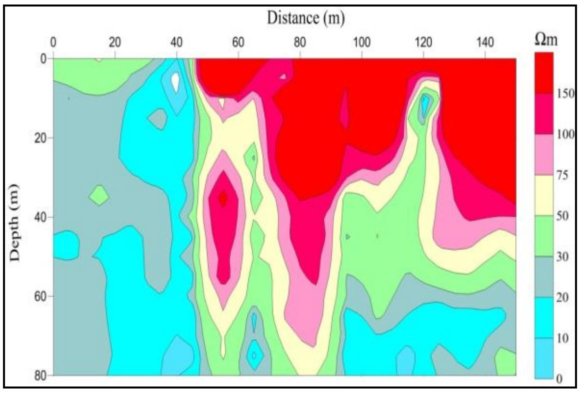

Fig. 6. Electrical resistivity section prepared along profile 11.

Resistivity section XI

Profile no.11 was surveyed parallel to p10 with the length of 140m and strike of NE- SW. Resistivity section was prepared in line P11 and shown in fig.6. As shown in fig.6, there is an anomaly that is the best anomaly in this area. The resistivity is 100 to over 150ohm and its horizontal interval is about 100m. Thickness of mineral body reaches to 50 meters in some places. According to this section there is a large mineral body with a very little overburden.

It is noteworthy that other resistivity sections, like profile4, that was not presented in this paper did not have any considerable anomalies.

As mentioned, several tranches and boreholes were suggested in order to validate the geophysical results. Drilling and sampling process confirmed geophysical results. Results of this research showed that the resistivity method was successfully performed and had a great application on prospecting Garmab sodium sulfate. Fig. 7 illustrates a trench located on profile 11. This trench is dug according to resistivity results. This location showed a considerable reserve, which confirmed the resistivity results in the developing steps of the mine. Comparing with other exploration methods, geophysical method, -specially resistivity method- are quick and low cost methods, therefore more effective planning and progress of exploration and mining would be achieved via this method. Also, geophysical methods should be investigated and developed in nonmetal minerals.

Fig. 7. view of mineral body in the location of profile 11, removal of overburden after resistivity surveying.

Conclusion

The most important results of this study could be summarized as follows, The mineral body, sodium sulfates, has a sharp resistivity contrast with the host rocks and associated rocks (marl and in some locations marl with gypsum), therefore, resistivity method was successfully used to detect the subsurface mineral bodies. Results revealed that the resistivity application was appropriate to highlight sodium sulfate minerals and its efficiency was very satisfying. In some locations, the gypsum causes some increment of resistivity, but this increment is not so high especially, where marl and gypsum are associated. On the other words; resistivity of the sodium sulfate bodies is too high to be undifferentiated by high resistivity of the associate gypsum. The CRSP array had a very good efficiency for detecting the anomalies. By this array has an excellent efficiency to detect anomalies in depth direction as well in lateral direction (direction of the profiles).Based on obtained results, some deposits were detected and some locations were proposed for drilling. Drilling results confirmed geophysical anomalies. This research showed that Garmab area has a good potential and can provide the nearby detergent factory's feed. Also it was suggested that the surveys be extended in another locations of the area.

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