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Application of magnetic and gravity methods to the exploration of sodium sulfate deposits, case study: Garmab mine, Semnan, Iran

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ABSTRACT

This study investigates the feasibility of using potential field (magnetic and gravity) data for geophysical exploration of sodium sulfate (salt-cake) resources; more specifically glauberite (sodium sulfate) and Eugsterite (sodium calcium sulfate) are two prevalent minerals of the Garmab mine in Semnan province, Iran.
The geophysical data were collected on several profiles perpendicular to geological structures of the area and the residual magnetic and gravity maps were generated. Based on the magnetic susceptibility and density measurements of ore and waste samples, the areas identified by low magnetic and high gravity anomalies were associated with high potential zones for glauberite mineralization.
Three-dimensional inversion of potential field data was applied to the residual data, leading to a petrophysical model of the magnetic susceptibility and density contrast of sought salt rocks. We found that the ore bodies could be successfully characterized by low-susceptibility and high-density. In this paper, the susceptibility and density models from inversion are consistent with the geological and drilling data. Results of the integrated application of magnetic and gravity data can be used to delineate sodium sulfate prospects as well.

1. Introduction

After sodium chloride (halite), sodium sulfate (salt-cake) is by far the most common mineral of the naturally occurring evaporite rocks with sulfate-rich nonmarine brine source. Sodium sulfate is widely used in chemical industries such as glass and textile manufacturing, filler in detergents, kraft paper and carpet (Warren, 2016). Sodium sulfate naturally occurs in a number of minerals (Table 1) while the most common and mineable ones are Thenardite, Mirabihte, Glauberite, Bloedite, and Burkeite. These mineral assemblages can be found as massive soluble salt deposits in most of the world's alkaline lakes or playas, in other saline mineral deposits and geologic formations (Garrett, 2001; Warren, 2010).

In general, two major types of saline hydrological mechanisms for the sodium sulfate deposits were described by Warren (2010): (1) Solar concentration of surface brines with associated increasing temperature in continental playa (evaporation), e.G. *Laguna* del Rey, Mexico (Sanchez-Mejorada, 1986), Quaternary playas of USA and the Miocene continental playa of Spain. (2) Crystallization of huge volumes of mirabelite on the margin of the lake during relatively dry winters from the more concentrated brine (Cooling-Freezing), e.g. Kara Bogaz Gol in Turkmenistan and Lake Kuchuk in Russia (Garrett, 2001; Warren, 2010).

The Garmab sodium sulfate mine discovered by local people in 1995 is located in Semnan Province, Iran. As shown in Fig. 1, the Garmab deposit is situated in the evaporite member of the middle Eocene of the Iranian Central Province. Based on X-ray powder diffraction (XRD) and chemical analysis on more than 100 samples, glauberite and eugsterite are the main minerals in this area (Samimi-Namin, 2006). Eugsterite (Table 1) is a common salt mineral formed during evaporation of non-alkaline waters. Glauberite is found as the principal sodium sulfate mineral in a number of very large deposits, both pure and mixed with astrakanite and eugsterite, interbedded or underlying thenardite. Glauberite is often found with lacustrine halite reservoirs, smaller amounts are often found in alkaline playas, and some are sporadically distributed in other soluble sodium sulfate or soluble-salt occurrences (Garrett, 2001).

The most common exploration method for sodium sulfate deposits are geological studies (e.g. tectonics, field studies, stratigraphic observations, facies analysis, sampling, mineralogy), geochemical exploration and remote sensing methods (Babel and Schreiber, 2014; Warren, 2010). These methods are well documented by Abdel Wahed et al. (2015), Khalili and Torabi (2003), Last (2002), Ortí et al. (2002),

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Table 1
Sodium sulfate minerals after (Babel and Schreiber, 2014; Garrett, 2001).

Mineral	Formula	Components of evaporite rocks	Na_2SO_4%
Thenardite	Na_2SO_4	common	100
Mirabelite (Glauber's salt)	$Na_2SO_4.10H_2O$	common, seasonal	44.1
Glauberite	$CaSO_4.\ Na_2SO_4$	common	51.1
Eugsterite	$2Na_2SO_4.CaSO_4.H_2O$	rare	62.3
Bloedite (Astrakhanite)	$Na_2SO_4.\ MgSO_44H_2O$	common	42.5
Burkeite	$Na_2CO_3.2Na_2SO_4$	rare	72.8
Loewite	$2MgSO_4.2Na_2SO_4.5H_2O$	rare	46.2
Hanksite	$9Na_2SO_4.2Na_2CO_3.KCl$	rare	81.7
Tychite	$2MgCO_3.2Na_2CO_3.\ Na_2SO_4$	rare	42.7
Darapskite	$Na_2SO_4.NaNO_3.H_2O$	rare	58

Crétaux et al. (2009) and Crowley (1993). Except for Mostafaie and Ramazi (2015) published work, geophysical methods have not been extensively used or are not current method for exploration of sodium sulfate deposits.

Although potential field methods are cost-effective and widely used geophysical methods in mineral exploration (Azizi et al. (2015), Bersi et al. (2016), Farhi et al. (2016)), the application of these methods for sodium sulfate deposit exploration is not well documented in literature. The main objective of this study is to investigate the integrated application of the magnetic and gravity methods in this area of interest. These methods were carried out over the Garmab area to simultaneously image physical models of magnetic susceptibility and density contrast. Geophysical outputs provide reliable information about rock properties and the subsurface structure of the studied site. This information can be used to determine the geometry as well as the depth and location of sodium sulfate ore deposits.

2. Geology

2.1. Regional setting

The Iranian plate is a mosaic of eight structural-sedimentary zones or provinces that were merged during the Oligo-Miocene Alpine-Himalayan Orogeny (Fig. 1). These zones are the Alborz, Central Iranian (Central Basin), Zagros, Sanandaj-Sirjan, Urmiyeh-Dokhtar (magmatic arc), Kopeh Dagh, Lut and Makran provinces (Heydari et al., 2003; Stocklin, 1968).

The study area is situated near the Alborz Mountain in the north of the Central Iranian Province (Fig. 1), which formed during subduction and the last stage of collision between the Arabian and Iranian plates. Subduction closed the Tethyan Seaway that connected East Tethys (initial Indian Ocean) with West Tethys (initial Mediterranean Sea). It formed volcanic arcs with back-arc and fore-arc basins on the northern edge of Tethyan seaway and a fore-arc basin in the south (Daneshian et al., 2017; Reuter et al., 2009).

The Central Iranian Province was a stable plate during the Paleozoic, but late Triassic movements caused the creation of horsts and grabens that are the physical remains of some large playas, which once covered much of the area (Bazargani-Guilani et al., 2011). This zone is surrounded by the Zagros mountains to the west, the Alborz mountains to the north and northeast, and the Lut desert in south (Fig. 1), and has an average elevation of 1200 m above the sea level. From the Alborz mountains southwards, the geological setting changes from the rocky body of the mountains, through alluvial fans and pediments, leading to floodplains and lowlands, ending in sandy and highly saline, barren lands, which are the remnants of ancient playas(Vahdati Nasab and Hashemi, 2016).

Fig. 2 shows the tectonic setting and stratigraphic framework of the study area. The oldest known orogenic phase in this region can be considered the orogenic phase before the Marl Dozahir sedimentation that

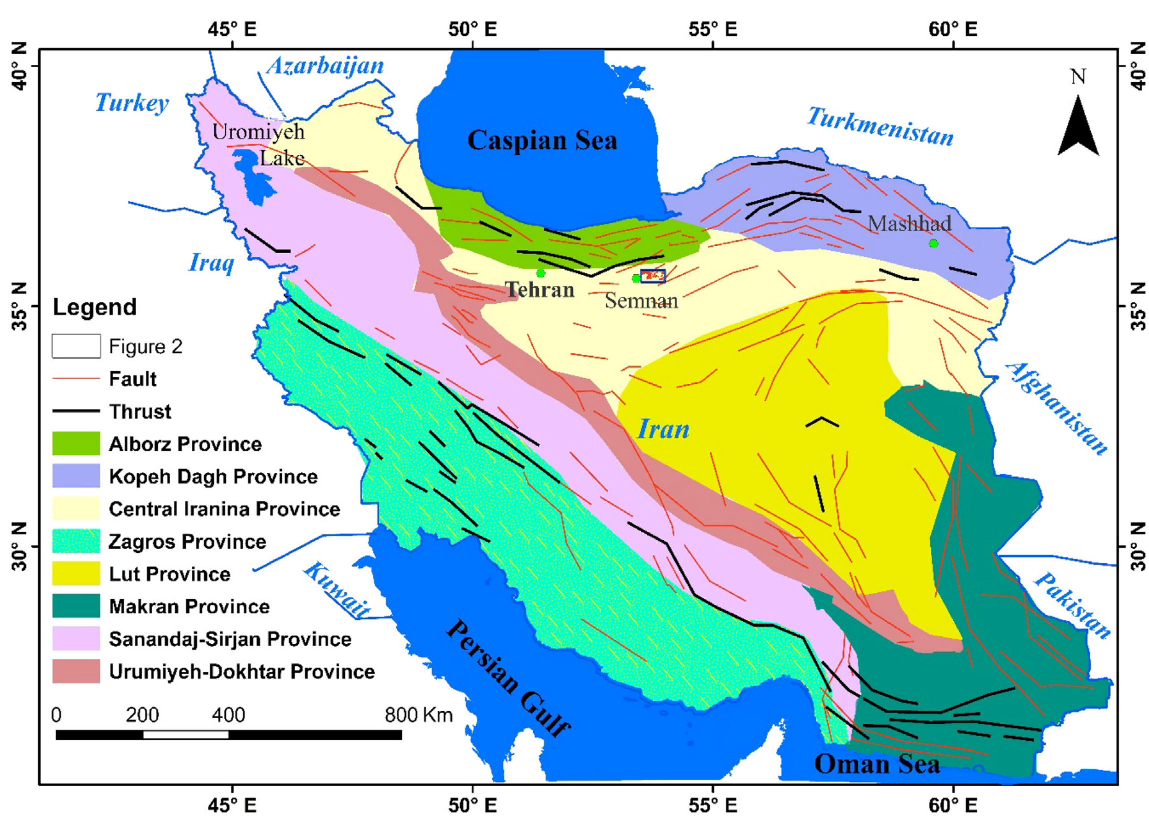

Fig. 1. The structural geology map of Iran. The location of the studied area has been superimposed on the map by a rectangle symbol, Reproduced from Heydari et al. (2003) and National Geological Survey of Iran Database.