Journal of Applied Geophysics 82 (2012) 1–10

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Two-dimensional resistivity imaging in the Kestelek boron area by VLF and DC resistivity methods

Murat Bayrak *, Leyla Şenel

Istanbul University, Engineering Faculty, Department of Geophysical Engineering, Avcılar Campus, 34320 Istanbul, Turkey

ARTICLE INFO

Article history:
Received 3 October 2011
Accepted 28 March 2012
Available online 6 April 2012

Keywords:
VLF
Dipole–dipole
Geoelectrical modeling
Current density
Boron deposit
Kestelek

ABSTRACT

A VLF and DC resistivity investigation was conducted in the Kestelek area, western Turkey, to determine the two-dimensional images of the boron deposits. The two-dimensional resistivity images were obtained by the inversion of tipper and resistivity data for VLF and DC resistivity methods, respectively. The VLF tipper data also were improved applying the Fraser and Karous & Hjelt (K&H) filtering to delineate the boundaries of the subsurface boron deposits. The main findings are: (1) moderate (>25 Ωm) and relatively high (>40 Ωm) resistivity zones in the two-dimensional models, which is mostly supported by the K&H real part of tipper as the negative current density peaks, may be interpreted as middle level of potatoes type colemanite and lower level of crystal type colemanite boron deposits inside the conductive units, respectively. (2) Transition from positive peaks (conductive zones) to negative peaks (resistive zones) in the K&H real part of tipper current density pseudosections may indicate the potential locations of the boron deposits. (3) Drilling well results obtained around two profiles of the study area are consistent with distribution of the resistive boron deposits in the two-dimensional resistivity models and K&H real part of tipper filtering images.

1. Introduction

Turkey holds about a 72% share of the total boron deposits of the world. About 92% of boron minerals are exported and the rest is used domestically. Boron ore and its various minerals' demand is increasing around the world (Kar et al., 2006). Turkey has started research and development activities on boron. For this purpose, National Boron Research Institute, BOREN, was established in 2003 under the authority of Ministry of Energy and Natural Resources in order to organize and sponsor the scientific studies. The important borate minerals from a worldwide commercial standpoint are borax, ulexite, and colemanite. They are produced in a limited number of countries, dominated by Turkey and the United States, which together furnish about 90% of the world's borate supplies. The main borate districts of Turkey are Bigadiç, Kestelek, Sultançayır, Emet and Kırka (Kistler and Helvacı, 1994). Western Turkey is significant from the point of view of boron deposit exploration. Development of the boron potential of the Kestelek region was first initiated in the 1954 by Mineral Research and Exploration Institute of Turkey (MTA). In most of the studies particular attention was focused on stratigraphy and reservoir features. In contrast, two-dimensional resistivity imaging of the region, which could show resistivity characteristic of the boron deposits, to this day has not been sufficiently explored. This motivated us to image the resistivity structure of the boron deposits in the region using VLF (Very Low Frequency) and dipole–dipole (DC) resistivity data.

Boron is the fifth element of the periodic table and is the only electron-deficient non-metallic element. Boron transforms from a non-metal to a superconductor at about 160 GPa (Eremets et al., 2001). Boron is hard and the resistivity of the pure bulk boron is ~10^6 Ωcm for the rhombohedral structure (Buhro et al., 2003). Boron concentrations in rocks range from 5 ppm in basalts to 100 ppm in shales, and averages 10 ppm in the earth's crust overall (Woods, 1994). Total annual world consumption of borates is: insulation, fibreglass, and heat-resistant glass, 41% of boron consumption; ceramic and enamel frits and glazes, 13%; detergents, soaps, and personal care products, 12%; and micronutrients, 6% (Kar et al., 2006).

Boron deposits can be detected by VLF and DC methods, since they produce strong variations in subsurface electrical resistivity. In the VLF and DC methods, resistivity is sensitive to high resistivity contrast in ore sites while VLF tipper parameters are sensitive to conductive structures of the subsurface. 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 (Carr, 1982).

The application of VLF method for cost effective imaging and detection of near surface targets for prospection of ore deposits has been in use for over 10 years; some of examples include Eze et al. (2004), Frasheri et al. (1995), Hutchinson and Barta (2002), Ligas and Palmoba (2006), Liu et al. (2006), McCaffrey et al. (1995), Paterson and Ronka (1971), and Saydam (1981). Bayrak (2002) applied the VLF method to chrome area to inspect the effectiveness of the method. He indicates that the resistivity changes, Fraser, and K&H filtered data

* Corresponding author at: Istanbul University, Engineering Faculty, Department of Geophysical Engineering, Avcılar Campus, 34320 Istanbul, Turkey. Tel.: +90 212 473 70 70/17835; fax: +90 212 473 71 80.
E-mail address: mbayrak@istanbul.edu.tr (M. Bayrak).

0926-9851/$ – see front matter
doi:10.1016/j.jappgeo.2012.03.010

consistent well with the extension of chrome ore, which correspond to known chrome mineralization Dunit/Harzburgite type rock and serpentinized rock boundaries. Thus, VLF might be also effective for the boron ore prospection.

Several researchers have also used DC resistivity method for ore areas located in the Mt. Milligan copper gold porphyry deposit, Canada (Oldenburg et al., 1997), in shallow coal mine workings (Johnson, 2003), in the East Pennine Coalfield, UK (Chambers et al., 2007), in uranium mining sides (Legault et al., 2008; Ramalho et al., 2009) and in Landusky gold mine, Montana, USA (Rucker et al., 2009). Doyle (1990) also extensively discussed the gold exploration by electrical and VLF methods.

Our objective was to produce two-dimensional resistivity images of subsurface boron deposits by employing VLF and dipole–dipole (DC) resistivity methods, using advanced two-dimensional inversion techniques in Kestelek boron deposits. Subsequently, both VLF and DC two-dimensional modelling results were interpreted in terms of the geological features and the possible boundary of the Kestelek boron field of western Turkey.

2. Geological setting

The Kestelek boron deposit is 27 km southeast of the town of Mustafa Kemalpaşa in the province of the Bursa (Fig. 1). It was discovered accidentally during a survey of lignite deposits for the Mineral Research and Exploration Institute of Turkey (MTA) in 1954. The known borates of the Turkey were deposited in the lacustrine environment during Miocene when the volcanic activity occurred since Tertiary to Quaternary (Helvacı et al., 2004). In Fig. 2a, generalized Playa lake sedimentation model showing borate deposits formation in Neogene basins of western Turkey is indicated (Helvacı, 2004). The Miocene sediments which contain the borates in the Kestelek area rest unconformably on a Palaeozoic and Mesozoic basement complex. The Miocene sequence contains from bottom to top: basement conglomerate and sandstones; claystone with lignite seams, marl, limestone, and tuff; agglomerates and volcanic rocks; the borate zone comprising clay, marl, limestone, tuff and borates; and limestones with thin clay and chert bands. These sediments were deposited during a tectonically stable period accompanied by extensive volcanic activity. A yellow to brown coarse-grained tuff unit, up to a few centimetres thick, occurs within the borate zone. This sequence is capped by loosely cemented Pliocene conglomerate, sandstone and limestone (Helvaci, 1994). The borate minerals occur interbedded with clay as nodules or masses and as thin layers of fibrous and euhedral crystals. Colemanite, ulexite, and probertite predominate and sparse hydroboracite is also present locally (Fig. 2b) (Helvaci and Alonso, 2000). The properties of borate minerals recorded from the Kestelek area are shown in Table 1 (Helvaci and Alonso, 2000; Koçak and Sözügüzel, 1989). Probertite, which forms in the same chemical environment as ulexite in the Kestelek deposit, indicates a period of higher temperature within the ephemeral lake. Calcite, dolomite, quartz, zeolite, smectite, illite, and chlorite are accessory minerals. Borate minerals in the Kestelek deposit, like the tuffs and clays in the borate zone, are characterized by very low concentrations of As, Sr and S relative to the other deposits in Turkey, and certain western U.S. borate deposits (Helvaci and Alonso, 2000). Volcanic rocks, tuffs and clays interbedded with the borates are the most likely sources for Ca, Mg, Na, Sr, B, As and S. In the Kestelek area, the extensive volcanic rock associations and tuff intercalations with the borates indicate that much of the sediment was derived from a volcanic terrain. Hydrothermal solutions, thermal springs and tuffs associated with local volcanic activity are thought to have been the source of the borates. The Kestelek deposit is characterized by high Ca (colemanite), very low Na, and very low chloride and sulphate (Helvaci, 1994). Smectite is the major clay mineral in the Kestelek borate mine, with 73 wt.% in the clay fraction (<2 μm). The Li_2O content of the clay samples from the Kestelek mine varies between 0.15 and 0.17 wt.%. Whole-rock chemical analyses of samples from the Kestelek mine waste dump show that they contain 0.22 wt.% Li_2O. These lithium amounts indicate that the clays associated with borate deposits are potential lithium resources, and that they may be considered for economic use in the near future (Helvacı et al., 2004).

3. VLF and DC resistivity survey

The VLF and DC resistivity survey, carried out during the summer of 2009, was made along two profiles across boron deposits in the study area, illustrated in Fig. 1a, b and c. The VLF data was achieved using the Scintrex EDA-OMNI instrument. The instrument is microprocessor controlled and facilitates automatic tuning; digital data capture and signal stacking. The radio magnetic field is recorded by the three orthogonal coils mounted in a cylindrical housing with a pre-amp signal circuit and the electric field is measured perpendicular to the magnetic field with two probes in contact with the ground. The VLF radio station transmitted from Germany (Rhauderfehn, DH038) at 23.4 kHz was used for two profiles. This radio station is quite stable.

The DC resistivity profiling measurements were made with a microprocessor-controlled signal averaged METZ equipment using dipole–dipole electrode array. In the signal averaged system, two consecutive readings (in both the forward and reverse directions) are taken automatically at each measurement point and then compared with each other. When acceptable measurements were obtained these readings are averaged. So, the signal-to-noise rate is enhanced. Dipole–dipole array can be used effectively when the instrument has comparatively high sensitivity and very good noise rejection circuitry (Loke, 2011). The pseudosection plotting for two-dimensional DC resistivity survey is also an important tool for data quality estimation (Dahlin and Loke, 1998), however it gives a distorted picture of the subsurface because the shapes of the contours depend on the type of array used as well as the true subsurface (Loke, 2011). Figs. 3g and 4g show the measured DC apparent resistivity pseudosections for profile 1 and profile 2, respectively. Good quality data usually show a smooth variation of apparent resistivity values in the pseudosection (Loke, 2011). Some of well locations (sk73 and sk2) near the VLF and DC resistivity stations are shown in Fig. 1a. The lithological sections of these wells are also presented in Fig. 5a and b, respectively.

3.1. VLF method

Powerful military radio transmitters operating in the 15–30 kHz in the world are sources of the VLF method. A theoretical background of this method extensively discussed in the literature (McNeill and Labson, 1991; Reynolds, 1997; Wright, 1988). In this method, horizontal electric (E_X) and magnetic (H_Y), and vertical (H_Z) magnetic field of electromagnetic components are measured. For a two dimensional structure, the x-direction can be considered to be the direction of the geological strike and preferably the direction to the VLF transmitter used. The y axis is the profile direction. Tipper is the ratio between the vertical and horizontal magnetic fields $\left(\text{scalar tipper} = T_{Ysca} = \frac{H_Z}{H_Y}\right)$ and depends on the near surface characteristics of the Earth. Vertical magnetic field (H_Z) results from entirely lateral changes in electrical conductivity (Oskooi and Pedersen, 2005; Pedersen and Becken, 2005). In the presence of a conductor in the underground, the total VLF field is elliptically polarized (Smith and Ward, 1974). The tangent of the tilt angle is a good approximation to the real part of tipper ($Re\ (H_Z/H_Y) = \tan \alpha x100$ in percent) and the ellipticity is a good approximation to the quadrature part of tipper ($Qu\ (H_Z/H_Y) = \varepsilon x100$ in percent) (Paterson and Ronka, 1971). The real and imaginary components are expressed as a percentage of the total VLF transmitter's primary field. Vertical component of the magnetic field decreases at sites far from conductors. The real part of tipper is sensitive to low resistivity