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TECHNICAL COMMUNICATION

# Successful Use of Geoelectrical Surveys in Area 3 of the Gol-e-Gohar Iron Ore Mine, Iran

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**Abstract** Geoelectrical surveys were conducted in Area 3 of the Gol-e-Gohar iron ore mine to provide geological and hydrogeological information. Open pit mining is currently underway in the northern part of the Area, and underground mining operations are planned for the southern section. Groundwater has already been encountered in the open pit mine. Twenty five resistivity soundings were first performed in the mine area; then, induced polarization (IP) measurements were carried out to remove ambiguities between clay and water-bearing layers. To investigate fault zones as water conduits, combined resistivity profiling surveys were also carried out. These measurements provided a detailed structural map of the pit area. Resistivity and IP results have subsequently been confirmed by observations at three monitoring wells and the mine pit wall. Monitoring and piezometric wells will be drilled at locations suggested by the results of the geoelectrical surveys. Drainage galleries may be developed to dewater the open pit mine. However, another option being considered is to start the underground mining with the idea that it will initially simply serve as a dewatering mechanism.

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**Keywords** Combined resistivity profiling · Gol-e-Gohar iron ore mine · Induced polarization · Iran · Resistivity

## Introduction

Groundwater encountered in open-pit and underground mines acts as a physical barrier to operational activities and reduces production efficiency. In addition to its economical and environmental impacts, groundwater can complicate design of drilling and blasting patterns. Kamkar-Rouhani and Hojat (2004) discussed surface and groundwater induced problems in mining operations.

The Gol-e-Gohar deposit comprises six main iron ore anomalies (Fig. 1). Area 1, about 2 km east of Area 3, is currently being mined and has reached an approximate depth of 180 m below the surface. Groundwater has affected mining operations of Area 1 in the following ways:

- Large inflows to the pit have interrupted production (Fig. 2);
- The need to pump water out of the mine site has increased costs (Fig. 2);
- Gradual erosion of mine walls and roads;
- Reduced slope stability of mine walls due to water penetration into joints and fractures in the walls;
- Reduced shear strength of soils and rocks;
- Reduced ore recovery as a result of lower slope angles of mine walls;
- Operational problems during drilling, explosion, exploitation, and transportation stages (Fig. 2);
- Environmental problems.

Area 3 is estimated to have the largest ore reserve of the anomalies. Considering the greater overburden thickness

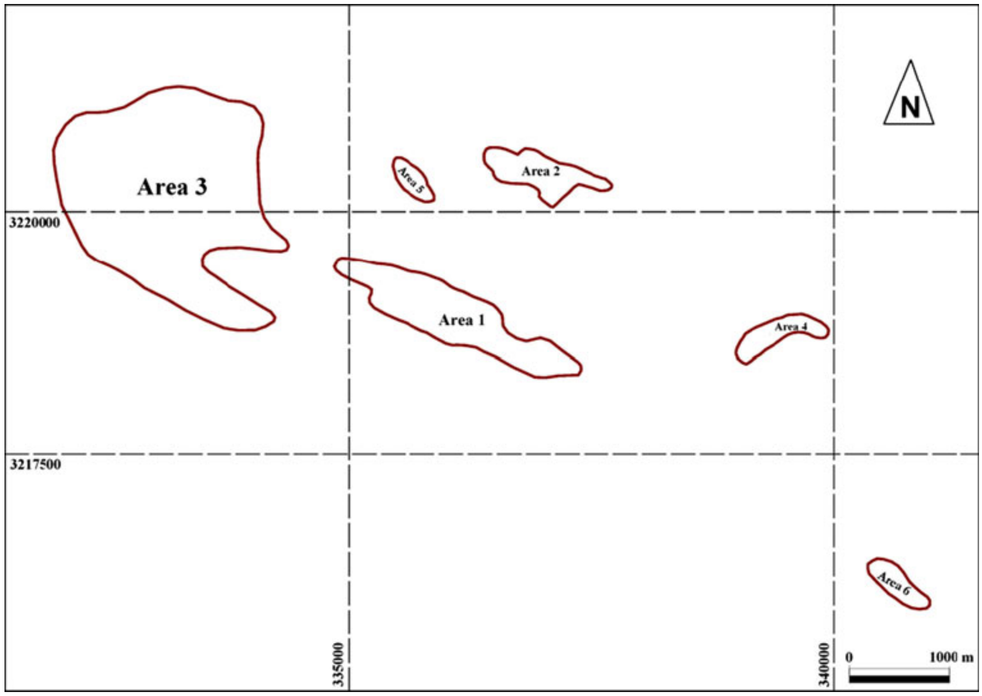


**Fig. 1** The six proven anomalies of the Gol-e-Gohar iron ore mine (UTM coordinates)

and ore body depth, more severe groundwater problems are expected in this area. Open pit mining of Area 3 has barely started; it was halted in 2007, due to the world iron ore price decrease, and has only restarted recently.

Dewatering is a way to address groundwater problems and is an important aspect of mining, for many reasons, including economics, mine safety, slope stability, and the environment. Moreover, drained water can be an important water supply after it is treated, especially in an arid region, such as Iran. Determination of the groundwater situation and geological discontinuities, such as faults, are crucial to the proper design of a dewatering system.

Geophysical methods can be used to determine such aspects and can be a cost effective alternative to expensive drilling and sampling programs in engineering, geological, and hydrogeological applications. Electrical resistivity is especially useful for characterizing porous media. The electrical conductivity of porous media depends on the porosity, pore geometry, fluid saturation, fluid conductivity, and surface morphology of the mineral grains (Sultan et al. 2008). The close connection between resistivity and the presence of aqueous fluids is one reason why electrical resistivity techniques are employed in diverse exploration projects and various environmental, hydrogeological, geotechnical, and civil engineering investigations (Stummer et al. 2004). Direct-current resistivity is most commonly used for groundwater studies. It is easy to do, non-invasive, relatively inexpensive, and uses automated data reduction techniques (Hagemeyer and Stewart 1990).

## Geology of the Survey Area

The Gol-e-Gohar iron ore mine is located 53 km southwest of the city of Sirjan in Kerman Province, Iran (Fig. 3). The Gol-e-Gohar deposits are situated in a metamorphic complex of probable Paleozoic age with a northwest-southeast trend, known as the Sanandaj-Sirjan zone, which is parallel to the Zagros thrust belt on the southwest, and is bounded on the northeast by the Urmieh-Dukhtar volcanic belt (Moxham and McKee 1990). The Gol-e-Gohar deposits are considered to be of sedimentary or volcano-sedimentary origin, laid down in deltaic or near-shore locations that resulted in abrupt lateral and vertical changes in the sedimentary environment. Subsequent deep burial, folding, metamorphism, and erosion left a group of folded or down-faulted magnetite-rich deposits as elongated remnants of an iron formation that originally had a broader, perhaps more continuous extent (Moxham and McKee 1990).

The average elevation of Area 3 is approximately 1728 m above sea level, with relatively flat desert topography (KME 1999). The landscape is interrupted by ridges and mesas of folded and uplifted metamorphic rocks of Paleozoic and Mesozoic ages, which rise 300–400 m above the surrounding plain. The area receives very little precipitation, mainly as rain, and thus, has a very dry climate.

The general shape of Area 3 deposit is semilenticular or tabular, elongated in a north–south direction. Overall length is about 2200 m north–south by about 2400 m east–west. The surrounding rocks are a metamorphic assemblage of

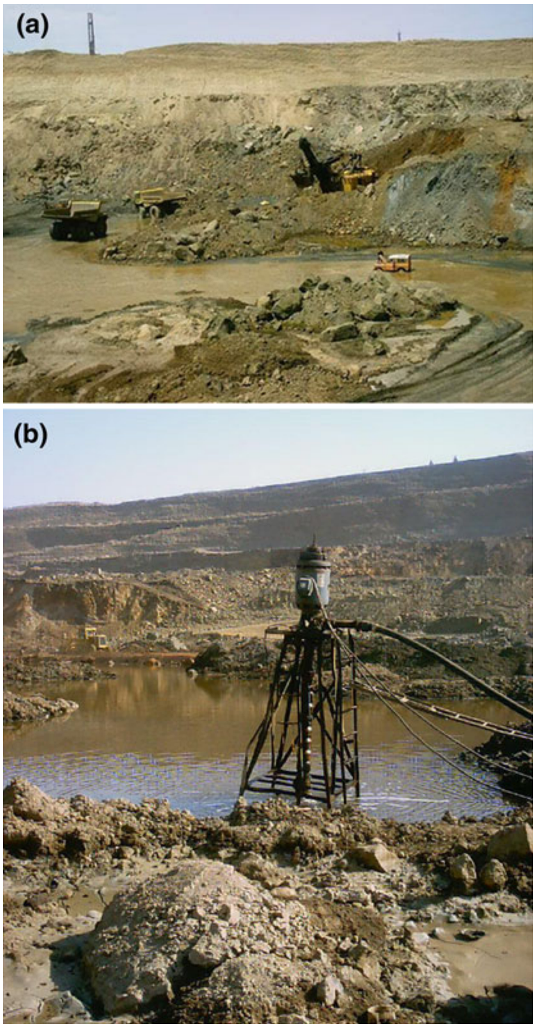


**Fig. 2** Examples of problems caused by the presence of groundwater in Area 1 of the Gol-e-Gohar iron ore mine: **a** Large inflows to the pit have resulted in operational problems; **b** The need to pump water out of the mine site

probable Ordovician–Silurian age, termed the Gol-e-Gohar complex lithostratigraphic unit. The whole area is covered by 100–200 m of Quaternary alluvium, which thins from south to north (ADC 2002).

## Geophysical Investigations

Various approaches are available to gather information about the subsurface. The best is direct observation of the sediments and rocks themselves. Of course, this is rarely possible to the extent that we would like. It's not often that numerous, deep valleys cut through an area of interest to the necessary depths so that all we need to do is correlate geologic sections from one position to another. It also is relatively unusual for an investigation site to contain numerous uniformly distributed wells that were logged by a professional geologist. More commonly, when subsurface information is necessary, we acquire physical measurements on the surface and use these to deduce subsurface geology. The value of geophysics is its ability to acquire information about the subsurface over a substantial area in a reasonable time frame and in a cost-effective manner (Burger et al. 2006).

### Resistivity Surveys

In electrical resistivity, direct current or low-frequency alternating current ($i$) is applied at the ground surface, and the potential difference ($\Delta V$) is measured between two points (Fig. 4). Variations in resistance to current flow at depth cause distinctive variations in the potential difference measurements, which provide information on subsurface structure and materials (Burger et al. 2006). The resistivity of the subsurface ($\rho$) is calculated from Eq. 1.

$$\rho = \frac{2\pi\Delta V}{i}\left(\frac{1}{\frac{1}{r_1}-\frac{1}{r_2}-\frac{1}{r_3}+\frac{1}{r_4}}\right) \tag{1}$$

where $r_1$, $r_2$, $r_3$ and $r_4$ are the distances between electrodes shown in Fig. 4.

Although some native metals and graphite conduct electricity, most rock-forming minerals are electrical insulators. Measured resistivities in earth materials are primarily controlled by the movement of charged ions in pore fluids. The resistivity values of some common materials are illustrated in Fig. 5. The resistivity value of groundwater, which has a resistivity range of 1–100 Ωm, depends on the amount of dissolved compounds (i.e. salinity), since these ions greatly enhance the ability of groundwater to conduct electricity.

Two basic types of electrical resistivity surveys are in common use, vertical electrical sounding (VES) and electrical profiling (mapping). The objective of VES is to determine how electrical conductivity varies with depth. Strictly speaking, VES works best for a situation in which the conductivity varies merely with depth, without lateral variations. Good to excellent approximations to this situation are commonly found in sedimentary areas with gently dipping or flat-lying beds, and in many such environments, VES has been successfully used for water prospecting. The objective of electrical mapping is to determine lateral variations in the conductivity of the ground. Mapping is primarily useful for detecting local, relatively shallow inhomogenities, and is typically used in ore prospecting and to delineate geologic boundaries, fractures, cavities, palaeochannels, etc. (Parasnis 1997). Various geoelectrical measurements carried out in Area 3 of Gol-e-Gohar mine are discussed below.

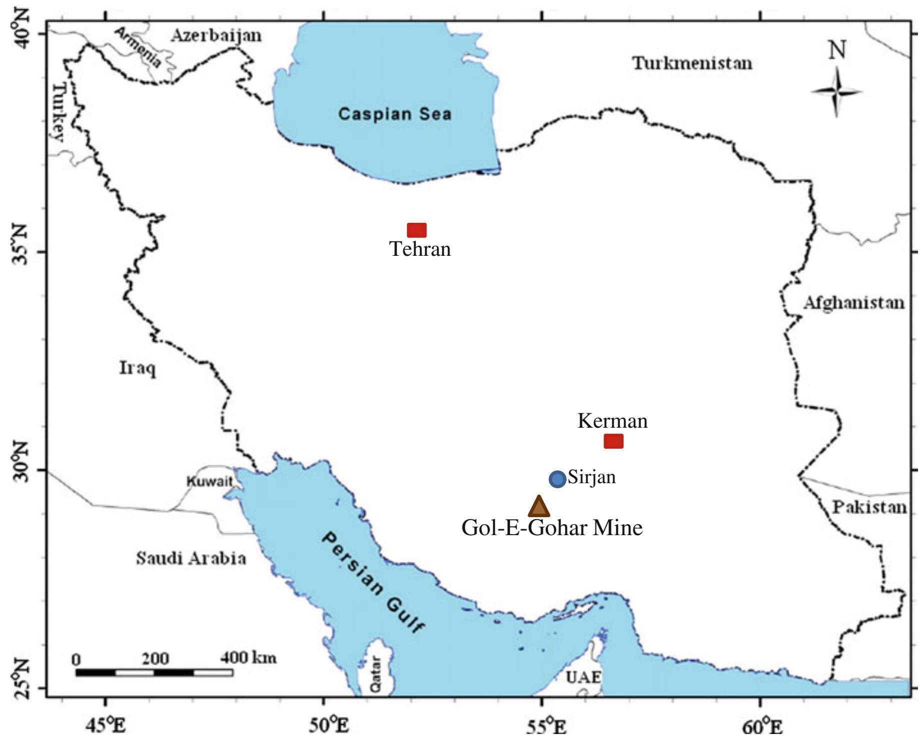


**Fig. 3** Layout of the Gol-e-Gohar iron ore mine, southwest of the city of Sirjan, Iran

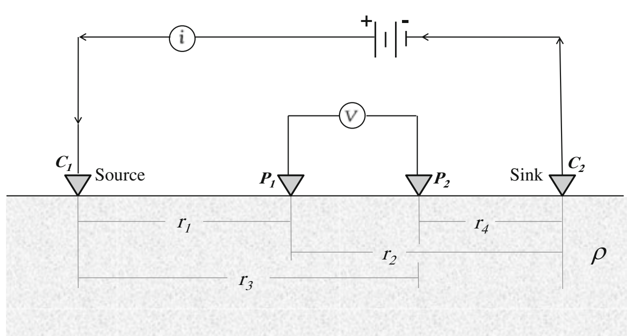


**Fig. 4** Diagram used to determine potential difference at two potential electrodes P1 and P2 (Burger et al. 2006)

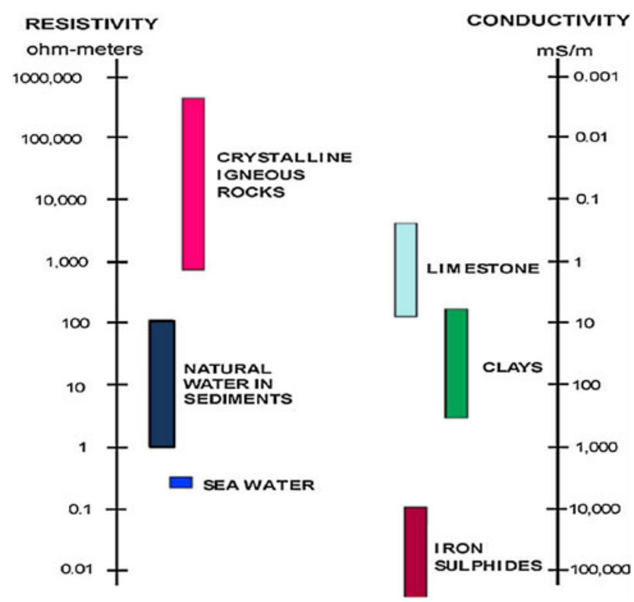


**Fig. 5** Resistivity values and conductivity values (inverse of resistivity) of some common materials (Liu, 2007)

## Resistivity Sounding Measurements

Twenty five VES were conducted in Area 3. Moderate topography and alluvial overburden allowed the resistivity surveys to be performed easily and quickly. Following preliminary studies, a square grid of 500 m by 500 m was selected to completely cover the study area for the VES surveys (Fig. 6). However, data were continuously evaluated during the survey so that the grid could be modified to 50 m spacing, if necessary. Schlumberger electrode configuration with maximum current electrode separation of 1400 m was conducted using the Swedish ABEM Terrameter SAS 4000. Four steel spike electrodes were used in connection with the instrument. VES measurements of Area No. 3 were completed in late 2003.

Schlumberger VES curves were initially interpreted using curve matching. Computer modeling (i.e. a VES software package) was then used to get the parameters of the best-fit model. The layer parameters obtained by curve matching were used to fix the range of initial values for the inversion programs used for estimating layer parameters more accurately. One-dimensional (1-D) interpretation of

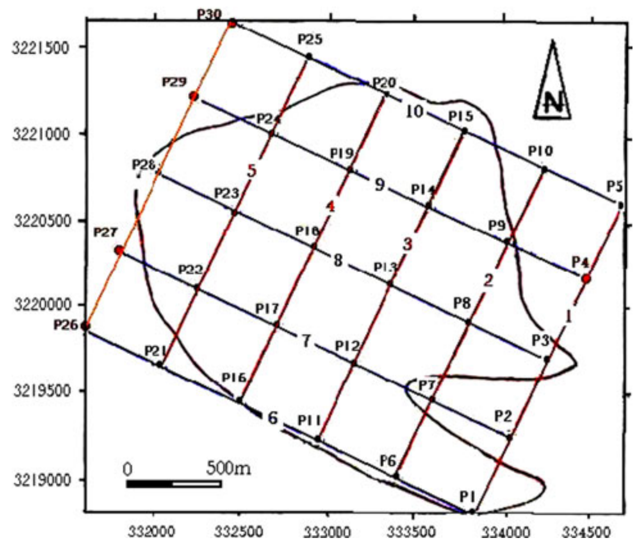


**Fig. 6** The square grid of 500 m–500 m for resistivity and IP sounding surveys; the closed curve surrounding most of the points shows the limits of Area 3 of the Gol-e-Gohar mine; points P4, P26, P27, P29, and P30, shown by red circles, were not measured in the sounding surveys

the sounding data resulted in an estimation of the depth of groundwater as 40–60 m, with an average thickness of 20–30 m for the water-bearing formation. Electrical resistivity of the water-bearing formation in the area was estimated to vary from 12 to 26 Ωm, indicating that the groundwater is likely saline, though the low resistivity of this zone could also be caused by the considerable clay content of the formation.

Various programs using either inverse or forward modeling methods are available to process apparent resistivity pseudo-sections and to perform 2-D imaging of the underlying structures (Bobatchev et al. 1990a, b; Loke and Barker 1996; Rijo et al. 1977). To obtain a more accurate resistivity image of the subsurface in the area, 2-D inverse modeling was carried out on the resistivity data using subsurface electrical imaging computer software packages such as Ipi2win (Bobatchev 2002) and Res2dinv (Loke 2000). Results of VES interpretations are completely discussed in Hojat (2003), and a brief description can be found in Kamkar Rouhani and Hojat (2004).

## Induced Polarization Measurements

If an electric current in the ground is interrupted, the voltage across the potential electrodes does not drop to zero instantaneously. Instead, it relaxes for several seconds (or minutes), starting from an initial value that is a small fraction of the voltage that existed when the current was flowing. This phenomenon has been termed induced polarization (IP) and is easily observed when electronically conducting minerals or clay minerals are present in the ground (Parasnis 1997).

Although most IP work has been in mineral prospecting and is of the mapping type, the method has been used in certain groundwater investigations together with resistivity VES surveys. Many clays have very low resistivity and cannot be distinguished in resistivity soundings from saltwater horizons (Fig. 5). In such cases, IP soundings can distinguish between clay layers (high IP) and other low-resistivity strata like saltwater beds (no or very low IP) (Parasnis 1997).

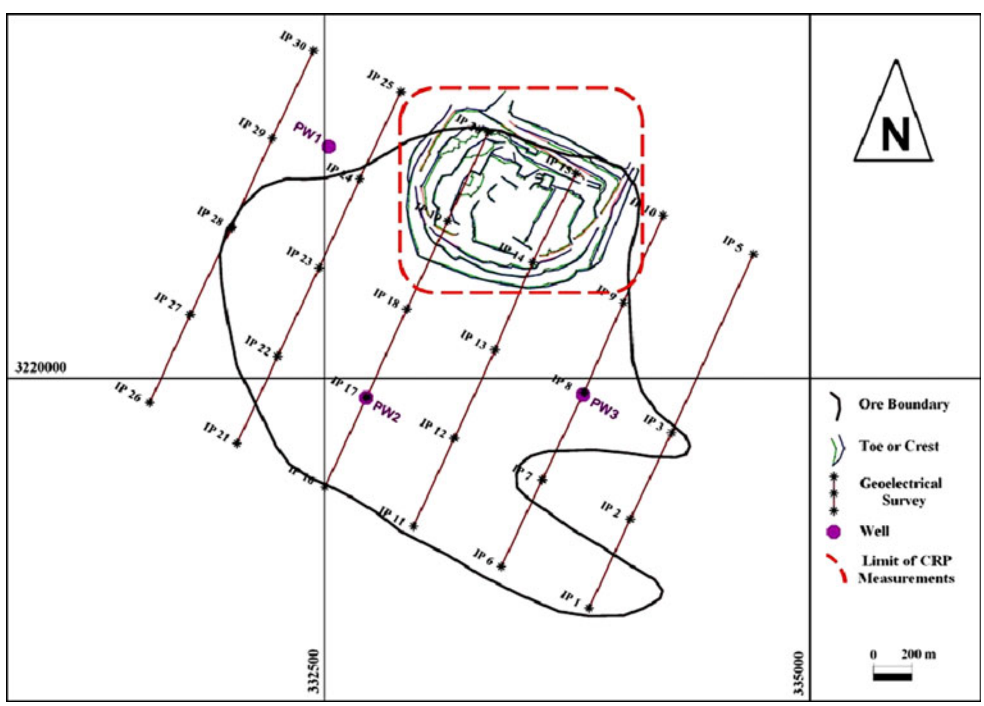


**Fig. 7** Map showing the boundaries of open pit activities in Area 3 of the Gol-e-Gohar iron ore mine. The locations of observation wells are also illustrated, along with the resistivity and IP sounding points. The area shown by the *dashed red lines* shows the limit of CRP measurements interpreted in Fig. 8

Since significant clay intrusions are present in Area 3 of the Gol-e-Gohar mine, induced polarization sounding measurements were also carried out at the VES points (Figs. 6 and 7) to remove the ambiguities of resistivity interpretations. This allowed low resistivity layers to be correctly interpreted as either water-bearing or clay layers.

## Subsequent Confirmation of VES Results

The northern part of Area 3 is being mined as an open pit. This provides a valuable opportunity to compare resistivity results with real observations as the mine goes deeper. Mining of Area 3 has reached a depth of about 60 m in 2010. Figure 7 shows the boundaries of open pit mining operations in the northern part of the study area. One can see that sounding points P14, P15, P19, and P20 are located on the mine walls. In order to control the interpreted resistivity layers of these points and get an idea of the accuracy of other points, the real layers encountered by mining were compared with what was determined by VES. The layer sequence observed on the southern wall of the mine near sounding point P19 can be subdivided into Quaternary detrital material, mainly mixed sand and gravel. However, clay minerals have also intruded these layers. As an example, the VES model of point P19 has three layers for its initial 60 m depth. It includes a surface layer of high resistivity, which was thought to be due to dry sandy gravel, a lower resistivity layer, which was attributed to sandy clay with gravel, and a medium resistivity layer of sandy gravel containing less clay. This interpretation properly matched the layers observed in the mine. Similar comparisons were done for the three other points and good correlations were observed.

Three observation wells were later drilled in the study area. These observation wells (PW1, PW2, and PW3 in Fig. 7) confirmed the results of the VES measurements. According to the information extracted from these wells, the water-bearing layer starts at a depth of 45–50 m, in accordance with the VES results, which indicated a groundwater depth of 40–60 m. Water samples from these wells were determined to be saline (Table 1), also confirming the VES interpretation.

**Table 1** Example of analysis (in epm) of samples obtained from observation wells drilled after resistivity sounding measurements in Area 3 of the Gol-e-Gohar mine

| Well # | Na | K | Ca | Mg | Cl | HCO3 | SO4 | EC |
|---|---|---|---|---|---|---|---|---|
| PW1 | 18.67 | 0.05 | 20 | 23 | 46 | 1.6 | 12.65 | 5,640 |
| PW2 | 95.4 | 0.1 | 86 | 40 | 235 | 0.7 | 10.29 | 19,920 |
| PW3 | 62.14 | 0.08 | 30 | 20 | 88 | 0.9 | 18.16 | 9,880 |

## Combined Resistivity Profiling Measurements

Hydrogeological studies of Area 3 show that the aquifer is fed by a number of faults. Therefore, it was necessary to detect the faults and fracture zones in the area. To do this, combined resistivity profiling (CRP) measurements with four electrode spacing of 40, 80, 120, and 160 m, were

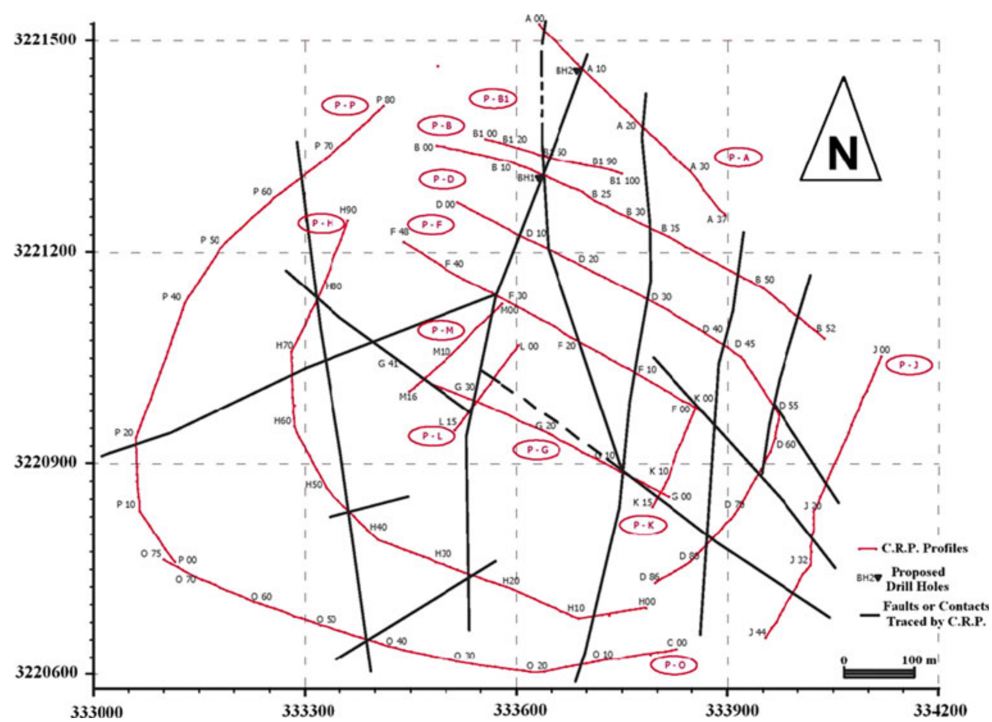


**Fig. 8** Location and interpretation map of CRP measurements in the northern part of Area 3 where open pit activities are being carried out. *Red lines* show CRP profiles. *Black lines* are the interpreted faults (ZPSCE, 2006)

carried out in the northern part of Area 3. Resistivity values were measured using a three electrode array for both forward and reverse movement along each profile. The CRP survey was conducted so that the whole area could be completely monitored. Location map of the CRP profiles and the interpreted faults are illustrated in Fig. 8. As can be seen, major faults were detected in the open pit area. These faults were visible in most profiles regardless of the electrode spacing and were interpreted as major water conduits. These results are proving to be very valuable in designing and siting monitoring and drainage wells.

## Dewatering System Design Solution

Area 3 is about 2 km west of Mine No.1 and comprises two anomalous zones that are joined at depth. The southern part has a greater cover of overburden (more than 140 m) than the northern part (with less than 100 m). Therefore, both open pit and underground mining methods are likely to be used for extraction of the deposit. Due to economical and technical reasons, open pit mining of the northern part of Area 3 is being conducted first, and underground mining operations will continue from the southern border of the open pit. This section discusses the proposed dewatering strategies for the open pit mine.

The groundwater level needs to be kept below the pit floor of Area 3 throughout the life of the mine. Mine dewatering and slope depressurization systems can be either active or passive. Active dewatering methods include surface wells, stage-level wells, sub-horizontal wells, and drainage galleries. Passive dewatering methods include inflow grouting, source grouting, ground freezing, and slurry walls. However, some of these methods are not practical in the open pit mine of Area 3. The primary dewatering strategy will focus on reducing groundwater level in permeable zones around the perimeter of the pit to dissipate pore pressures in the pit walls.

Pumping wells have been operating in Area 1 of the Gol-e-Gohar mine for several years, and observation and piezometric wells show that these wells were not successful in slope depressurization. Therefore, pumping wells are not recommended for dissipation of pore pressures in the pit walls of Area 3. Using a drainage gallery beneath the northern wall would seem to be a better option. Monitoring and in situ permeability tests are required to determine the gallery configuration.

An alternative option is to start underground mining activities in advance. Since underground mining operations will continue from the southern border of the open pit mine, the provided underground openings can initially play the role of an open pit dewatering system.

A secondary dewatering strategy focuses on lowering the groundwater level within the pit. Although open pit activities have reached groundwater, mining operations cannot cease. Based on the geoelectrical results and hydrogeological observations of the area, five pumping wells are proposed to be drilled along the fault considered to be the main water conduit. Two of these wells are illustrated in Fig. 8. The other three, not shown in this figure, are located beyond the pit limits.

It should be noted that monitoring and piezometric wells and in situ permeability tests will be needed to determine how effective these strategies are. Due to the fact that fault zones are the most probable source of the water, monitoring and piezometric wells can be effectively located in the fault zones. CRP measurements have provided a great amount of valuable information required for preliminary dewatering design. Resistivity and IP measurements of Area 3 have provided reliable information about the depth to the water table and the thickness of the water-bearing layer. During the next few months, the impact of mining activities on groundwater and the degree of natural drawdown or drainage will be determined. Analysis of this information will be used in the final dewatering design.

## Conclusions

In order to effectively carry out dewatering strategies in the open pit mine of Area 3, a huge amount of data is required. Therefore, geoelectrical surveys were carried out to investigate the groundwater and geological features in order to design a suitable drainage system. Subsequent confirmation of resistivity interpretations indicates that the use of the various geoelectrical surveys, which were applied as a suite of complimentary geophysical tools, were successful in predicting groundwater and geological conditions of the study area.

Commencement of open pit mining in the northern part of the area allowed us to compare resistivity measurements at sounding points P14, P15, P19, and P20 with the actual strata. The layers observed on the mine walls at a 60 m depth properly correlated with the resistivity and IP interpretations. The geophysically predicted water layer was also confirmed by monitoring wells drilled in the area. Moreover, mining activities first encountered the water table at a depth of 45 m, in accordance with the resistivity and IP interpretation of the points located in the northern part of Area 3.

The presence of fracture zones, which may act as water conduits, were also known from CRP measurements. Pit inflows will likely be dominated by seepage from these fault zones.

Based on the geoelectrical results, a preliminary pattern of monitoring and piezometric wells will soon be installed. In situ permeability tests will be carried out to determine the hydrogeological characteristics of the water-bearing layers. Following these studies, remedial plans to reduce water pressure behind the mine walls and lower the groundwater level within the mining area will be initiated. Drainage galleries are considered to be a likely method for effective dewatering of the Area 3 open pit. However, another option is to start underground operations in advance, using the underground void space to drain the open pit.

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