

Mapping underground cracks using 2D electrical resistivity tomography: the case of the landslide of Kef Essenoun phosphate deposit, Djebel Onk (northeast of Algeria)

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Abstract The landslide of Kef Essenoun phosphate deposit (northeast of Algeria) occurred on September 2007, when a large mass of rocks detached from the rock mass scale and filled almost entirely the pit (the career). Recently, new cracks oriented N–S and NE–SW with large sizes have appeared in several places near a slide area and even in the alignment of the 2007 slide area. To understand the nature of the deformations recently observed at the surface, and to favor safety measures that can be implemented rapidly, it is essential to obtain maximum information on the deep structure of underground cracks and areas of weakness. Electrical resistivity imaging or tomography (ERT) is well suited for characterizing the bedrock surface thanks to the ability of the technique for detecting resistive features as well as discriminating subtle resistivity variations. For the present investigation, a Wenner transect was conducted through a visible crack area near the landslide area. The electrode spacing was 2 m and the length of the transect was about 60 m. In this case study, the survey results suggest that ERT is a cost-effective tool that can easily be deployed to gather valuable subsurface data and to aid in the detecting and mapping of underground cracks and other subsurface cavities.

Keywords ERT · Landslide · Underground cracks · Kef Essenoun phosphate deposit · Djebel Onk · Algeria

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Introduction

The intensive exploitation of mineral resources, to meet the growing and continual need of the global market, often has a negative impact on the environment. Resource extraction from the Earth usually results in ground subsidence and/or cavities, sometimes causing collapses of underground structures (case of underground mining) or landslides in open mining (case of career). This second case poses a major hazard for human activities and often causes substantial economic losses and property damages (Hong et al. 2007; Nadim et al. 2006).

An actual example from Algeria is the landslide of the Kef Essenoun phosphate deposit of September 7, 2007, in which a large mass of rock detached from the rock mass scale and filled almost entirely the pit (the career) (Fig. 1a, b), with no reported injuries to miners. The affected area was approximately 11,000 m², with an average thickness of about 70 m (35 m of phosphate ore and 35 m of overlying land) (Fig. 2). This landslide of an estimated volume of 7.7 million m³ triggered wide media coverage due to the size of the event and the resulting economic loss. Recently, new cracks oriented N–S and NE–SW with large sizes and lengths up to 280 m (Fig. 3a–d), appeared in several places, near the slide area and even in the alignment of the latter. This new event has received much attention, causing great concern among officials of the phosphate mining society (SOMIPHOS-FERPHOS group), in that it can be considered as a potential cause of its reactivation.

Direct investigations to determine landslide characteristics by using geotechnical methods along with borehole data provide only the well data. Also, the high cost of such methods implies that they are not always suitable (Jomard et al. 2007; Lee et al. 2008). Alternatively, geophysical surveys provide detailed information about landslide anatomy, as well as provide facilities for immediate survey over enormous areas at a

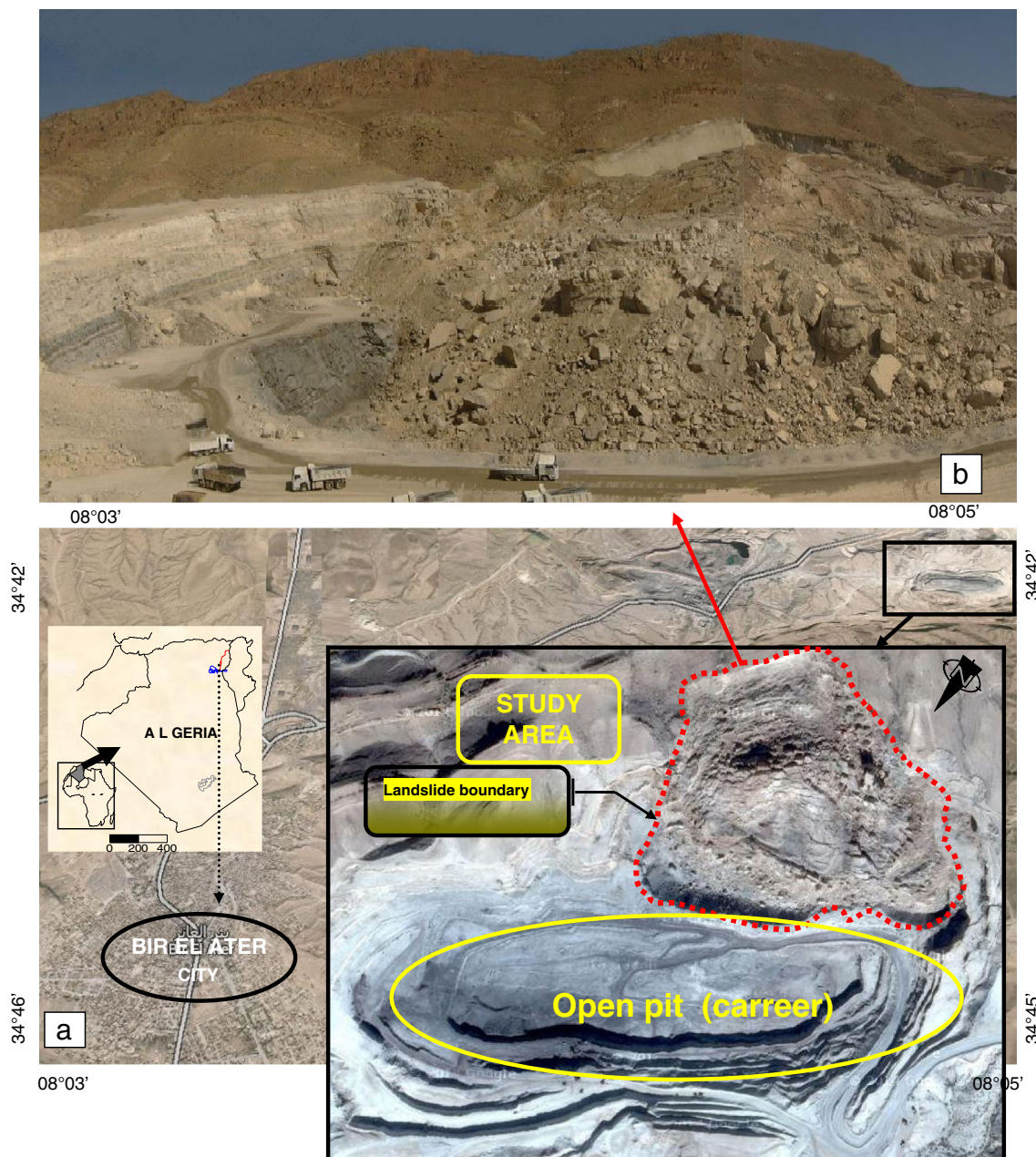


Fig. 1 a Satellite photo showing the study area and landslide boundary. b Scenic view of the site showing the landslide area

relatively low cost (Bogoslovsky and Ogilvy 1977). Generally, geophysical methods are not invasive and the results can be transformed into the geotechnical means and are crucial in the investigation of landslide areas (Cosenza et al. 2006).

Techniques used in applied geophysics include seismic reflection and refraction (Cook 1965), gravimetry (Colley 1963; Butler 1984; Bishop et al. 1997; Rybakov et al. 2001), ground-penetrating radar (Ballard 1983; Annan et al. 1991; Nouioua et al. 2013), and resistivity tomography (Zhou et al. 2002; Fehdi et al. 2011). Nowadays, there are several geophysical methods for the mapping of fractured rocks (Orellana 1972; Frohlich and Kelly 1985).

In comparison with the ground-penetrating radar and the seismic reflection, Schrott and Saas (2008) consider that electrical resistivity imaging or tomography (ERT) is the most successful geophysical method for the study of internal characteristics of active and dormant landslides. The purpose of this technique is to determine the subsurface electric resistivity distribution by taking measurements along a survey line at the surface. A measurement is normally performed by injecting electrical current into the ground through two current-carrying electrodes and measuring the resulting voltage difference at two potential electrodes. The apparent resistivity is calculated using the injected current, the measured voltage, and a geometric factor related to the

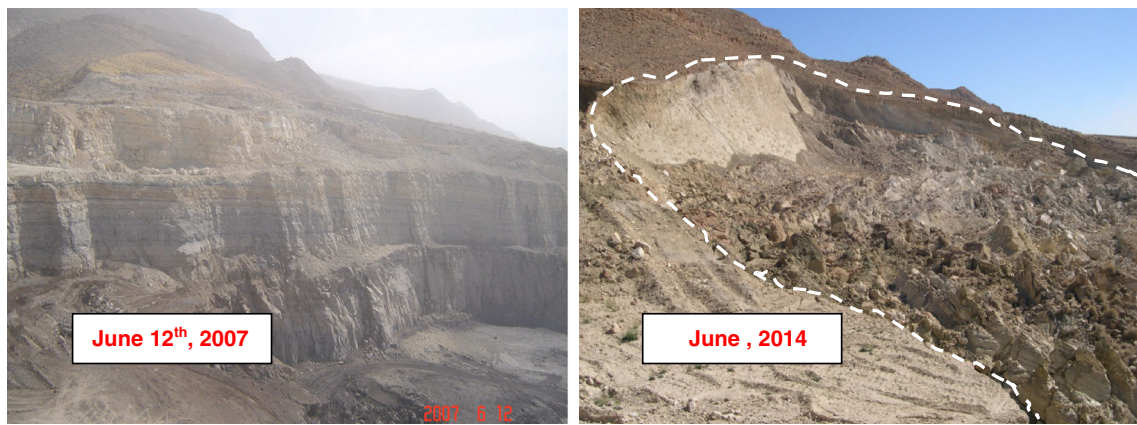


Fig. 2 Career before and after slide

arrangement of the four electrodes (Morelli and Labrecque 1996; Parasnis 1997).

In this paper, a case study is discussed to demonstrate the potential of ERT for mapping underground cracks and cavities. The survey sites are located in Kef Essenoun near Bir El Ater City, Algeria.

Geological setting

The phosphates of the area of Djebel Onk, located in the southeast of Algeria, are part of a succession of sedimentary deposits formed at the end of the Cretaceous–Eocene era. Djebel Onk represents an important reserve of phosphate rocks (about 2

billion m³), which is a calcareous mountainous solid mass about 20 km long. It comprises several sectors of phosphate formations among which is Kef Essenoun. This deposit is located southeast of Algeria, exactly 9 km southeast of Bir El Ater City and 20 km from the Algerian–Tunisian border (Fig. 4). The deposit consists of a layer of phosphate with rather constant and homogeneous characteristics throughout its extent, i.e., over a surface of ~3.16 km² (3.5 km long and 0.9 km wide). The main structure is that of monoclinical, dipping 10° to 15° towards the south. Elevations are approximately (810 m above sea level (a.s.l.)) in the northeast and (710 m a.s.l.) in the southwest. The lithological succession of the Kef Essenoun layer is characterized by the most significant thicknesses of the phosphatic beam, which are 35 to 45 m in the phosphatic basin of Djebel Onk.

Fig. 3 a, b, c Photos showing the width of the cracks. d Overall view of the crack extending more than 280 m



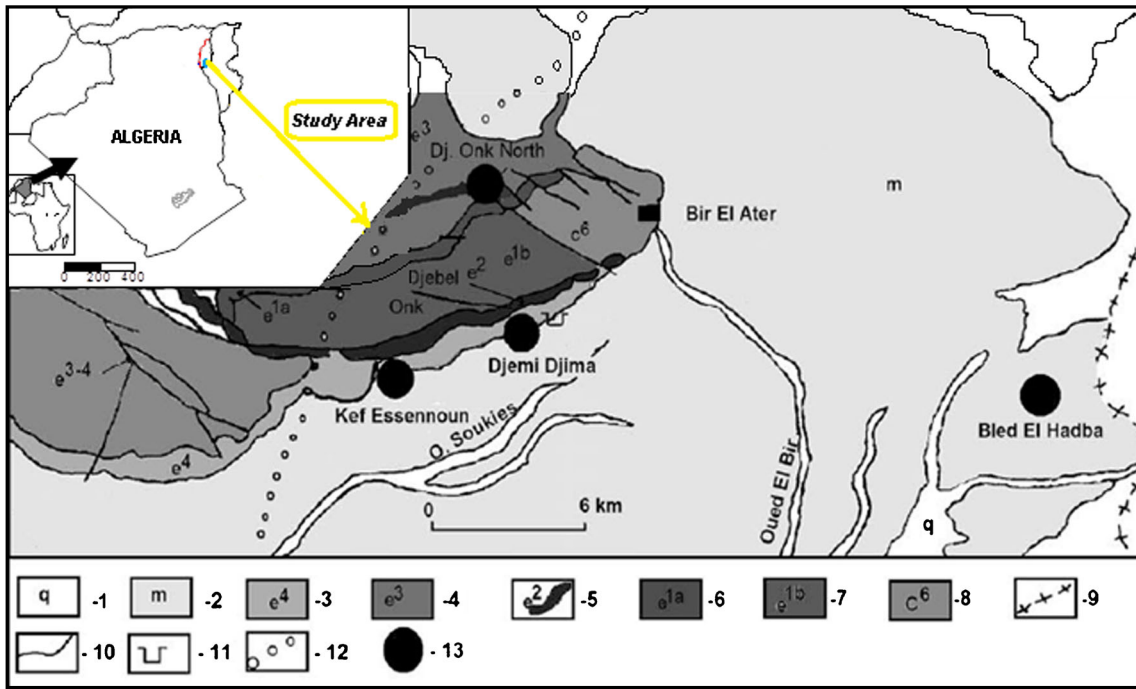


Fig. 4 Schematic geological map and location of Djebel Onk phosphate deposits (Kassatkine et al. 1980): 1 alluvial deposits (Quaternary); 2 sand and clay; 3 marl and limestone (Lutetian); 4 marl and limestone with phosphate level (Ypresian); 5 marl, limestone, dolomite, and main phosphate layer (Thanetian); 6 coquina limestone end marl (Montian); 7

marl and limestone (Danian); 8 limestone (Maastrichtian); 9 Algerian–Tunisian border; 10 geological outline of the main phosphatic layer; 11 open pit; 12 shallow of Ain Fouris: western limit of the main phosphatic layer; 13 phosphate deposit

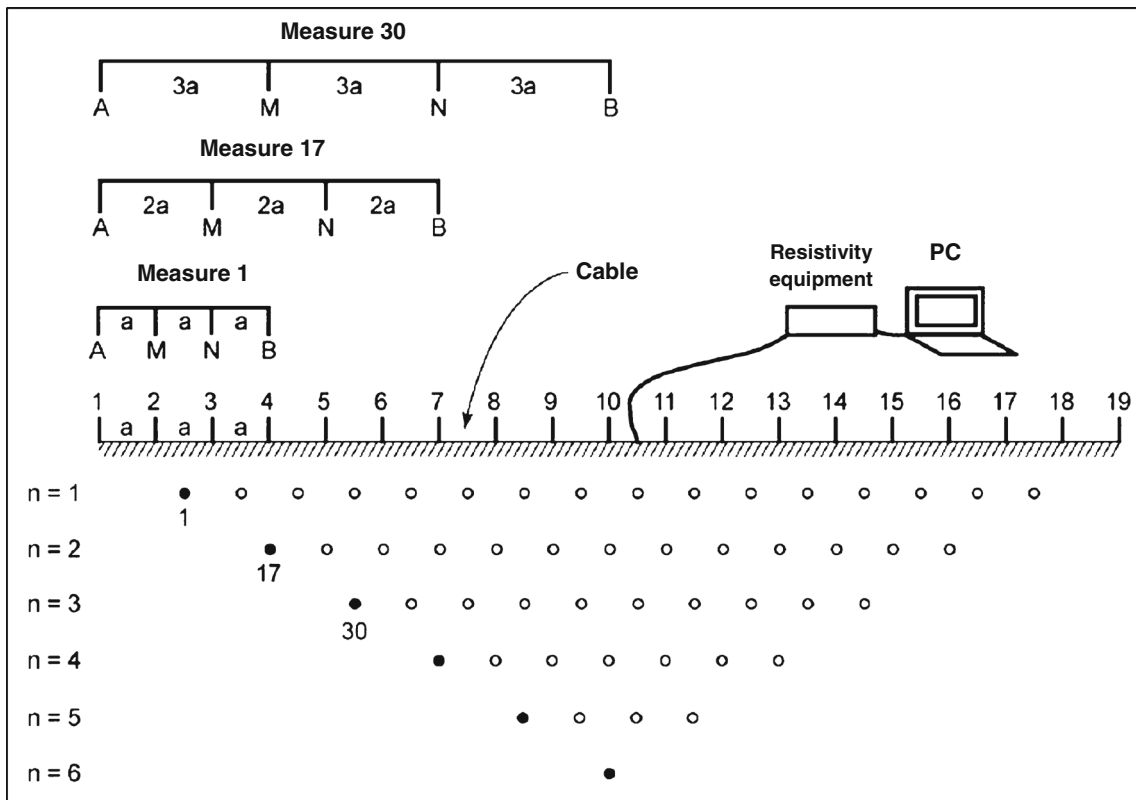


Fig. 5 Arrangement of electrodes for a 2D acquisition and measurement sequence for the Wenner configuration

Most of the layer consists of dark and light phosphates, with variable grain size ranging from fine (100 μm) to coarse (up to 1 mm). Clear, dark brown phospharenites (25 % of the reserve) are present above dark phosphates in the northern part of the layer (EREM 1987). The phosphatic beam is made up, from bottom to top, of marl–phosphate–dolomite alternations and phosphated dolomite, which is the productive layer. Chemically, the productive layer is remarkable for its strong contents of P_2O_5 and its low contents of MgO , for both types of ores. The average contents of P_2O_5 range between 25 and 27.9 %, for a general average of 26.53 %. The contents of MgO are constant and weak (2 and 3 %) throughout the extent of the layer. There are many minerals of the gangues associated with the phosphated elements in the phosphatic rocks: quartz, calcite, dolomite, ankerite, siderite, feldspars, clays, gypsum, and organic matters, among others.

Electrical resistivity tomography technique

This technique may be frequently used for site investigation in karst areas, especially when the overburden soil is clay dominated (Cook and Van Nostrand 1954). The electrical conductivity of clayey soil and carbonate rock has an electrolytic origin, whereas most earth materials do not conduct electricity very well. According to Archie's law (LaMoreaux et al. 1984), electricity is conducted through interstitial water by ionic transport. Archie's law is given by

$$\rho = a\rho_w\phi^{-m}$$

where ρ is the rock resistivity, ρ_w is fluid resistivity, and ϕ is the fraction of the rock filled with the fluid, while a and m are two empirical parameters (Keller and Frischknecht 1966).

Carbonate rock generally has a significantly higher resistivity than clay soil because it has much smaller primary porosity and fewer interconnected pore spaces. Its typical resistivity value is more than $1000\ \Omega\ \text{m}$ (Telford et al. 1990). Clayey materials tend to hold more moisture and have a higher concentration of ion to conduct electricity, therefore having resistivity values less than $100\ \Omega\ \text{m}$ (Telford et al. 1990). The high contrast of resistivity values between carbonate rock and clayey soil favors the use of the resistivity method to delineate the boundary between bedrock and overburden. As for the traditional resistivity method, four metal stakes or electrodes are driven about 0.3 m into the ground.

One pair of electrodes is used to introduce direct-current electricity into the subsurface, and the second pair of electrodes is used to measure the potential (voltage) difference in the soil. After a data point is obtained, the electrodes are moved to gain data at different locations at the same depth (electric profiling) or at different depths at the same location (electric sounding). The resistance of the ground circuit is calculated by Ohm's law: resistance=voltage/current. The resistivity is then calculated using the electrode geometry and the resistance. However, the measured resistivity is affected by how the electrodes are placed into the ground with respect to the electrode geometry. It can also be heavily dependent on the direction of each line in case of anisotropy problems in the rocks (Al-Amoush and Abou Karaki 1997). Commonly used electrode geometries include Wenner, Schlumberger, pole–dipole, and dipole–dipole.

2D tomography acquisition

A 2D acquisition generally uses a large number of electrodes connected to a multi-conductor cable and placed in a profile.

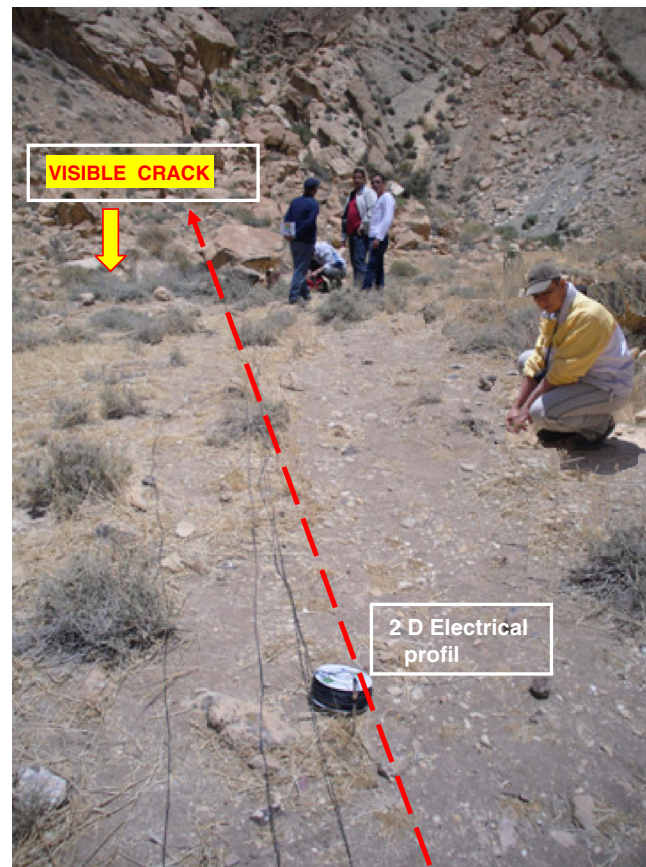


Fig. 6 Photo showing the realized profile through the crack

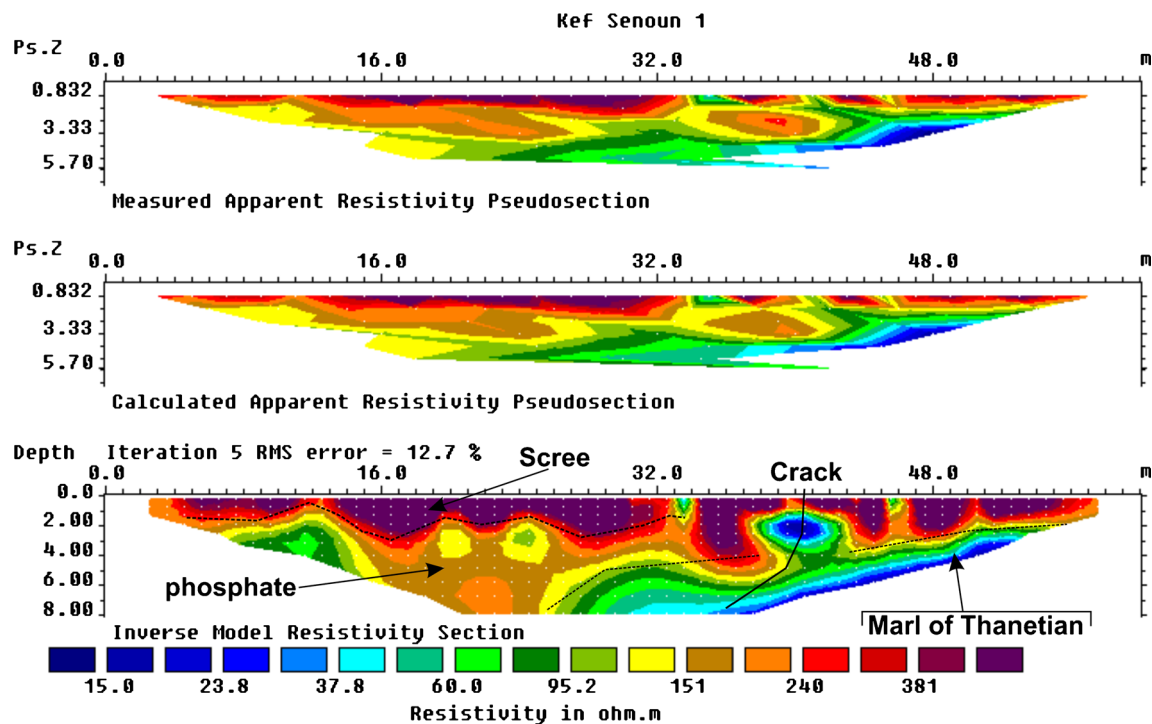


Fig. 7 The result of 2D inversion of Wenner array data from the study area

For a good 2D image, it is necessary that the coverage of measurements is also 2D and uniform. Given a Wenner configuration, for example with 19 electrodes, the distance between two electrodes is denoted as a . In Wenner configuration (Fig. 5), the first measure will be using electrodes 1, 2, 3, and 4, where electrodes 1 and 4 will be used for current injection (A and B) and 2 and 3 measure the potential (M and N). The entire device is moved along a straight line with a distance a . Electrodes 2 and 5 will be then used for current injection and 3 and 4 to the extent of the potential. The process is repeated until electrode 19 is reached. We obtained, for the first level of acquisition, 16 (19–3) opportunities.

As the characteristic of the Wenner configuration is to keep a constant distance between all electrodes, we took for the next level a distance equal to $2 \times a$. The first step will involve the second level then electrodes 1 and 7 for the current injection and 3 and 5 for measuring the potential. The process is repeated again until electrode 19. The second level will therefore include 13 possibilities (19–2×3). We conducted measures of each level of acquisition with $3 \times a$, $4 \times a$, etc.

Methods of processing and interpreting data

The electrical tomography profile was measured across the area, using SARIS Scintrex resistivity equipment by

Wenner configuration with $a=2$ m and eight levels of investigation. The total length of the profile was 60 m. The values directly measured in the field are apparent resistivities. In fact, each measure represents a value that incorporates the resistivity of a certain volume of the soil. From these values, we tentatively found the dimensions and resistivities of different actual buried structures. The raw data acquired on the field were recorded in a file of a specific format. Each measure is defined by its horizontal and vertical coordinates, the value of measured potential, the intensity of injected current, and the value of the apparent electrical resistivity. Then, all data were examined in light of the measures to eliminate questionable data. This was possible through a judicious representation of the action that illustrates the point by level of acquisition with a very limited scale. This type of representation emphasizes the points, whose resistivities are very high or very low with respect to their neighbors. The brutal change of resistivity values cannot be due to a geological phenomenon; in most cases, these values are removed to not distort the results of inversion.

To obtain an image representing the quantitative changes of electrical resistance, we proceeded to model the subsurface along a profile east–west direction through a visible crack in the surface as shown in Fig. 6. The modeling was done by an inversion process based on an iterative method that attempts to minimize the difference between the measured pseudosection and a pseudosection recalculated from a model of electrical

resistivity theory. This modeling process is modified with each iteration until the calculated and measured data reach an acceptable agreement or until no further improvement is possible. Measuring the deviation between the theoretical model and the model is expressed as root-mean-squared “RMS.” While this is a good indication of the quality of a cross section, it is not always the iteration which has the lowest RMS error profile that gives the most geologically correct. In general, the most reliable model is located just after the iteration where the RMS error does not significantly change (<0.5 % improvement), which usually happens between four and six iterations.

Field results

We used a Wenner array configuration and a multi-electrode system with 31 electrodes 2 m spaced. The investigation depth increases with the increasing distance between electrodes. The maximum investigation depth for this array is about 8 m. Apparent resistivity data were inverted with the L2 norm-based least-squares optimization method using the RES2DINV to generate a model of the subsurface structure and stratigraphy based on its electrical properties. The resulting image along the survey line obtained over the study area (Fig. 6) is formed by three panels (Fig. 7). The first panel located on top represents the pseudosection of the measured apparent resistivity. The middle pseudosection is the model calculated by the inversion program. The last panel is the inversion model section.

The obtained electrical tomography is perpendicular to the axis of movement of the slide in order to obtain maximum information on the deep structure of the basement. It allowed us to map the Thanetian formations. Thus, we highlight a resistant near-surface layer which correlates with the scree. Next, we distinguish a layer of intermediate resistivity which is similarly true in the limestone of the upper Thanetian (phosphate). In depth, the environment becomes conductive and can be attributed to the marls of the lower Thanetian. Around station 40, only on the right side of the profile, we distinguish a formation where the resistivity is lower which we interpret as related to the saturation of marls and clays. This near-surface conductive area perfectly correlates with the observed crack, well developed in depth and forming a very large cavity filled with conductive materials. These cracks are probably caused by recent landslides.

Conclusion

In order to forecast the occurrence of landslides at a regional scale, a geophysical survey was conducted in the Kef Essenoun phosphate mine of Bir El Ater region, Algeria.

The results presented in this paper illustrate that ERT is a cost-effective tool that can easily be deployed to gather valuable subsurface data. The conducted 2D cross-borehole resistivity tomography allowed the mapping of the complex geometry of the bedrock surface. The tomographic images computed within RES2DINV have revealed the presence of a resistant formation near the surface layer which correlates with alluvial fans. We distinguished a layer of intermediate resistivity which is similar in the limestone of the upper Thanetian deposit (phosphate). In depth, the environment becomes conductive and can be attributed to the marls of the lower Thanetian. This conductive area near to the surface perfectly correlates with the observed crack, which are well developed in depth and forming a very large cavity filled with conductive materials. The profile has showed clearly the high potentiality of ERT to determine the geometry and evolution of the underground cracks, which are probably caused by recent landslides.

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