Characterization of Lava Caves, Using 2D Induced Polarization Imaging, Umm Al Quttein area, NE Jordan

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Abstract

The possibility to detect lava caves in the basaltic flows in the shallow subsurface using Induced Polarization (IP) imaging survey was a significant subject in recent years. The application of this method to caves in the large intra-continental volcanic field of the Harrat Al- Shaam, NE Jordan are reported. The Harrat is composed of a series of basaltic flows that stretch for many kilometers below their eruptive vents. Such long flows are possible only because lava tends to build long tunnels in which the lava is thermally isolated, thus preventing its early solidification.

The IP imaging technique is very sensitive to horizontal changes in the resistivity method and is an excellent tool to map vertical structures such as cavities or intrusive dikes. This technique was used in the Umm El-Quttein area to investigate the subsurface and test if we can image existing caves and if these might be a potential hazard of the roads in the area. The IP measurements were made with the time-domain method and processed by using the least square inversion approach that will automatically determine true 2D resistivity models. The quantitative interpretation obtained from 2D inversion modeling indicates that the lava caves produce anomalies characterized by a high resistivity at around 3010 Ohm-m with a depth of less than 19 m, and very intense anomalies; likely ascribable to open fractures. These may be filled with clay or carbonate sediments, that decrease the apparent resistivity values but increase the chargeability (MF). This technique therefore was successful in detecting lava caves within the complex structures of the Jabal Quis volcano. Furthermore processing is possible within a few hours.

Key words: Lava caves, archaeological importance, 2-D induced polarization imaging, time-domain, potential hazard environment, NE Jordan.

1. Introduction

The Harrat Al-Shaam lies in the northwest of the Arabian plateau and is composed of large fields of predominantly alkali olivine basaltic lava (Fig.1). The lava covers an area of 45,000 km² and stretches over 700 km NW-SE, from Syria through Jordan to Saudi Arabia (Coleman et al., 1983). The Jordanian part of the plateau is geomorphological known as Harrat El-Jabban with an area of about 11,400 km², it is estimated that the lava is less than 150 m thick (Osaka, 1989; Bender, 1974; Khalil, 1991; Al-Malabeh, 1994; and Shaw et al., 2003). The basalt plateau forms a very irregular landscape, difficult to access. Fissure eruptions produced vesicular pahoehoe and "aa" lava flows, isolated volcanoes, and pressure ridges (Bender, 1975; Guba and Mustafa, 1988; and Wallace at el., 1994). Eruption of these volcanic fields started in the Oligocene, the youngest are about 400 000 years old (Tarawaneth et al., 2002).

The volcanic and tectonic evolution of the Arabian Harrats was poorly understood. The lava flows is a key to understand the magma supply which transport for improving real time lava flow hazard assessment.

The volcanic lava fields of Harrat Ash Shaam comprises of sub-horizontal lava flows less than 25 m thick; several of scoria cones, extensional faults, and large fissure eruptions in strike NW-SE and N-S directions that emanated from dike systems, forming elongated ridges (Bender, 1974; Barazangi, 1983; and Guba and Mustafa, 1988; Al Malabeh 1994). The source of alkali basalts and basanites from Harrat Ash Shaam are melts of deep, garnet-bearing asthenosphere magmas, mixed with lithosphere mantle melts of Miocene to Pleistocene age (Shaw et al., 2003).

Generally lava tunnels (originally termed pyroducts; Coan, 1844) developed in low viscosity lavas with constant and low to moderate flow volumes (i.e., Peterson et al., 1994). They allow the lava to cover the topography at low slopes, typically of less than 2° (i.e., Kempe, 2002). Investigation of tunnels both inactive and active on Hawaii shows that these tunnels form in the majority by progressive advancement and inflation of sheets flow at the front of pahoehoe flows (i.e, Kempe, 2002; Kauahikaua et al., 1998). Less common is the formation by crusting over of lava cannels, a process mostly cited in textbooks on vulcanology (i.e., Ollier and Brown, 1965; Greeley, 1971; Calvari and Pinkerton, 1998). Apart from lava tunnels (often called lava tubes, a term that incorrectly assumes lava flow through a tube system upper pressure, while the lava in tunnels flows with an oven surface like a river in an underground canyon) other processes can also form caves, such as the deformation of half solidified lava sheets resulting in non-continuous pressure ridge caves. The study area contains both remnants of lava tunnels and pressure ridge caves in lavas formations of Umm El-Quttein, El-Mukeitite, Al-Bishriyya, Al-Hamidiyya, and Asfar (Al-Malabeh, 2005; Kempe et al., 2008).
The first cave in the area was found by A. Al-Malabeh in 1985. In the vicinity of Umm El-Quttein many sinkhole occur, possibly collapse feature above underlying lava tunnels. Such holes are also noticed near some of the ruins in the northern Badia, among them the Umm El-Jimal area, the largest of these ruined cites of the southern Hauran (fields observations of Al-Malabeh). The archaeological sites date back to Nabataean times as shown by inscriptions found in the ruins (Dussaud, 1907; Butler, 1907).

One of these mentions the name of the Nabataean King Rabbel, dated to the year 93 A.D. (Butler, 1907, 1920). The sites have then been occupied continuously in Roman and Byzantine times. It is a hypothesis that these old settlements are related to the lava caves that served as dwelling caves and as water resources. The area currently is under speleological exploration and many caves have already been documented in this northwestern section of the Harrat El-Jabban (Kempe and Al-Malabeh, 2005; Kempe at al., 2006; Kempe et al., 2008). Furthermore Al-Oufi (Al-Oufi et al., 2008), used the VLF-EM technique to study the subsurface for the occurrence of lava tubes, faults and dikes and geoelectrical and seismic refraction methods have been used to study the location of a proposed dam in the volcanic lava fields (Batayneh et al., 2001).

Also the seismic activity at the locations of the ancient cities of Jordan (Al-Tarazi, 2003) was looked at. These investigation studies were gives results in more accurate definition and clearly interpretations on the lava caves of archaeological importance in northeast part of Jordan. In present study, 2D of Induced Polarization (IP) imaging survey using time-domain method was performed in Umm El-Qutein cave successions (Fig.1) based on principles electrical properties of the basalts; to determine characterize edges end of the lava caves, and to an evaluate their extent that are formed the potential hazard environment of road Umm El-Quttein.

This technique is increasing use in the engineering and environmental studies, an especially in detect of the vertical structures such as cavities and dikes (Ward et al., 1995; Loke, 2001).

Engineering and environmental examples of the successful use of IP surveys include the detection of clay minerals (Iliceto et al., 1982; Vinegar and Waxman, 1984), the detection of inorganic and organic contaminations (Cahyna et al., 1990; Ruhlwe et al., 1999; Olhoeft, 1985, 1992; Vanhala et al., 1992), permeability evaluation (Sturrock et al., 1999), and the detection of underground mine voids or tunnels (Sheets, 2002).

However, The IP techniques were development of the mineral exploration such as, mineralization of copper or gold mineralized (Telford et al., 1990). The IP parameters include the time-domain chargeability (M), normalized chargeability (Mn), percentage frequency effect (PFE), and the metal factor (MF). These parameters were developed as measured of instruments limitations and the way of the IP effect (Edwards, 1977; Ward et al., 1995).

Generally, the dipole-dipole array configuration is based on used two current electrodes (A) and (B) and two potential electrodes (M) and (N) arranged on a straight profile (Fig.2). This array is widely used in resistivity surveys, because of the low electromagnetic coupling between the current and potential circuits (Reynolds, 1997). The study area is located in the lava caves successions of Pre-Quaternary age. One of these successions is called Al-Howa tunnel (Fig.1) (Kempe and Al-Malabeh, 2005).
Since the stability of the lava caves are depends on the presence of the fractures in the basalts rocks, collapse of the cave that almost by filled with sediments or carbonates (Fig.3), then the IP imaging survey was undertaken in order to achieve useful information for possible future restoration work, and interpretation IP data in an environmental investigation for these caves. Further, the chargeability \((M)\) we find from the IP measured that is closely related to lithological structures and characteristic \((M)\) due to lithology from IP data due to cavity fractures.

2. IP Parameters and Model Inversion
The IP parameters \((M, PFE, \text{ and } MP)\) are very sensitive to the bulk conduction and the surface polarization properties of the rocks. The weight of the IP parameters are measured from the conductivity that yields the normalization IP parameters, where the conductivity is calculated from the resistivity equation (Wong, 1979; Seigel, 1959; Pelton et al., 1978):

\[
\sigma_a(w) = \frac{1}{\rho_a(w)}
\]  
(1)

where \(\rho_a(w)\) is the complex resistivity response function in unit (Ohm-m) at homogeneous media, \(\sigma_a(w)\) is the conductivity of the material in unit siemen per meter \(Sm^{-1}\). The apparent resistivity values for dipole-dipole array are given by the formula as follows:

\[
\rho_a = \pi an(n+1)(n+2) \frac{V}{I}
\]  
(2)
where, \( \rho_d \) the apparent resistivity (Ohm-m), \((a)\) the spacing electrode, \((n)\) the number of factor value. The spacing between both electrodes pairs is \((a)\). The first sequence of measurements is made with a value of \(1\) for \((n)\) between the current electrodes \((A)\) pairs and potential electrodes \((M)\) pairs (Edwards, 1977). The spacing \((a)\) is integer multiple and \((n)\) factor is increased to \(2, 3, \ldots\) to \(6\), so increase the depth of penetration (Fig.2). The chargeability \((M)\) is often measured with instruments that operate in the time domain method. This is characteristic of chargeability \((M)\) measured (Summer, 1976; Schön, 1996) is defined

\[
M = \frac{1}{V_p} \int V_s dt
\]

where, \(V_s\) is a residual voltage integrated over a time window defined between times \(t_s\) and \(t_f\) after termination of an applied current, \(V_p\) is the measured voltage at some time during application of the current and \(\Delta t\) equals the length of the time window of integration. Units of chargeability are typically quoted as millivolts per volt (mV/V).

According to Van Voorhis et al., (1973) the IP effect is measured with the percentage frequency effect \((PFE)\) in the frequency domain, and can be expressed by the following equation:

\[
PFE = \frac{\sigma'_{bulk}(f) - \sigma'_{bulk}(0)}{\sigma'_{bulk}(0)} \times 100
\]

where, \(A\) constant at the spread between measurement frequencies.

The metal factor \((MF)\) value for IP properties can be calculated from either time domain or frequency domain measurements (Edwards, 1977), in the time domain expressed by equation:

\[
MF_d = \frac{1000 \times M}{\rho_{DC}}
\]

in the frequency domain expressed by:

\[
MF_d = \left( \frac{100000 \times (\rho_{DC} - \rho_{AC})}{\rho_{AC}^2} \right)
\]

where, \(\rho_{DC}\) and \(\rho_{AC}\) the apparent resistivity values measured at low and high frequencies (Van Voorhis et al., 1973; Summer, 1976; Edwards, 1977).

The \(PFE\) and \(MF\) are both controlled by apparent resistivity \((\rho_d)\) curves (Edwards, 1977), and it distinguished the relationship characterization of the anomaly. The weight of the IP parameters can measured conductivity that yields the following normalized IP parameters which mean quadrature conductivity, metal factor \((MF)\), and normalized chargeability as called term \((Mn)\). According to paper publishers Lesmes and Frye (2001) defined the normalized chargeability \((Mn)\) as global estimate of interfacial magnitude (defined as chargeability divided by the resistivity magnitude), and that is given by:

\[
Mn = \frac{M}{\rho}
\]

(Slater and Lesmes, 2002) developments improved of IP interpretation and are given the normalized chargeability by equation:

\[
M_n = \sigma'_{rock} M
\]

and,

\[
\sigma'_{rock}(w) = \sigma'_{bulk} + \sigma'_{surf}(w)
\]

The bulk conductivity is given from Archie’s Law (Archie, 1942):

\[
\sigma'_{bulk} = \sigma_w \phi^m S^n
\]

where, \(\sigma'_{bulk}\) is the bulk conductivity, \(\sigma'_{surf}\) is the surface conductivity, \(\sigma'_{rock}\) is the quadrature conductivity, \(\sigma_w\) is the solution conductivity, \(\phi\) is the porosity, \(S\) is the saturation, and \(m\) and \(n\) are the cementation and saturation exponents, respectively.

In addition, the relationship of resistivity with formation factor \((F)\) can be expressed by:

\[
F = \frac{a}{\phi^m} > 1
\]

where, \(a\) is empirical constant based on the geometry of the pores and equal to \(1\), \(m\) is the cementation present and ranges from 1.3 for un cemented soils or sediments to 2.6 for highly cemented rocks, such as dense limestone. These IP parameters are proportional to the quadrature conductivity measured in the complex resistivity.

Theoretically, the inversion modeling of electrical imaging (tomography) is based on the smoothness constrained last-squares approach and used to calculate apparent resistivity values (deGroot-Hedlin and Constable, 1990; Sasaki, 1992). This approach is depending on a quasi-Newton optimization technique (Loke and Barker, 1996a). The least-squares inversion is given by equation:

\[
(J^TJ + uF)d = J^Tg - uFr
\]

where, \(F\) is a smoothing matrix, \(J\) is the Jacobian matrix of partial derivatives, \(r\) is a vector containing the logarithm of the model resistivity values, \(u\) is the damping factor, \(d\) is model perturbation vector, and \(g\) is the discrepancy vector.

In the Gauss-Newton least-squares approach, the \(J\) is recalculated after all iteration either the finite-
difference or finite-element method (Dey and Morrison, 1979 a,b; Silvester and Ferrari, 1990; and Sasaki, 1992). To reduce the computing time, a quasi-Newton used updating method to estimate the J after all iteration (Loke and Barker, 1996a). For more detail described about mathematical approach for Gauss-Newton least-squares inversion reading to publishers Loke and Barker (1996 a,b). Equation 12 tries to minimize the square of the spatial changes of the model true resistivity with depth, and produce a model with a smooth variation of resistivity values.

3. Geological Setting

The geology of the study area is little complex structures of pressure ridges, Cenozoic basaltic flows, basaltic dikes, vesicular basalts with affected by fractures that filled with carbonate sediments. The pressure ridges are represents one features structures in the study area, and appears elliptical ground plane and an asymmetrically rising small dome shaped with open fissures. These ridges are most probably related to the cooling process (Guba and Mustafa, 1988). Published investigation on the basaltic plateau in NE Jordan revealed that they consist of six separated basalt flows, from B1 to B6 (Van Den Boom and Sawan, 1966).

The thickness of basalt decreases towards south of Jordan (Bender, 1974). Most recent flows still display visible flow textures, such as pahoehoe and "aa" lava flows that are producing features of lava caves. The average density of basalt about of 2.5 to 2.77 g/cm³, and the saturate surface of 2.70 to 2.85 g/cm³ (Navasreh, 1993). The absolute ages for these basaltic flows were obtained from K-Ar dating that ranges from 13.5 to less than 0.5 Ma (Barberi et al., 1979; Moffat, 1988), whereas in recent years published as Tarawneh et al., 1993 subdivided the basalt Harrat Ash Shaam based on K-Ar dating into three phases; the first is of Oligocene age 26 to 22 Ma, the second phase is of late Miocene age 12 to 8 Ma, and the third phase is of Pre-Quaternary age 6 to less than 0.5 Ma. The pyroclastic rocks are most abundant in the study area; they are composed of olivine, pyroxene, plagioclase, and accessory minerals. All the basalts have been affected by fractures, joints, and fissures that become filled with secondary minerals. Due to interaction of water rock and chemical transport by the hydrothermal processes, the primary minerals in the basaltic rock matrix are partially transformed or altered, into different minerals. In the Umm El-Quttein area occur a few zeolite minerals of analcime type by recorded in some samples collected from the lower horizons of Jabal Quis volcano (Al-Malabeh, 1993). Common secondary minerals are zeolite; clay minerals such as smectite and kaolinite, calcite, and gypsum in the study area (Abed et al., 1985; Dwairi, 1987; Khalil, 1991; Al-Malabeh, 1993; and Tarawneh, 2002). Further, the secondary minerals were observed inside Al-Howa tunnel which is composed of calcite, gypsum, and quartz are abundant covered mostly the wall of tunnel, plagioclase and iron oxides. These minerals may formed secondary mineralized has filled with the caves within the investigated area.

4. Data Acquisition and Processing

The IP imaging field data were collected using an Iris Syscal R1 resistivity meter instruments with 250W converter and 12V, over the lava caves locations (Fig.1). The measured field data were processed by 2D inverse algorithm modeling based on work Loke and Barker (1996a). In our case the spacing (a) between both electrodes pairs in dipole-dipole array configuration equal to 20 m, and the maximum depth level of the investigation was used (n) equal to 4 that equal to 24.4 m depth. Three profiles were performed consisted of A1, A2, and A3. The IP imaging survey was used the time-domain method in the study area. This method is very sensitive to horizontal changes in resistivity, but relatively insensitive to vertical changes in the resistivity.

This means that it is good in mapping vertical structures, such as cavities and dikes, but a relatively poor in mapping horizontal structures (Loke, 2001). The forward problem is solved using the finite element method, and the IP resistivity is found using an iterative last-squares inversion approach. The chargeability data was processed and yield to filtering after the definition of Seigel (1959), to improve the IP measurements interpretation in the basalt plateau environment (Fig.4).

![Fig.4: Diagram showing of window output filtering chargeability data for example profile A3.](image-url)
5. Field Results and Discussions

IP imaging survey was investigate to identify the subsurface structure of lava caves using time domain method at NE Jordan. The resistivity mapping results from a dipole-dipole array is shown in Figure (5), with different depth layers below the surface. Areas of continuous high resistivity indicate good delineate the lava caves, whereas areas of low resistivity surrounding of the caves correlated with fractures zones that has been resistivity values of less than 760 Ohm-m. The lava cave has been resistivity values may reach to greater than 3010 Ohm-m; with depth levels ranges between 8.32 and reached a maximum to 19.24 m. These limitations of the lava caves with different depth layers are indicate depicts the caves that resulted from lava sheets by inflation of initial lava delta within lava flows B6.

This interpreted indicates to demonstrated mechanism theory of lava caves formed has been described recent publishers Al-Malabeh et al. (2004) and Kempe and Al-Malabeh (2005). These anomalous from IP resistivity distributions measurements are indicating clearly continuation to the caves or tunnels flow in length and thickness, are coincide with interpretation results of VLF-EM technique (Al-Oufi, et al., 2008). This high resistivity continuous display that as elongated anomalous on profiles A1, A2, and A3 at depth layers 8, 13.94, and 19.24 m, clearly indicate the limitations for these caves across road Umm El-Quttein in trends NE to SW direction of the investigated area (Fig.5).

IP data was plotted on log-log graph, based on interpretation of the relationship apparent resistivity ($\rho_a$) with chargeability ($M$), and normalized chargeability ($M_n$), that derived from IP parameters at depth layer 8.32 from below the surface (Fig.6 and 7). The resistivity decreasing with increase the chargeability ($M$) which suggests introducing to fracture features; located between stations 710 to end the profile (Fig.6). This relationship is correlated with normalized chargeability ($M_n$) that has values over than 0.120092 mS/m. This illustrating that the dense basalt layer is affected by highly fractured which almost filled with clay or carbonate sediments. Figure (7), display the relationship between increasing the resistivity with decrease the ($M$) and decrease the ($M_n$) values less than 0.006169 mS/m, between stations 500 to 530 m. This indicates to closely the lava cave that may influence with secondary mineralized.

To identify the engineering properties for these caves, where made IP interpretation using inversion models are shown in Figures (8, 9, and 10). These models were created to support interpretations of the IP data. Figure (8) shows the inverse models of apparent resistivity ($\rho_a$), chargeability ($M$), metal factor ($MF$) pseudosections, respectively. Profile A1 (Fig.8), yield to accurate interpretation of IP inverse model.

Resistivity data shows a high resistivity values in the top layer grater than 1172 Ohm-m, and located between stations 640 to 660 m as labeled (A).

The geological model for this profile is interpreted that the lava cave collapsed (Al-Howa) which has depths ranges from 1.71 to 12.6 m. Anomaly (B) shows low resistivity zone with less than 44.1 Ohm-m. This anomaly correlated with ($M$) data values about of 7.67 to 13 mV/V, and has ($MF$) values grater than 1791 mV/Ohm-m. This anomaly indicates that the fractures of dense basalt layer are filled with solid minerals from carbonate sediments or clay which reached to 27 m depth. Anomaly (C) shows in the top surface of low resistivity values less than 19.4 Ohm-m. This anomaly indicates to Wadi Quis that affected by unconsolidated sediments, and reached a depth to 13 m. The vesicular basalt shows at anomaly (G) with high resistivity values about of 516 to less than 1172 Ohm-m, and extending a depth from 15 to 27 m.

Profile A2 across in NW to SE, and extending on the lava strike is shown in Figure (9). The anomaly (A) shows high resistivity values over than 10246 Ohm-m in the near surface and located between stations 520 to 540 m. This anomaly feature represents the extent of lava cave (Al-Howa) that extending to depth 12.7 m, and across the road Umm El-Quattein. A lower resistivity around 303 to less than 93.8 Ohm-m occurs between stations 490 to 520 m as labeled (B). This anomaly is correlated with the ($M$) values; which have been values around 13.3 mV/V. This relationship indicates to a change in surface conduction due to the fracture zone of dense basalt layer, which has high ($MF$) values over than 1592 mV/Ohm-m, and depth ranges from 12.7 to 22 m. This anomaly attribute to materials in dense basalt layer could be filled with clay or carbonate sediments. Figure (7), display the relationship between increasing the resistivity with decrease the ($M$) and decrease the ($M_n$) values less than 0.006169 mS/m, between stations 500 to 530 m. This indicates to closely the lava cave that may influence with secondary mineralized.
Fig. 6: Interpretation of resistivity ($\rho_a$), chargeability (M), and normalized chargeability (Mn) curves derived from the IP parameters for profile A1.

Fig. 7: Interpretation of resistivity ($\rho_a$), chargeability (M), and normalized chargeability (Mn) curves derived from the IP parameters for profile A2.

Fig. 8: 2-D IP resistivity model at A1 profile: (a) inverse model resistivity; (b) inverse model chargeability; (c) inverse model metal factor.
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Anomaly (C) shows in the top surface of low resistivity values less than $19.4 \, \text{Ohm-m}$. This anomaly indicates to Wadi Quis that affected by unconsolidated sediments, and reached a depth to 13 m. The vesicular basalt shows at anomaly (G) with high resistivity values about of 516 to less than $1172 \, \text{Ohm-m}$, and extending a depth from 15 to 27 m.

Profile A2 across in NW to SE, and extending on the lava strike is shown in Figure (9). The anomaly (A) shows high resistivity values over than $10246 \, \text{Ohm-m}$ in the near surface and located between stations 520 to 540 m. This anomaly feature represents the extent of lava cave (Al-Howa) that extending to depth 12.7 m,
and across the road Umm El-Quttein. A lower resistivity around 303 to less than 93.8 Ohm-m occurs between stations 490 to 520 m as labeled (B). This anomaly is correlated with the (M) values; which have been values around 13.3 mV/V. This relationship indicates to a change in surface conduction due to the fracture zone of dense basalt layer; which has high (MF) values over than 1592 mV/Ohm-m, and depth ranges from 12.7 to 22 m. This anomaly attribute to materials in dense basalt layer could be filled with clay or carbonate sediments. This interpreted indicates that increase a quantity of mg % in this layer which consist of olivine, plagioclase, clinopyroxine, calcite, quartz, iron oxide minerals (Khalil, 1991; Al-Malabeh, 1994; Ibrahim et al., 2001). Wadi Quis shows in the top layer with low resistivity of less than 29 Ohm-m as labeled (C) and occur underlying of vesicular basalt layers that located between stations 410 to 470 m; with resistivity values of 980 to less than 3169 Ohm-m, as label (G). This anomaly extending a depth from 8.72 to 27 m; and has (M) values around 22.4 mV/V.

The lava cave anomaly show high resistivity values grater than 5986 Ohm-m, and extending a depth to 8.72 m as label (A) on profile A3 (Fig.10). Thin layer fracture of sediments shows underlying the cave with decreasing in resistivity with less than 114 Ohm-m; (M) values about of 28.4 mV/V, and has high (MF) values grater than 2449 mV/Ohm-m as labeled (B). This layer suggests that filled with clay or spread carbonate sediments, which has been a depth from 12.7 to 22 m. While in the top surface at NW of profile A3 (Fig.10) reveal a Wadi Quis with decrease in resistivity value with less than 42.5 Ohm-m as labeled (C), and extending a depth to 8.72 m that bearing by unconsolidated sediments. The source of this Wadi is results from recharges and precipitation falling over the study area and from Jabal Druze. For more accurate interpretation shows the vesicular basalt layer as anomaly (G) with resistivity values of 827 to less than 2225 Ohm-m. This layer has depth may reach to 27 m. Figure (11) illustrate the distribution of resistivity that corresponding with the lava caves at 8.32 m depth. The interpretation of IP resistivity (Fig.11) suggests that the lava caves have several interconnected form tunnels toward N21ºE direction, and increase and decrease in width with increasing thickness of the investigated area.

Geometric survey for the lava caves outcrop were given by Kempe et al., (2006), and combined with interpretation results of VLF-EM technique (Al-Oufi et al., 2008). In Figure (11) we an estimate a total length of lava caves investigated approximately of 1600 m; a volume of 28,800 m³, but considering a dimension of 3x6 m at profile A1. The volume of caves or tunnels may increase to 48,000 m³ with a dimension of 3x10 m at profile A3. This is display that the volume of caves may be a little bigger to southward direction of the study area. These caves showing that sub-parallel to the last phases of youngest eruptive flows strike in trends NE to SW direction; which distinguished between very negative anomalies had obtained from interpretation results of VLF-EM measurements (Al-Oufi et al., 2008). This interpretation of IP mapping is detect the result of potential hazard environment to road Umm El-Quttein overlying the extent of the lava caves, between depth levels 8.32 and 19.42 m below the surface (Fig.5;11).
6. Conclusions
Under characterization assessment of the lava caves in NE Jordan; were reconnaissance investigation using IP imaging survey with time-domain method, in order to identify their extent, depths, and geometric properties of potential hazard environment which producing collapse features overlaying of road Umm El-Quattein. The investigation results were conducted and can be recognized on presence of lava caves associated mineralized fractures in dense basalt layer. To obtain information on rocks quality; the IP parameters were analyses, including of apparent resistivity ($\rho_a$), chargeability ($M$), and metal factor ($MF$). The amount of chargeability depends on the content on the mineralized of the rocks and the specific surface area. IP parameters assist in identification of the IP anomalous and lead to relationship between structure features and IP measurements. An IP imaging results from mapping profiles A1, A2, and A3; display that a good elongated anomalous of high resistivity more than 3010 Ohm-m were identified in the top surface, and have the same orientation. This indicates likely is related to the lava caves and extends toward N21ºE direction that near ancient sites across road Umm El-Quattein. This interpretation indicates that the cave body filled with air and has depth levels ranges between 8.32 and reached a maximum to 19.24 m. These anomalous may suggests that the lava caves resulted by lava sheets and reached a maximum to 19.24 m. These anomalous suggest that the basalt rocks are highly fractured and filled with clay or carbonate sediments, which indicate to increasing content of mg % that attribute to mineralized fractures in the basalt layer. The vesicular basalt layers were recognized that characterized by high resistivity around 827 to less than 2225 Ohm-m which represent of B6 flows. The lava caves indicate to significant their locations in our study and results are display that road Umm El-Quattein may constitute a risk environment due to extent for these caves; such as sudden collapse features. The IP technique is rapid and economical for mapping the extents of lava caves and determines their edges locations in a shallow subsurface and most accurate that reflect interpretation of the subsurface structures. This technique is new used in Jordan on the basalt environmental.

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Barberi, F., Capaldi, P., Gasperini, G., Marinelli, G., Santacroce T., Scandone, R., Treuil, M. and Varet, J. (1979): Recent basaltic volcanism of Jordan and its ranges between 303 to less than 93.8 Ohm-m; ($M$) values ranges between 13.3 and 28.4 mV/N, and increasing in the ($MF$) values from 1791 to more than 2449 mV/Ohm-m. These anomalous suggest that the basalt rocks are highly fractured and filled with clay or carbonate sediments, which indicate to increasing content of mg % that attribute to mineralized fractures in the basalt layer. The vesicular basalt layers were recognized that characterized by high resistivity around 827 to less than 2225 Ohm-m which represent of B6 flows. The lava caves indicate to significant their locations in our study and results are display that road Umm El-Quattein may constitute a risk environment due to extent for these caves; such as sudden collapse features. The IP technique is rapid and economical for mapping the extents of lava caves and determines their edges locations in a shallow subsurface and most accurate that reflect interpretation of the subsurface structures. This technique is new used in Jordan on the basalt environmental.


Leyden: Late E. J. Brill, II, a part 2, 137-142.


Leyden: Late E. J. Brill, III, IV, V, VI, a part 3, 5, 6.


Paris: Ernest Leroux.


