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2-D and 3-D mapping of soil and rock structure in karst terrain of southwestern Missouri using the non-invasive electrical resistivity tomography method (ERT)

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2-D AND 3-D MAPPING OF SOIL AND ROCK STRUCTURE IN KARST TERRAIN OF SOUTHWESTERN MISSOURI USING THE NON-INVASIVE ELECTRICAL RESISTIVITY TOMOGRAPHY METHOD (ERT)

By

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ABSTRACT

Electrical resistivity tomography data were acquired in an extensively karstic area of southwestern Missouri. The interpretation of the electrical resistivity tomography data was constrained by multichannel analysis of surface wave data and limited boring control. The objective of the study was to determine if variations in the moisture content of the soil and shallow rock are related to ground surface topography. Analysis of the acquired electrical resistivity tomography data showed that resistivity values of soil and shallow rock beneath and in proximity to identified natural and man-made surface run-off pathways are typically low compared to the resistivity values of soil and rock elsewhere, with the exception of soil and rock in proximity to interpreted prominent joint sets. It is concluded that the resistivity of soil and rock beneath natural and man-made drainage pathways is frequently anomalously low because greater volumes of moisture seep into the subsurface along surface flow pathways than elsewhere in the study area.

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1. INTRODUCTION

A geophysical survey was conducted in southwestern Missouri using electrical resistivity tomography (ERT) tool. This method was proved to be the most accurate and efficient geophysical method for investigating subsurface karst-related features and it provide detailed information regarding the nature and extent of karst terrain (Wightman et al., 2008).

Karst terrain is highly challenging among other subsurface topographies and formations. Numerous problems arise when assessing and evaluating the dissolution of these terrains: the potential collapse of karst features, the erosion soil into the solution-widened bedrock joints and the characterization of the soil filling the solution-widened joints.

The objectives of using (ERT) for the study of this area were intended to specify the nature of the subsurface beneath the site and determine if variations in the moisture content of soil and shallow rock are related to ground surface topography. The acquired (ERT) data using in this study showed that resistivity values of soil and shallow rock beneath and in proximity to identified natural and man-made surface run-off pathways are typically low compared to the resistivity values of soil and rock elsewhere throughout the site, with the exception of soil and rock in proximity to interpreted prominent joint sets.

The scope of work focused on planning complete systematic investigation of the project area to identify and map all the possible occurrences of karst features, evaluating the geologic and hydrological conditions to determine the relationship between resistivity values beneath the drainage pathways by measuring the resistivity values in addicted zones correlating to moisture content and comparing results to resistivity values of rock and soil else throughout the site.

Based on the interpretations of the ERT data, the study located and dictated zones of low resistivity values directly beneath the drainage pathways correlated to moisture content, as a result the investigation can limit the areas of karst features typically associated with moisture content.

1.1. STUDY OBJECTIVES

The objectives of using the electrical resistivity tomography method (ERT) for the study of this area were intended to:

- To determine if variations in the moisture content of soil and shallow rock are related to ground surface topography.
- To identify the anomalously low resistivity zones in karst terrain beneath natural and man-made surface run-off drainage pathways comparing to the resistivity values of soil and rock elsewhere throughout the site.
- To demonstrate if the zones of anomalously low resistivity in karst terrain are related to sinkholes and solution-widened joints or related to possible effects of ground surface topography
- To determine whether the topography of top of rock is correlated to the surface drainage pathways or not.
- To evaluate the geologic and hydrological conditions, monitor the surface drainage pathways and groundwater flow patterns beneath the surface.

- To image the subsurface and map the variations of the top of rock; map the variations in soil thickness; study the properties of rock and soil.

1.2. STUDY SIGNIFICANCE

The objective of this investigation was to determine if variations in the moisture content of soil and shallow rock in the study area was related to ground surface topography. This work is significant because it demonstrated that zones of anomalously low resistivity in karst terrain can be caused, in places, simply by the downward seepage of groundwater flowing along natural and man-made surface drainage pathways. The results of this investigation demonstrate that not all zones of anomalously low resistivity in karst terrain are related to sinkholes and solution-widened joints. The interpreter of electrical resistivity tomography data acquired in karst terrain should consider the possible effects of ground surface topography, rather than simply identifying all low resistivity features as being related to karst processes.

2. STUDY AREA

The study site is situated on the southwestern, located immediately north and west of the intersection of highways 60 and 160, within the (Figure 2.1 and 2. 2).

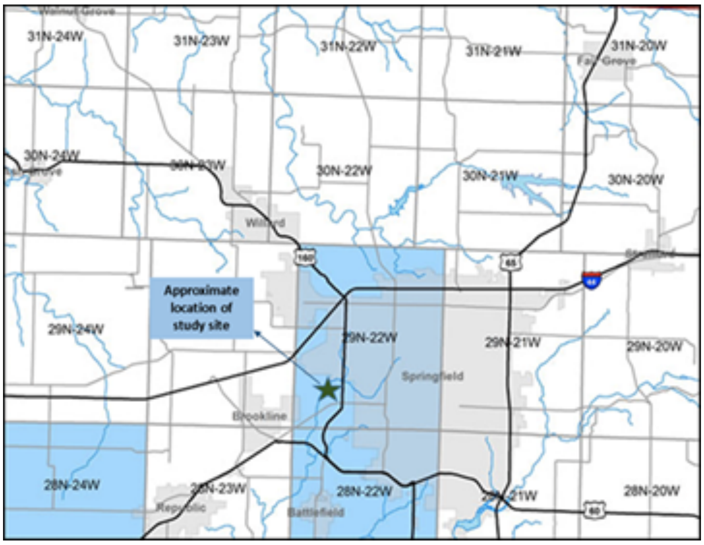


Figure 2.1. Map showing the location of the Route 60/160 study site.

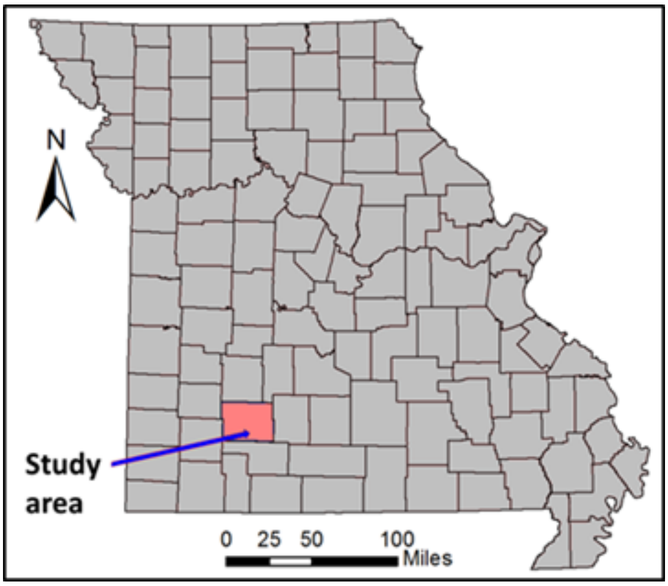


Figure 2.2. Site location map. Red region represents the study area in southwestern Missouri.

Much of land in southwestern Missouri is low rounded hills that contain streams, springs, and various karst features such as sinkholes, especially where the Springfield Plateau aquifer is present at the surface (Loyd et al., 1993).

The climate at the study site is humid with moderate winters and warm summers. Annual rainfall averages 40 inches per year and the air temperature averages 55^0 F (National Oceanic and Atmospheric Administration, 1985).

The soils in the study site are predominantly residuum. Soils in the site are moderately well drained and generally low sloping (Loyd et al., 1993). (Based on work of Fellows), residual soil in the area is red to reddish-brown residual clay with admixed cherty fragments.

According to U.S. Geological Survey, about 15,981 sinkholes have been surveyed in Missouri. Karstic features such as caves, springs and sinkholes are well presented in the study site. More than 2500 sinkholes and 245 caves have been found in the southwestern region (Greene County Comprehensive Plan, 2007). This system of subsurface caverns could create the potential for differential settlement of the above layers with new sinkholes caused by solution-widened joints/fractures and air-filled cavities. Investigation surveys obtain information from the depth to the top of bedrock and the correlated potential problems of widened joints area may affect the stability of the studied project.

Bedrock in the study site according to the drilled boreholes through the geotechnical investigation is revealed to be highly-dissolved Burlington-Keokuk Limestone, characterized by the presence of pinnacles, cavities, and cutters (Fellows, 1970), which indicate that the depth of bedrock varies and represent lateral variation of karst features.

2. GEOLOGICAL AND STRATIGRAPHIC SETTING

3.1. STRATIGRAPHIC OVERVIEW

The study site is situated on the Springfield Plateau, which consists of Paleozoic carbonate with nearly horizontal limestone that is attainable to the formation of karst features, shale, sandstone, and dolostone with additional sedimentary rock that overlies the igneous and metamorphic rocks. The study site is in an area underlain by Burlington-Keokuk Limestone (Middendrof et al., 1987). The geologic and stratigraphic units of this study site are listed in Table 3.1.

Table 3.1. Geologic and stratigraphic units in the study area (Vandike, 1993).

System	Series	Group	Formation		Thickness (ft)
Mississippian	Osagean		Burlington- Keokuk Formation		150-270
			Elsey Formation		25-75
			Reeds-Spring Formation		125
			Pierson Formation		90
	Kinderhookian	Chouteau	Northview Formation		5-80
			Compton Formation		30
Ordovician	Canadian		Cotter Formation		600
			Jefferson-City Formation		
			Roubidoux Formation		150
			Gasconade Formation	Upper Gasconade Dolomite	350
				Lower Gasconade Dolomite	
				Gunter Sandstone Member	25
Cambrian	Upper		Eminence Formation		500
			Potosi Formation		
		Elvins	Derby-Doerun Formation		
			Davis Formation		150
			Bonneterre Formation		200
			Lamotte Formation		150
Precambrian	Crystalline rock				

The study location is situated on the Springfield Plateau, which underlain by Precambrian crystalline rock. Precambrian basement is overlain by the Cambrian Lamotte Formation sandstone. Sandstone layers are covered by approximately 200 feet of Bonneterre dolomite and about 150 feet of Davis Formation shale. Around 500 feet of dolomities from Derby-Doerun Formation, Potosi and Eminence Formations overlie the Davis Formation shale. Cambrian period is capped by Eminence Formation dolomite.

Around 350 feet of upper and lower Ordovician-aged Gasconade dolomite overlies the 25 feet Gunter Formation sandstone layer. Dolomite, dolomitic sandstone and sandstone present in Ordovician period in Roubidoux Formation of about 150 feet that overlies the Gasconade dolomite. Below the Springfield Plateau, about 600 feet of dolomite divided between the Jefferson-City and Cotter Formations are lain at the top of Ordovician period. In the location, Cotter Formation dolomite is covered by about 30 feet of Mississippian limestone that overlain by a sequence of about 80 feet thick of Northview shale and siltstone and 90 feet of Pierson limestone.

Burlington-Keokuk Formation Limestone that forms the bedrock of Springfield Plateau of thickness vary between 150 to 270 feet overlies the cherty limestone in Pierson and Reeds-Spring Formations.

3.2. THE GEOLOGIC SETTING

The study area is located on the Springfield Plateau sub-province of the southwestern part of the Ozarks Plateaus Physiographic Province (Emmett et al., 1978). The bedrock surface consists of thick Mississippian-age limestones and cherty limestones above Ordovician and Cambrian-aged strata (Figures 3.1) and (Figure 3.2).

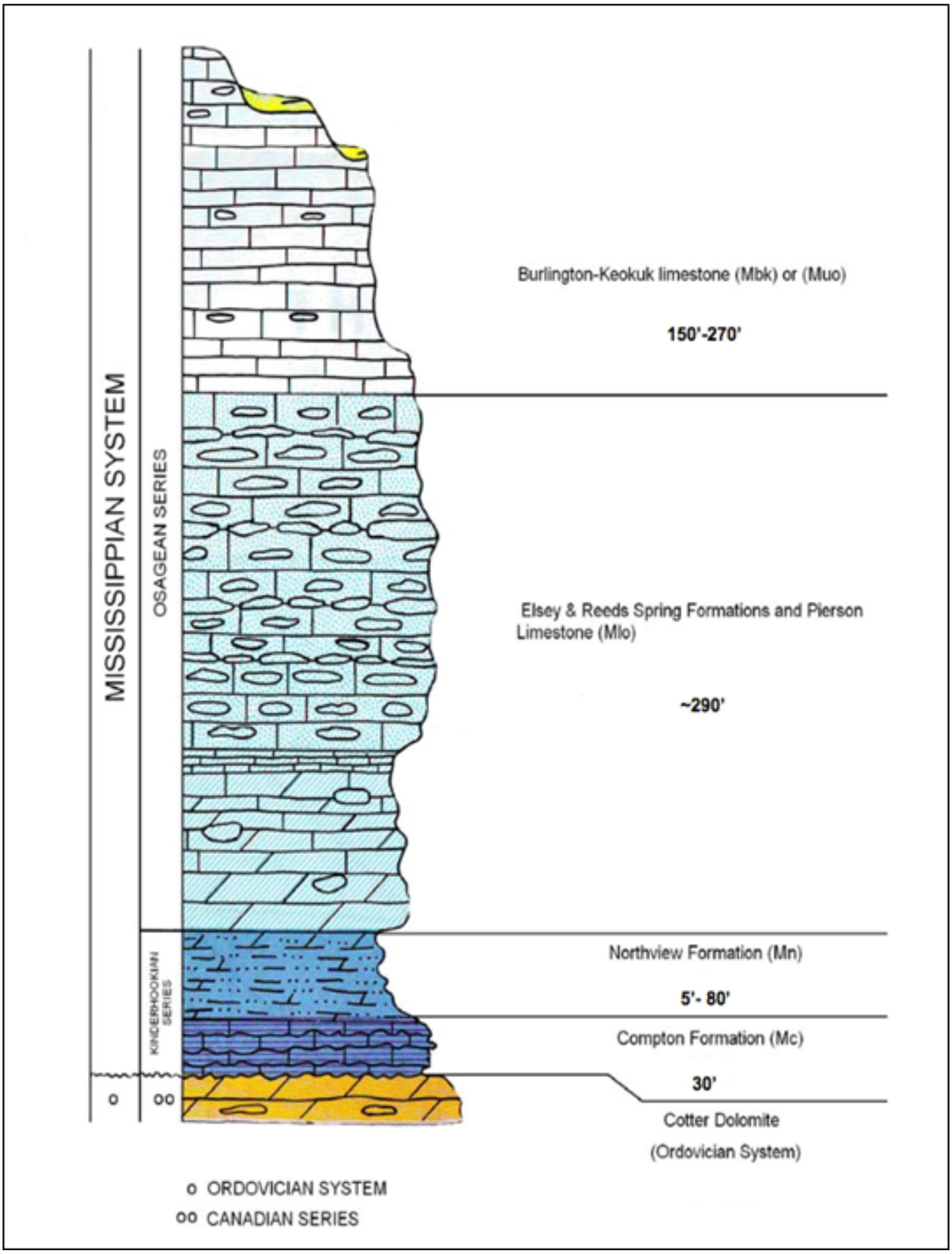


Figure 3.1. The stratigraphic column of the Mississippian system at the study area (Fellows, 1970).

The stratigraphic column of the Mississippian-aged Formation indicates that the Mississippian Formation is consisting of limestone. Cross section in (Figure 3.2) shows the lateral distribution of Mississippian-aged Formations throughout the southwest of Missouri cross were formations subjected to various internal and external activities and events that reflected in a wide disturbance in these formations. The internal activities have led to the folding and faulting of these formations while the external activities; weathering and erosion has resulted in the extensive disturbance of the outcropping and subsurface strata by creating prominent karst topography, including the extensive cave systems and sinkholes and the underground drainage systems and the widening of joints of these formations (Middendorf et al., 1987) and (Fellows, 1970).

Limestone strata of the study area are extensively weathered, and a thin layer of cherty clay residuum varying from a few to approximately 40 feet overlies the irregular bedrock surface (Fellows, 1970).

The Mississippian-aged Burlington-Keokuk Limestone in this location consists of pure calcium carbonate $CaCO3$ which is formed form of accumulation and deposition of calcareous fragments of organisms in the shallow marine environments (Figure 3.3). Weathering primarily affects the thickness of formations which may be highly variable. Joints and fractures occurring in the limestone could influence both surface and subsurface drainage patterns and may cause weathering into cutters and pinnacles in the bedrock surface. According to (Whitfield et al., 1993), the clay residuum in the study site is mapped as cherty clay residuum consisting of the clay loam to silty clay loam containing sub angular to angular fragments of chert up to one foot in diameter.

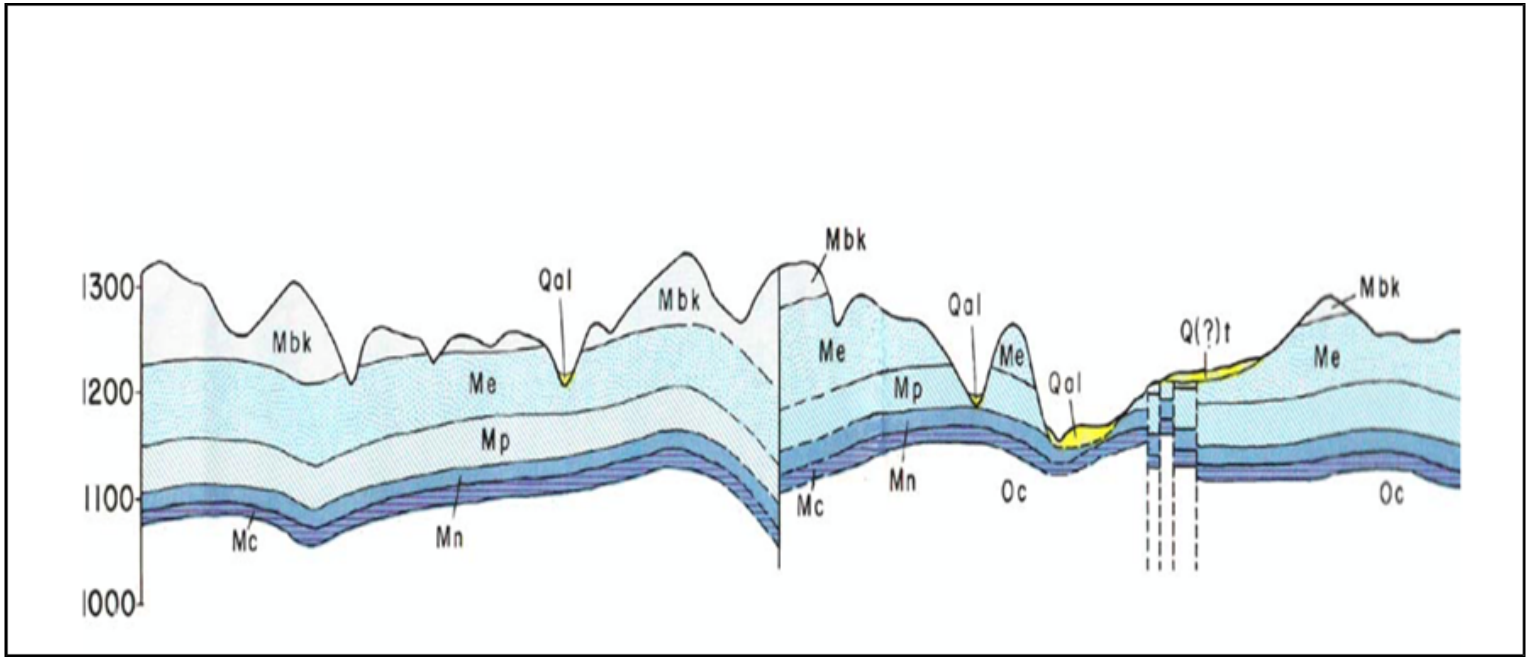


Figure 3.2. Cross section shows the lateral distribution of Mississippian Age Formations throughout the southwest of Missouri (Fellows, 1970).

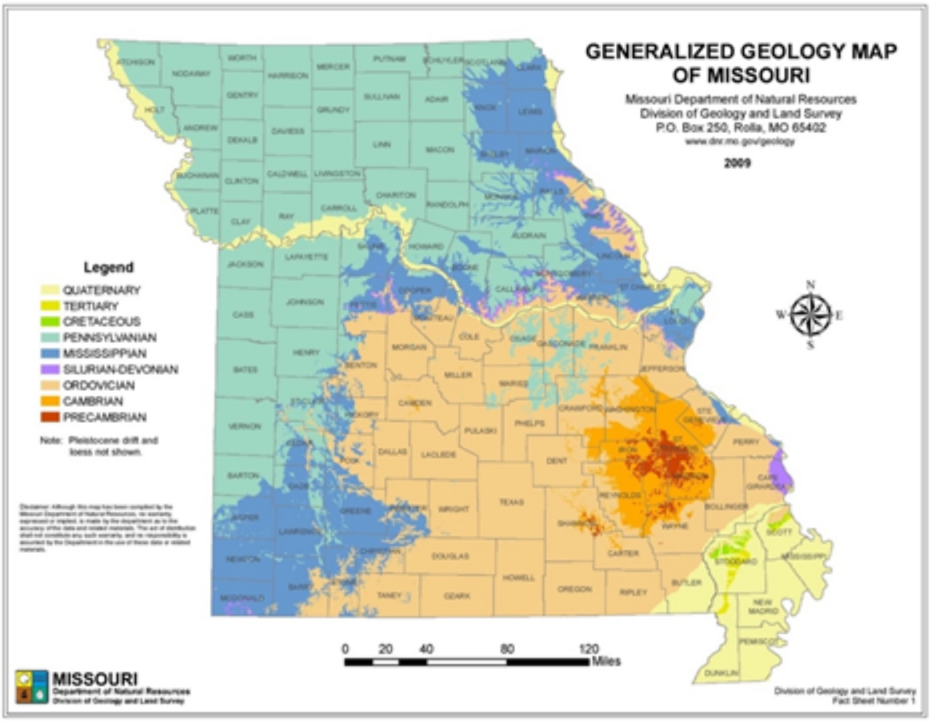


Figure 3.3. Geological map of limestone occurrence in Missouri indicating that the area is underlain by Mississippian-aged Burlington-Keokuk Limestone (Missouri Department of Natural Resources Division of Geology and Land Survey, 2010).

Dips in the area are gently trending to the west with minor and few degrees of folding which parallel the fault systems. Faults in Missouri trend mostly in a northwest direction, with a few in northeast direction (McCracken, 1966). Faults are prominent structures of the Springfield Plateau. In the southwestern portion of the plateau, the Seneca fault system has a northwestern trend (Figure 3.4). Faults in the study area are northeast and northwest high angle gravity faults with throw of up to 300 ft. (McCracken, 1971).

A Fault features may affect the rocks where the drainage pattern in the county has developed along the zones of structural weakness, which give probable joint structure and fracture patterns that may be related to the development of karst terrain. Solution-widened joints and fractures in bedrock are results of weathering along these faults.

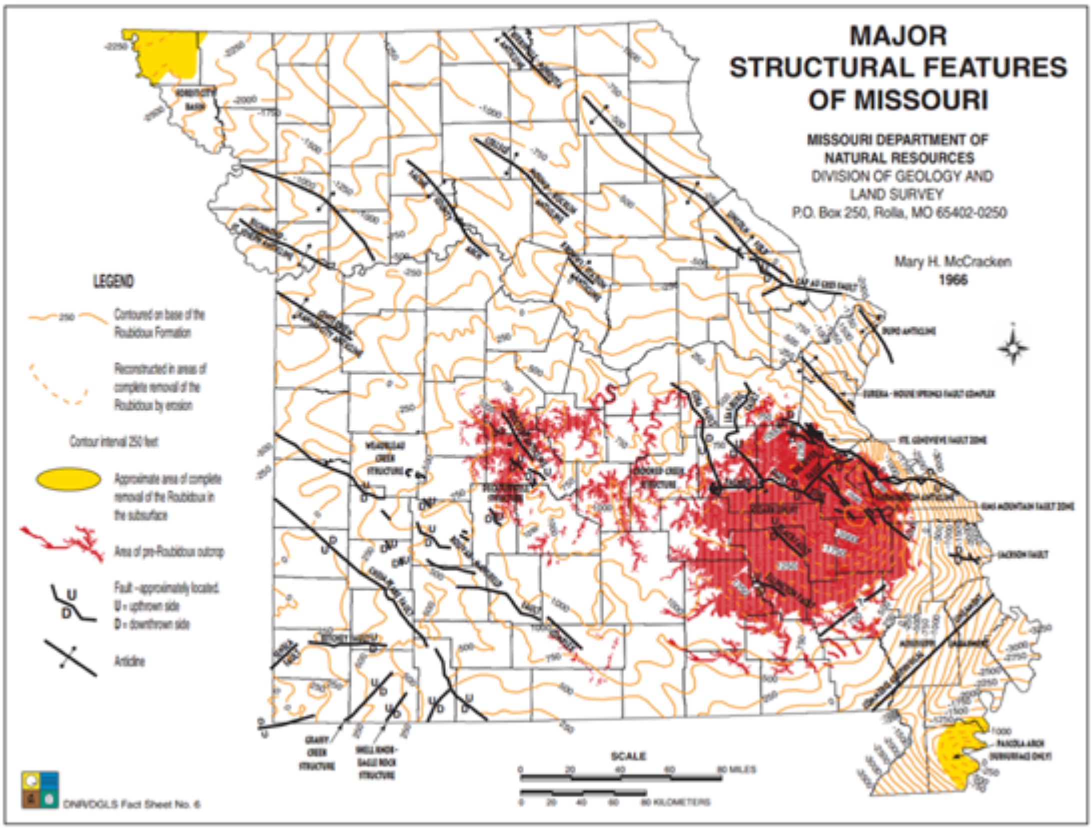


Figure 3.4. Structural features of Missouri (McCracken, 1966).

3.3. HYDROLOGIC SETTING

Three bedrock aquifers underlie the Springfield Plateau: the St. Francis Aquifer, the Springfield Aquifer, and the Ozark Aquifer which is considered the most important aquifer of groundwater in the area (Emmett et al., 1978). The Ozark Aquifer is confined and artesian aquifer; its thickness arises from north to the south with an average of 1,200 feet in the Springfield area (Figure 3.5). The upper and lower portions of the aquifer consist of dolomite. In most places, though, water levels in the Ozark Aquifer are well below land surface. High yielding dolomite units generally have considerable secondary porosity and permeability that is a result of slightly acidic groundwater dissolving part of the rock and creating enlarged fractures and bedding plane openings.

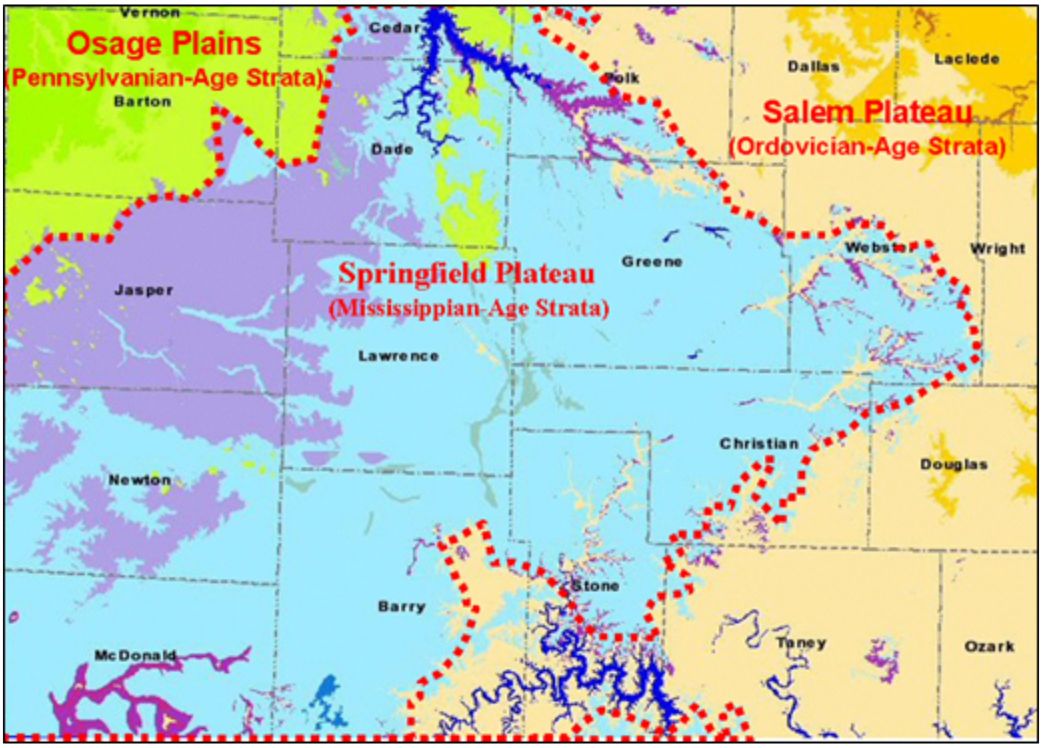


Figure 3.5. Generalized map of southwestern Missouri showing the various provinces (Missouri Department of Natural Resources).

As discussed in Section 3.1, Springfield Aquifer thickness varies from 100 feet to more than 300 feet, encircling the Burlington-Keokuk Limestone (Figure 3.6). The Springfield Plateau groundwater province occupies the southwestern part of the state and a small region of central Missouri south of the Missouri River. Most of southwestern Missouri is considered as an unconfined aquifer, where its top allows surface water to pass through the clay into the bedrock. The jointed bedrock is further considered as secondary porosity and becomes an important factor of the solution-widening process of joints.

The sedimentary rock sequence in the Springfield Plateau rests at the top Precambrian-age igneous and metamorphic rocks. The hydrogeological significance of these basement units is that they serve as a confining unit and do not allow a significant interchange of groundwater. The Precambrian rocks are overlain by up to 150 feet of

Cambrian-age Lamotte-Reagan Formation sandstone. The unit in the southwestern Missouri contains less arkosic materials. It is overlain by the Bonneterre Formation, which contains up to about 200 feet of dolomite. The unit thins in the western part of the province. The Davis Formation overlies the Bonneterre Formation and reaches a maximum thickness of about 150 feet in the province. In the eastern counties, it contains a significant percentage of shale, but to the west the unit is principally limestone.

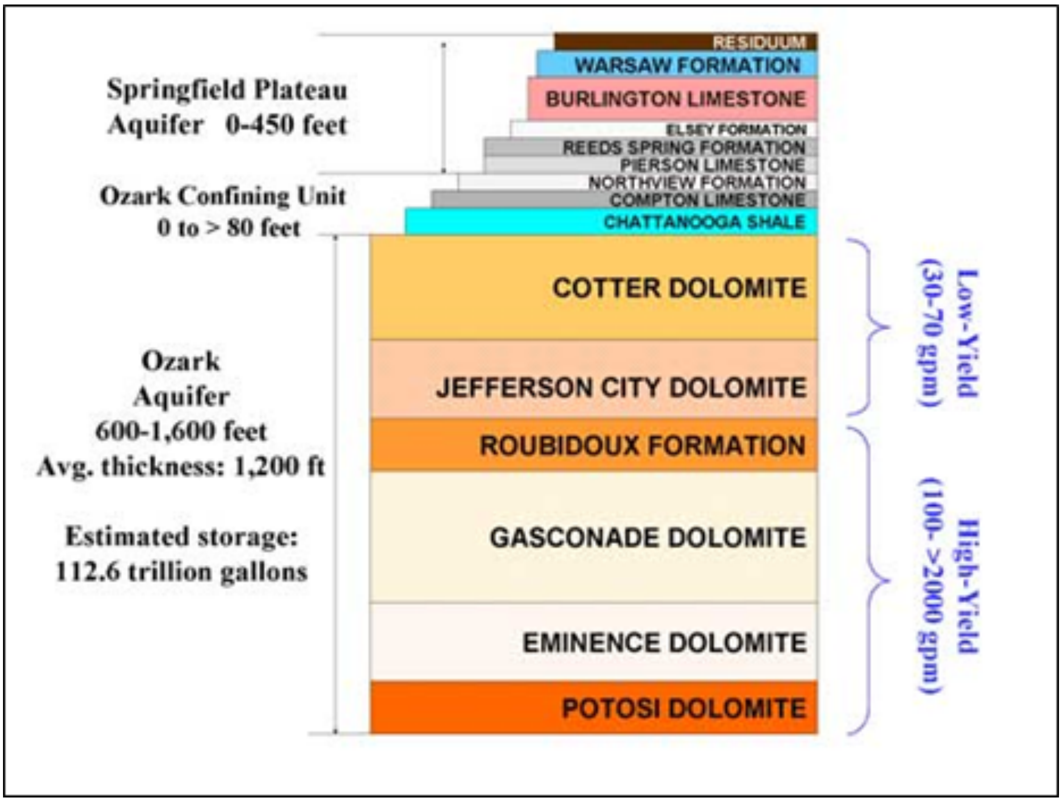


Figure 3.6. Stratigraphic units comprising the Springfield Plateau and Ozark aquifers in southwestern Missouri and yield estimate (Missouri Department of Natural Resources).

Based on United States of Geological Survey studies, low-permeability units between the Ozark Aquifer and the shallower Springfield Plateau Aquifer form an aquitard and greatly limit the vertical interchange of water between the two aquifers.

Throughout most of the region, the Compton Limestone and Northview Formation form the Ozark confining unit. Although these units have low hydraulic conductivities, they allow some water to move through them.

4. KARST FEATURES DEVELOPMENT

Diversely environmental and engineering problems arise in areas where natural geologic substrates are subject to solution and erosion, which can generate voids in the subsurface. Such areas are known as karst.

The term “karst” applies to a distinctive type of landscape that develops from the dissolving of water on soluble bedrock, primarily limestone, marble, dolostone, gypsum, and halite. Karst landscapes are characterized mostly by shafts, sinkholes, sinking streams, springs, subsurface drainage systems, and caves. The unique features of karst are the result of a complex of climate, topography, geology, hydrology, and biological factors. Karst can be found at all attitudes and elevations, with rock types potentially containing karst covering approximately 20% of the earths land surface (Ford & Williams, 2007).

Karst features areas were published by the American Geological Institute (AGI) as shown in (Figure 4.1), indicates that Missouri is mostly underlain by carbonate rocks characterized as a karst terrain. Most of the counties of Missouri are underlain by rocks that contain carbonate units. Significant karst development occurs in southeastern and southwestern Missouri where carbonate rocks are more exposed and covered by permeable rocks. (Figure 4.2) shows the different distribution of rock units in Missouri.

Dark green color on the map in (Figure 4.2) showing Missouri karst that mainly formed on subcropping carbonate rocks. The light green color represents buried carbonate rocks. The light blue color represents buried evaporite rocks (gypsum and halite), dark blue represents the exposed. Red and yellow represent pseudokarst; red is volcanic and yellow is unconsolidated material (Veni et al., 2001).

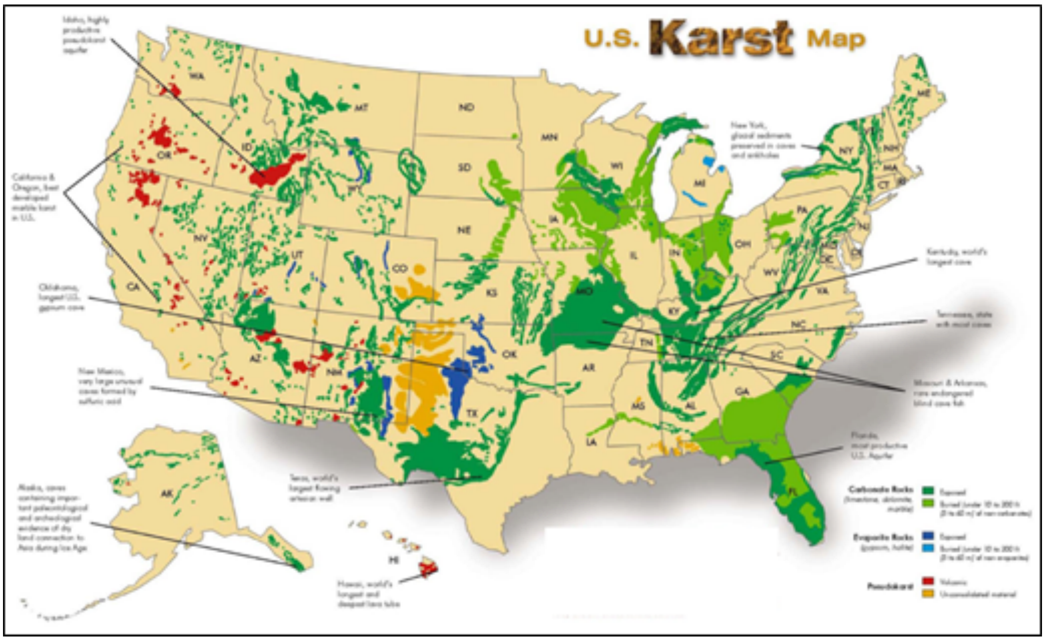


Figure 4.1. Karst map of the US published by AGI (Veni et al., 2001).

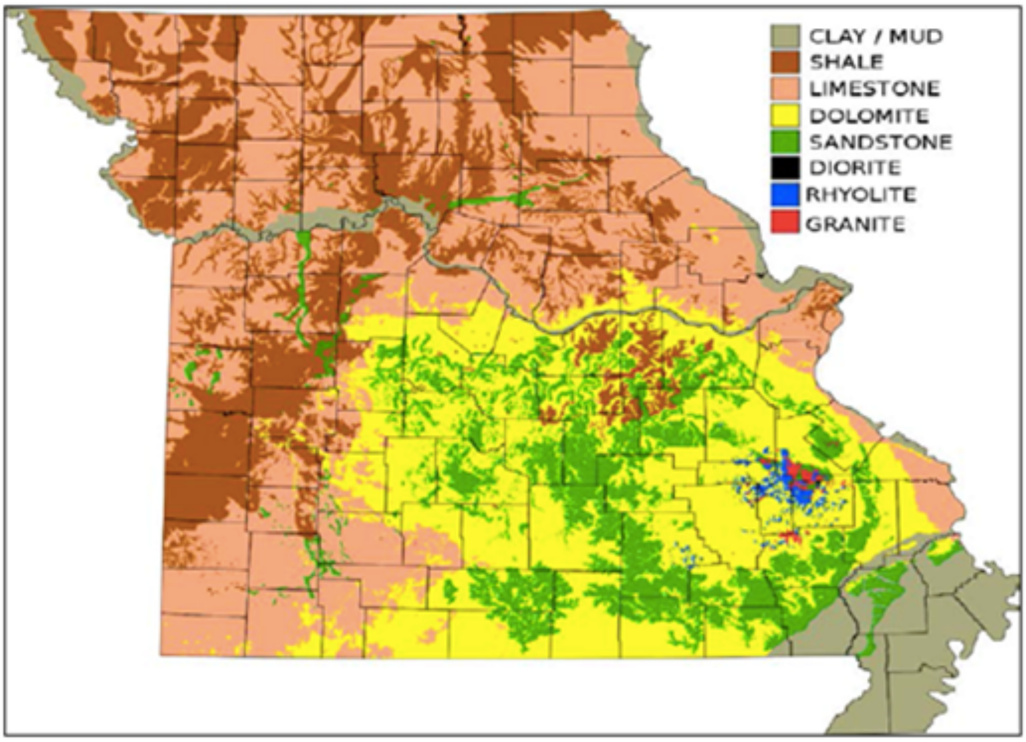


Figure 4.2. Geologic map show the distribution of different rock units in Missouri. (Source:http://upload.wikimedia.org/wikipedia/commons/a/a1/Missouri_Geology Primary_Rock_Types_v1.png). About 59% of the state is underlain by thick carbonate rock units that host a wide variety of karst features.

4.1. KARST FORMATION

Karst is formed primarily because of the dissolution of rocks such as limestone, dolomite, marble, gypsum, and salt which are examples of carbonate rocks made up of carbonate minerals, like calcite ($CaCO_3$) as in limestone and marble and dolomite ($CaMg[CO3]_2$) in dolostone, and both (especially calcite) are susceptible to dissolution when exposed to slightly acidic water. Meteoric water absorbs carbon dioxide (CO_2) from the atmosphere and thus becomes slightly acidic. After meteoric water reaches the ground, it passes through soil that may increase CO_2 concentration. At the point where water reaches beds of carbonate rock, it starts to react with soluble minerals. Dissolved matter will be washed away, and as a result, features such as dissolution-widened joints and air-filled voids start to form. Rainwater dissolves the limestone by the following reaction:

$$H_2O + CO_2 \longrightarrow H_2CO_3$$

$$CaCO_3 \longrightarrow Ca^{2+} + CO_3^{-2}$$

$$CO_3^{-2} + H_2CO_3 \longrightarrow 2HCO^{3-}$$

$$CaCO_3 + H_2CO_3 \longrightarrow Ca^{2+} + HCO^{3-}$$

Karst features developed primarily in carbonate fractured rocks. According to (Jennings, 1966; White, 2002) lithified carbonate rocks develop smaller features of karst than the competent and stronger carbonate rocks. Cracks and joints that interconnect in the soil and bedrock allow the water to reach a zone below the surface where all the fractures and void spaces are completely saturated with water, the volume of which is dependent on the porosity of rock. The larger the proportion of voids in a given volume of soil or rock, the greater the porosity. When these voids are interconnected, water or air can migrate from one void to another. Thus, the soil or bedrock is said to be permeable because fluids (air and water) can easily move through them. Permeable bedrock makes a good aquifer because the rock layer can hold and conduct water. If the ground water that flows through the underlying permeable bedrock is acidic and the bedrock is soluble, a distinctive type of topography known as karst topography can be created (Figure 4.3).

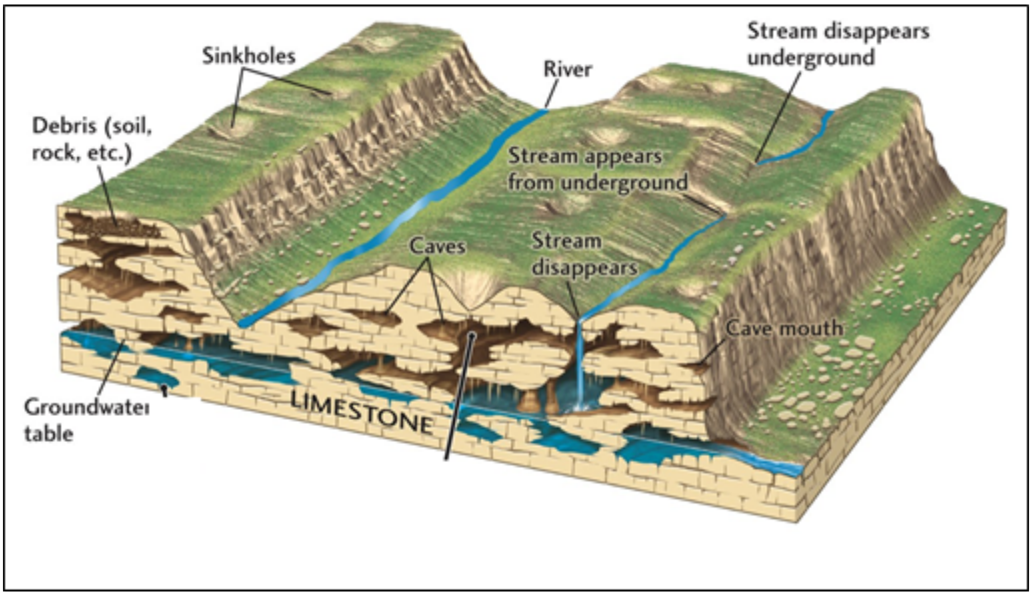


Figure 4.3. Example of karst topography showing the karst features in karst terrain (https://cetologydotorg.files.wordpress.com/2015/01/karst_topography.jpg).

Regional climate strongly influences karstic landforms in that it controls the recharge to water flow regimes. The dissolution of calcium carbonate in water is largely dependent on the availability of biogenic carbon dioxide. Biogenic carbon dioxide is highly concentrated in deep soils and in tropical areas where decomposition of organic matter is rapid. As a result, the most mature karst occurs in wet tropical environments.

Dissolution of limestone is reduced in temperate regions, and less in arid glacial areas. In Missouri, dissolution generally occurs through joints, which are often in-filled with piped fine-grained sediments such as clays and silts that are eroded and transported downward by infiltrating surface water through solution-widened joints.

Karst features range in scale from microscopic (chemical precipitates) to entire drainage systems and ecosystems that cover hundreds of square miles, and broad karst plateaus.

4.2. DEVELOPMENT OF KARST SYSTEMS

Many factors determine the degree and stage of karst system development. These factors include the types and physical properties of the carbonate formations, the degree of jointing and fracturing of these formations, and formation thickness and the topographic setting. On the other hand, the weather and environmental condition are the primary factors that reflect the degree and intensity of karst development.

The abundance of slightly acidified water from rainfall, snow melt surface, and subsurface flow coupled with intensive and extensive fracturing and jointing will result in intensive and extensive development of karst features. The present-day karst features in southwest Missouri are attributed to the once prevailing humid conditions in past geological times.

Slightly acidic groundwater percolates through the rock joints and fractures and slowly dissolves the carbonate rock, forming solution-widening joints. When tightly-spaced perpendicular intersecting joint sets are present, they are widened by solution, leaving spires of bedrock separated by joints that narrow with depth. These features are known as pinnacles. Generally, dissolution of these rocks causes the thinning of the roof followed by subsidence of the overlying soil that is definable by the roof collapse forming a steep-sided cone-like shape, pointing inward. Such features are known as collapse sinkholes and are formed in moisture-rich areas an oval shape and a rim on the surface. The features that result from this process are identified as solutional sinkholes. The continuation of the dissolution might lead to (Figure 4.4).

Depressions would probably create favorable conditions for the collapse sinkholes in areas with natural or man-made depressions that collect enough water for wetting the proximal surface, while the surrounding is dry. In such conditions, collapse takes place, forming a collapse sinkhole as shown in (Figure 4.5).

Other factors that might cause subsidence or collapse sinkholes is water withdrawal by natural causes such as the migration of groundwater and/or the seasonal variation of groundwater levels, or by anthropogenic reasons such as the over pumping of groundwater. These factors will end up creating underground space that will be filled by subsidence or catastrophic collapses of the overlying surface.

Studying karst features and their development is essential for the understanding of the contaminant and hazards flow of subsurface soil and groundwater (Figure 4.6).

According to the United States Geological Survey (2004) 20% of the United States is highly susceptible to sinkhole development. Missouri is named as one of the 7 states that present the greatest damage from sinkholes activity. Most have been associated with dissolution of bedrock at the intersection of joints (Robinson & Anderson, 2008).

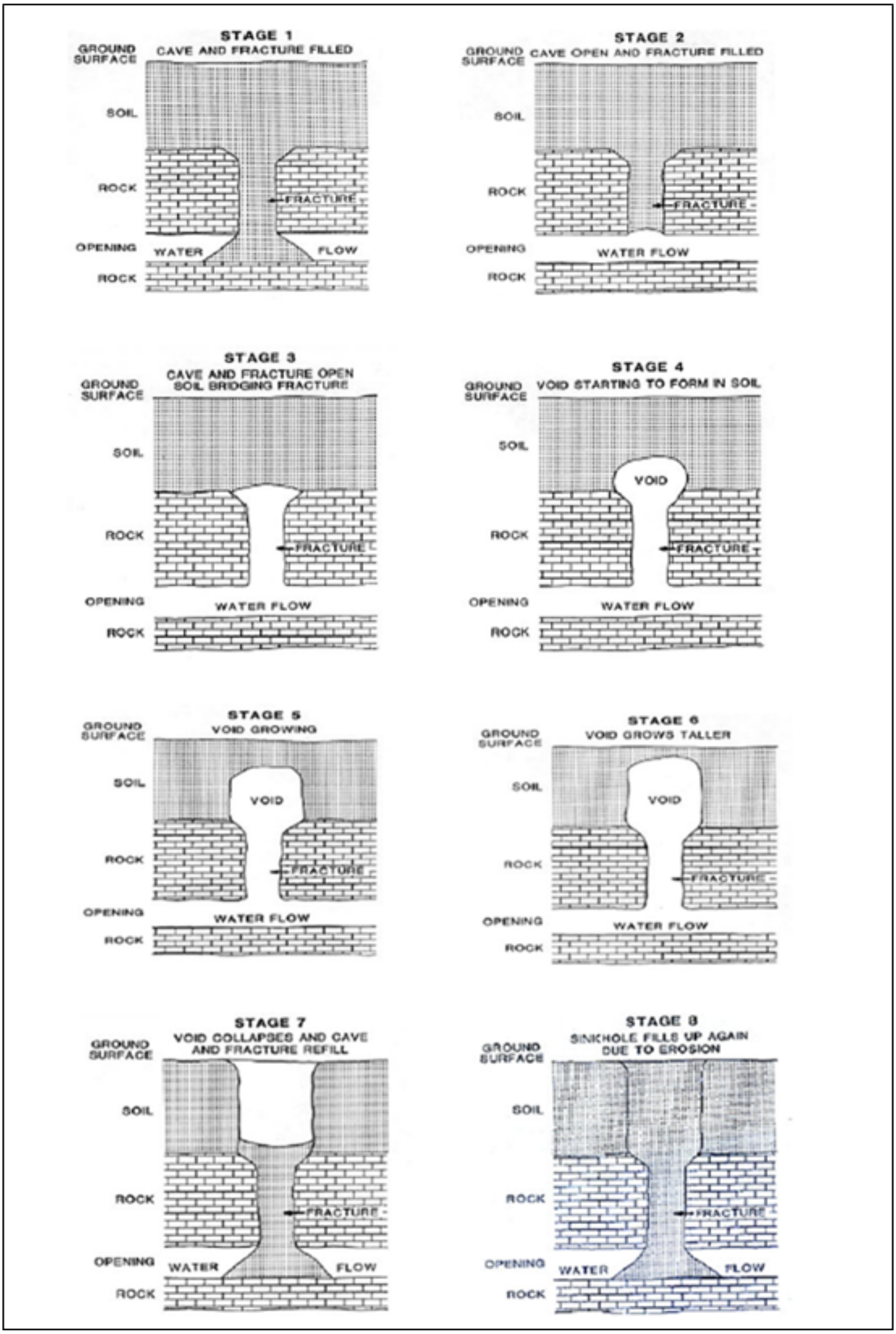


Figure 4.4. Stages of sinkhole formation process (Missouri Department of Natural Resources web site).

Figure 4.5. Sinkhole collapse that occurred in the southwestern Missouri town of Nixa which developed near the intersection of two nearly orthogonal solution-widened joint sets (Anderson, 2006).

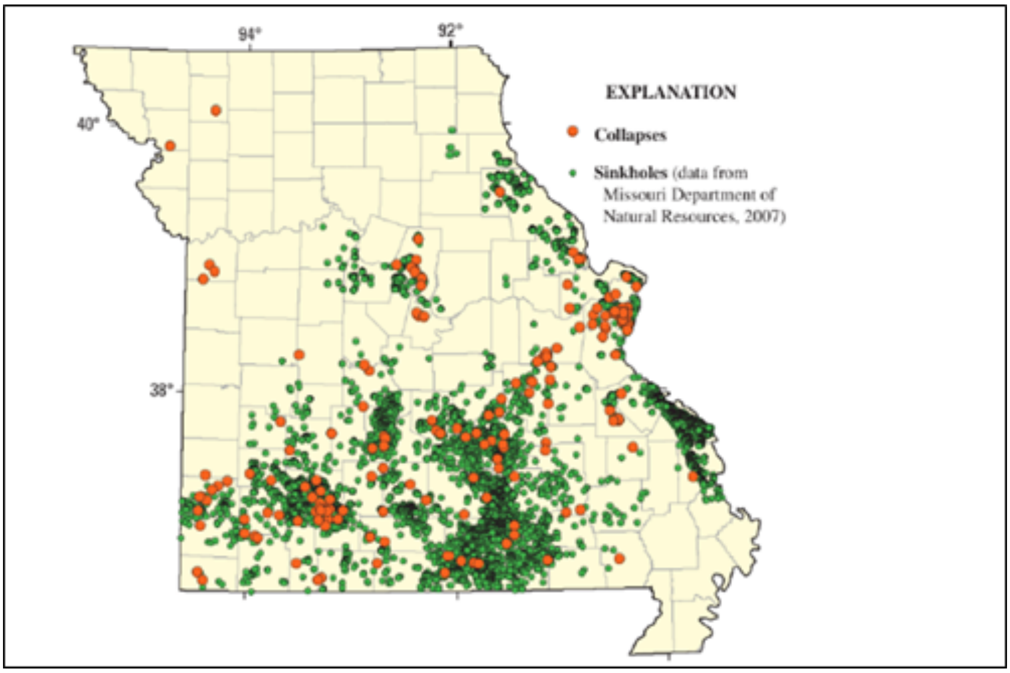


Figure 4.6. Distribution of sinkholes in Missouri. (Missouri Department of Natural Resources, 2007).

5. LITERATURE REVIEW: ELECTRICAL RESISTIVITY TOMOGRAPHY

Karst terrains have been studied in different sites by demonstrating ERT surveys. ERT method is an effective geotechnical and environmental engineering method, less time consuming, relatively inexpensive, and less labor-intensive. ERT data are used in various applications: determining depth of bedrock, monitoring groundwater table levels, acquiring data about soil thickness. According to (W. Zhou, 1999), ERT method is preferred in characterization of karst features. Following published papers recommended that ERT techniques are effective in sinkholes investigations if combined appropriately with geologic data and preliminary site investigation:

- Resistivity Method by Neil L. Anderson, Derek B. Apel and Ahmed Ismail, 2006.
- Assessment of Karst Activity at Clarksville Study Site by Jon Robison and Neil L. Anderson, 2008.
- Assessment of Karst Activity at Highway Construction Sites Using the Electrical Resistivity Method by Neil L. Anderson, Derek B. Apel and Ahmed Ismail, 2006.
- Interpretation of Electrical Resistivity and Acoustic Surface Wave Data Acquired at Nixa Sinkhole Study Site by Neil L. Anderson, 2006.
- Electrical Resistivity Techniques for Subsurface Investigation by Steve Cardimona, 2008.
- Electrical Imaging of the Groundwater Aquifer at Banting, Selangor, Malaysia by Umar Hamzah, Rahman Yaacup, Abdul Rahim Samsudin, Mohd Shahid Ayub, 2006.

- Reliability of Dipole-Dipole Electrical Resistivity Tomography for Defining Depth to Bedrock in Covered Karst terrains by W. Zhou, B. F. Beck, J. B. Stephenson, 2000.
- Investigation of Bridge Foundation Sites in Karst Terrains via Multi-Electrode Electrical Resistivity by Dennis R. Hiltunen and Mary J. S. Roth, 2008.
- Electrical Imaging Surveys for Environmental and Engineering Studies by Dr. M. H. Loke, 2008.

6. BASIC THEORY OF ELECTRICAL RESISTIVITY

6.1. THEORETICAL CONCEPTS

The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated (Loke, 2011).

The fundamental physical law used in electrical resistivity method is Ohm's Law that describes the current as a measure of the rate of electron flow, and defines the voltage as the electromotive force that drives the current. Therefore, the resistance R is viewed as a constant independent of the voltage and the current that represents the opposition of the medium to the flow of current. In equation form, Ohm's law is given by the equation:

$$V = IR \quad (1)$$

The resistivity of a material is defined as the resistance (in ohms) between opposite faces of a unit cube of the material. For a conducting cylinder of resistance ∂R, length ∂L and cross-sectional area ∂A (Figure 6.1), the resistivity ρ is given by the equation:

$$\rho = \partial R \frac{\partial A}{\partial L} \quad (2)$$

Substituting $\partial R = -\frac{\partial V}{I}$ in equation (2):

$$(\partial V)/\partial L = -\rho\, I/\partial A = -\rho J \quad (3)$$

Where, J is the current density.

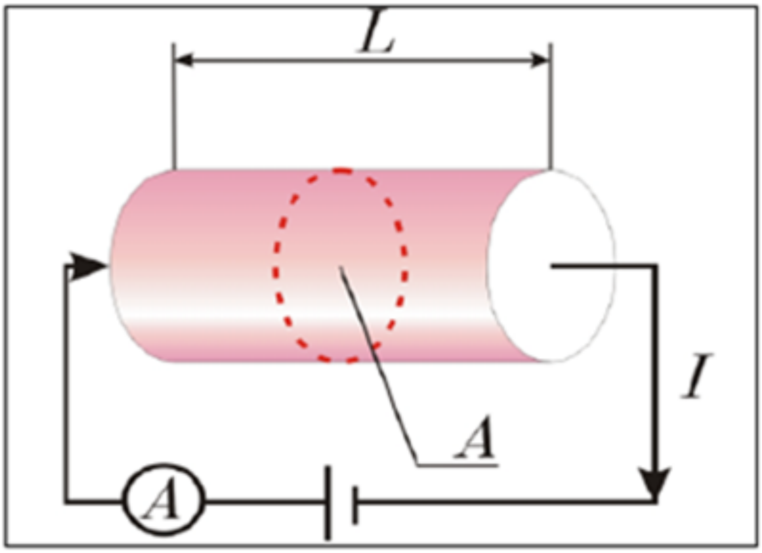


Figure 6.1. Resistivity parameters for a conducting cylinder.

For pair of electrodes on the surface of a medium of uniform resistivity, the potential value in the medium for such a configuration (Figure 6.2) is given by:

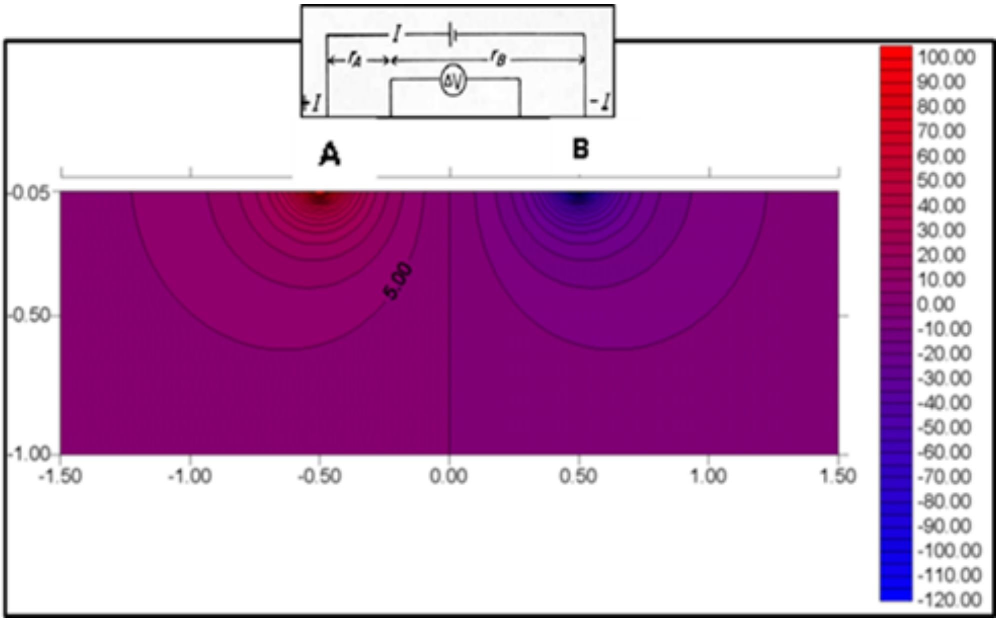


Figure 6.2. The potential distribution caused by a pair of current electrodes. The electrodes are 1 m apart with a current of 1 ampere and a homogeneous half-space with resistivity of 1 Ohm. (Loke, 2011).

Most rocks conduct electricity by electrolytic process, where the electrical current is carried by the passage of ions in pore water (Robinson, 1988), therefore the porosity is considered a major factor affects the resistivity of rocks, where the resistivity increases as porosity decreases. (Figure 6.3) shows the range of resistivities estimated for common rock types. Also, the resistivity of subsurface materials depends on the lithology, fluid content and degree of water saturation in the rock. Resistivities of some rocks and minerals are given in Table 6.1.

6.2. RELATIONSHIP BETWEEN RESISTIVITY AND GEOLOGY

Variations in the resistivity of subsurface materials are mostly a function of lithology, clay content, fluid content, porosity, and degree of water saturation in the rock. Resistivity values in of earth materials and rock types are shown in (Figure 6.3) and (Table 6.1). Most of materials are considered to be conductors or insulators.

Electric current flow in the subsurface is primarily electrolytic. Electrolytic conduction involves passage of charged particles by means of ground water. Charged particles move through liquids that infill the interconnected pores of permeable mass of soil (Robinson, 1988). When Electrical Resistivity Tomography surveying using to detect karst terrain, electrical current flow in the subsurface is primarily electrolytic.

Considering the truth that resistivity values of subsurface materials are not the same everywhere regarding to variations of physical characteristics. The values of resistivity measured in the field calculated as the average of the two equipotential surfaces, and known as apparent resistivity (ρa).

Based on works of Anderson et al., (2006) typical resistivity values of subsurface materials in southwestern Missouri are characterized as follows:

- Intact limestone corresponds to high resistiviy values (>400 ohm-m).
- Intesively fractured rock and moist soils correspond to resistivity between (100 to 400 ohm-m).
- Moist clays correspond to low resistivity values (<100 ohm-m).
- Air-filled cavities correspond to high resistivity values (>10000 ohm-m),

depending on the conductivity of the surrounding strata and depth/size/shape of void (Anderson et al., 2006).

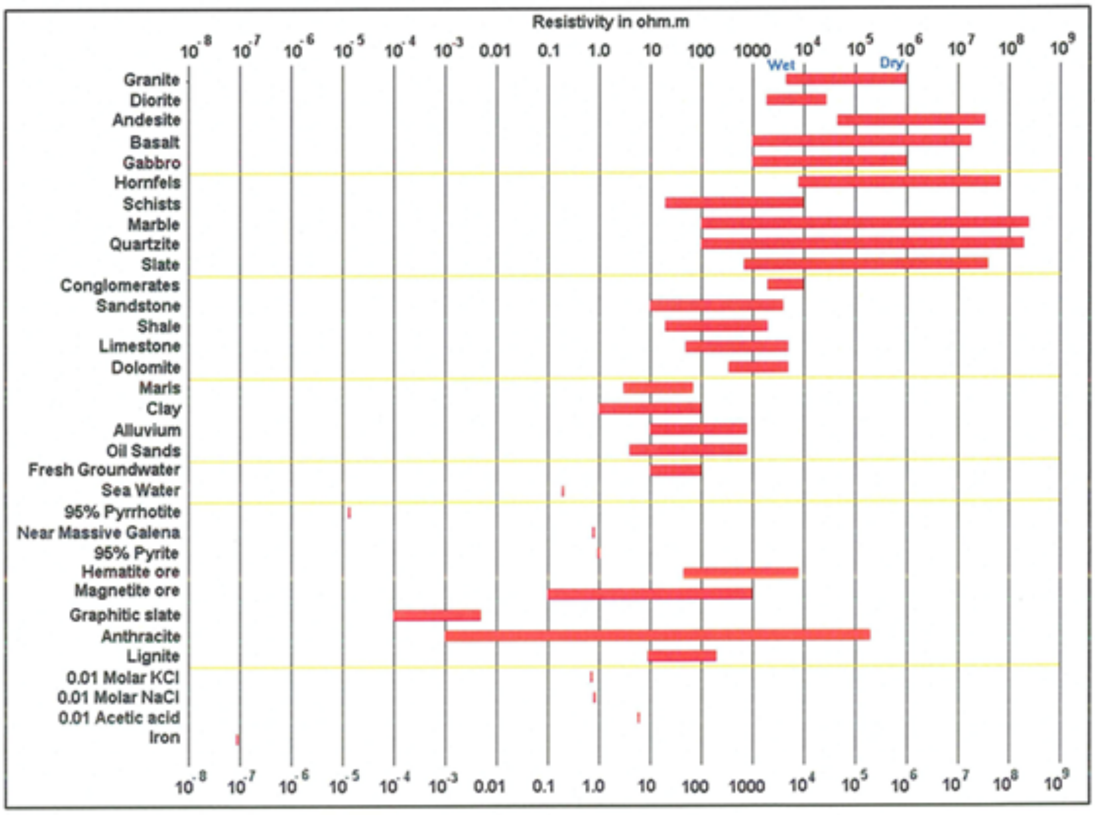


Figure 6.3. The estimated range of resistivity values of common rock types (Keller and Frisschknecht 1966).

Table 6.1. Resistivities of some common rocks, minerals and chemicals (Robinson, 1988).

Earth Material	Resistivity, Average or Range (Ohm-m)	Earth Material	Resistivity, Average or Range (Ohm-m)
Granite	10^2-10^6	Sandstone	1-10^8
Diorite	10^4-10^5	Limestone	50-10^7
Gabbro	10^3-10^6	Dolomite	10^2-10^4
Andesite	10^2-10^4	Sand	1-10^3
Basalt	10-10^7	Clay	1-10^2
Peridotite	10^2-10^3	Brackish water	0.3-1
Air	~ 0	Seawater	0.2

7. OVERVIEW OF GEOPHYSICAL TECHNIQUE USED

7.1. THE ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

ERT is used in this study. Electrical resistivity tomography. ERT measures the spatial variations in the electrical resistivity of soil and rock of the subsurface, and it has been as an effective geophysical tool in determining the karst terrain features. ERT methodology is widely used as the best geophysical method for determining depth of bedrock and locating the sinkholes and areas of subsurface dissolution by measuring the spatial variations of soil and rock resistivity values beneath the surface.

7.2. 2D AND 3D ERT DATA ACQUISITION

Supersting resistivity unit is used to acquire data in ERT survey (Figure 7.1). Supersting which powered by one or two 12-Volts battery is used to measure the variations in resistivity values (apparent resistivity of materials below surface). In this unit, electric flow currents pass through the electrodes that attached to the ground by using stakes. In this system, each pair of electrode serves the current and the other pair serves as voltage electrodes (Nwokebuihe, 2014). Each survey apply its standard arrays depend on its target. Many arrays are used; Wenner, dipole-dipole, Schlumberger, and pole-dipole arrays. According to Coskun (2012) dipole-dipole array is recommended for using in ERT survey because of its relatively lateral and vertical high resolution rather than other arrays and considering dipole-dipole array as effective geophysical tool in investigating karst terrain (Loke, 1991).

In this study, ERT electrodes were spaced at 5 feet intervals. More electrodes can be added to increase the depth resolution rather increasing the spacing between electrodes. Typically, the relation between the imaged depth and electrode spacing is inverse.

Figure 7.1 Supersting resistivity unit that used in ERT data acquisition.
(Source: https://www.indiamart.com/proddetail/electrical-resistivity-survey-service-6174260997.html).

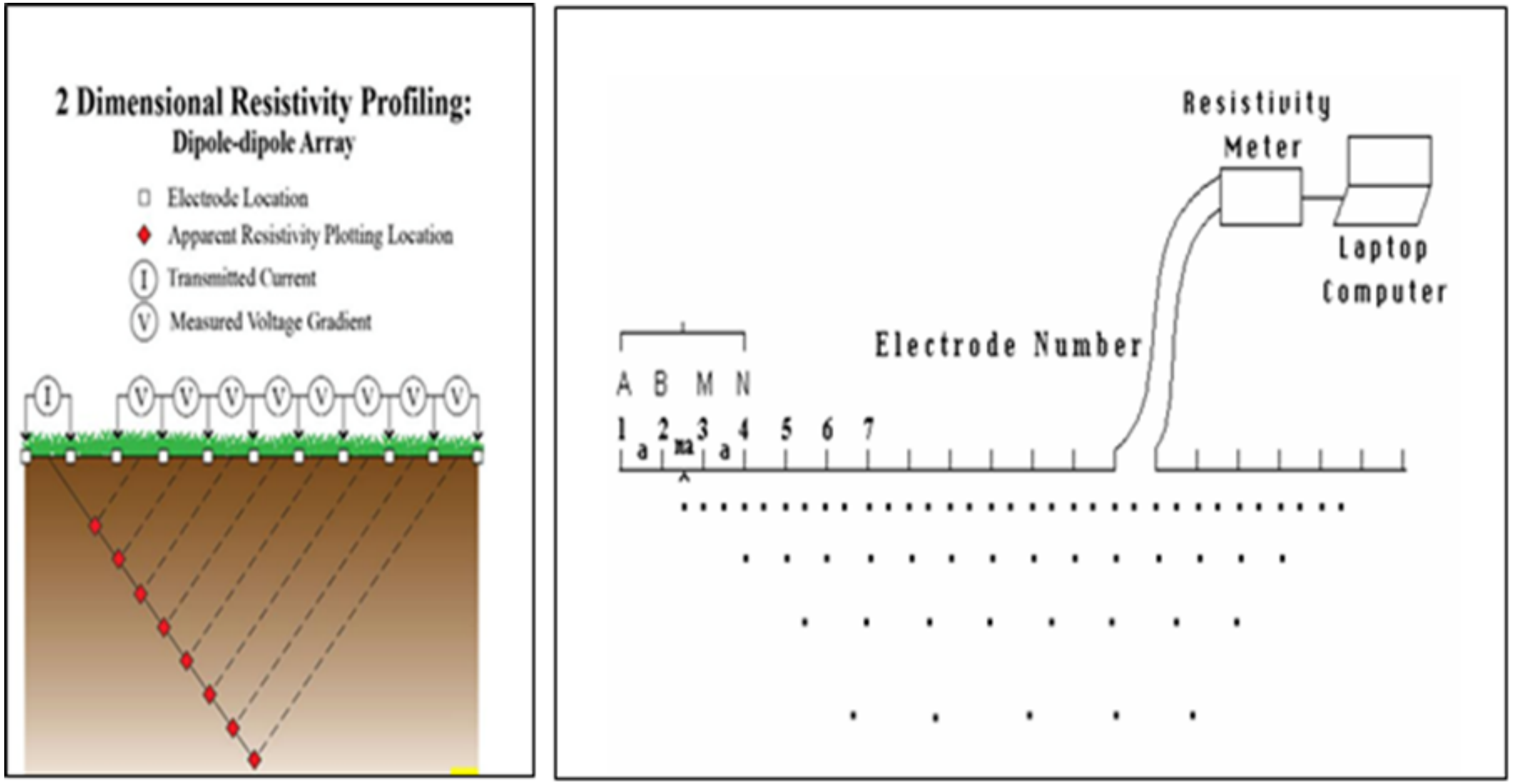


Figure 7.2. Configuration of dipole-dipole array used in the field.

7.3. ERT DATA PROCESSING

RES2DINV software program is used in ERT data processing. Raw data downloaded from Supersting control unit to the laptop computer for processing. The model applied by inversion process by transforming the apparent resistivity measured in the field to true resistivity.

The first step in processing is the inspection to remove bad data points (Figure 7.3.) which recognized by high or low apparent resistivity values and remove it.

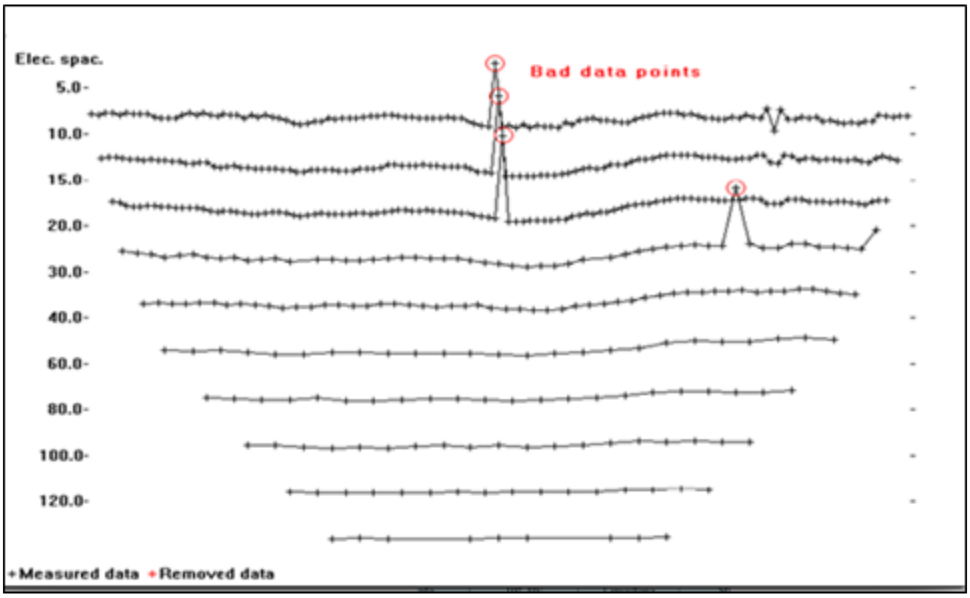


Figure 7.3. Field data raw set with a few bad data points (Loke, 2011).

To generate the 2D resistivity image representing the true resistivity distribution along the traverse, inversion of data is runned (Figure 7.4). Optimization during the processing reduces the difference between the calculated and measured apparent resistivity values. (RMS) error is used to calculate the difference which should remain low as possible as can. For a good quality geologic model, RMS error of 5% is recommended by (Loke, 1999).

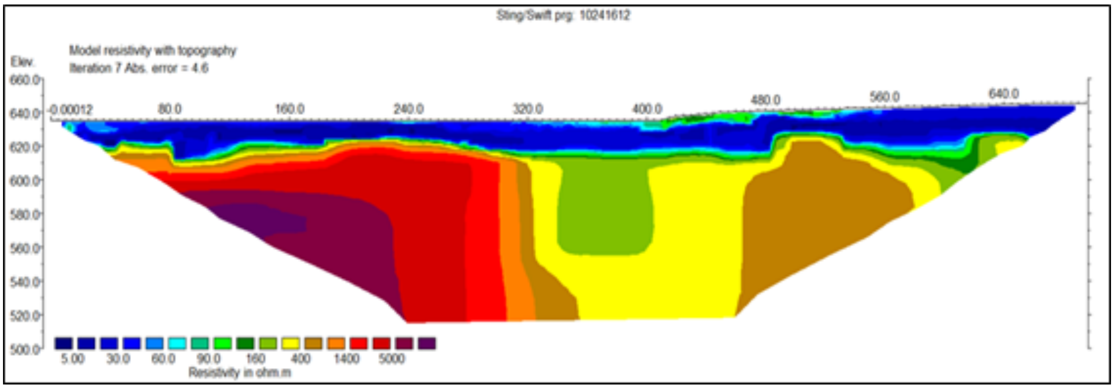


Figure 7.4. A typical ERT profile.

7.4. ERT DATA INTERPRETATION

ERT interpretation is based on the inversion model generated using the inversion software (RES2DINV) that shows the different ranges of resistivities of the imaged earth materials.

Basically, four subsurface materials are using in interpretation of ERT data by using their typical resistivity value: moist clay, moist soils, highly fractured rocks and relatively intact limestone, and air-filled cavities (Muchaidze, 2008). (Table 7.1) shows the typical values of these materials.

Resistivity values vary with saturation of water, therefore electrolytic processes in pores, fractured rock, and joints are highly dependent on moisture content. Conductivity increase within the saturated zones and as a result, current flow through these materials produces lower resistivities zones while air-filled zones have very high resistivity values because of low conductivity prosperities.

Table 7.1. Typical resistivity values for different subsurface materials (Keller & Frischknecht, 1966).

Subsurface material	Description	Resistivity (Ohm-m)
Moist clays	Very low resistivity and varies based on its degree of saturation, porosity and layer thickness	< 100
Moist soils and intensely fractured rock	Moderate resistivity and could based on its degree of saturation, porosity and layer thickness	100 - 400
Relatively intact rock	Slightly higher resistivity and could vary based on its degree of saturation, porosity and layer thickness	> 400
Air-filled cavities	Very high resistivity and could vary depending on the conductivity of the surrounding strata and the depth/size/shape of void	Usually > 10,000

8. BORINGS

In sinkholes investigation, drilling of borings considered very common method. Holes used to be drilled during sinkholes investigation. Borings drilled in the study site were used to acquire data while acquisition in progress. The purpose was to gain subsurface truth to constrain the data interpreted by ERT data. The data of boring logs provided a good representation of the moderately irregular bedrock surface, along with widened joints beneath the site. The data proved to be consistent with the interpreted data which detected that the depth to top of rock in the study area was shallow and vary approximately from (5-35) feet.

8.1. COREHOLE DATA

Coreholes were drilled in the studied area using hollow-stem augers and HQ coring to correlate with and use in the interpretation of ERT data. Corehole that used in this study is shown in (Figure 8.1).

The corehole in Figure (8.1) is located at the east of the study site. It was drilled to a total depth of 38 feet bgs. Brown clayey fine sand with gravel was present to a depth approximately 10 feet where Burlington-Keokuk Limestone with chert was encountered. Fractures were generally horizontal and the rock quality (RQD) was generally good to excellent. No voids were encountered.

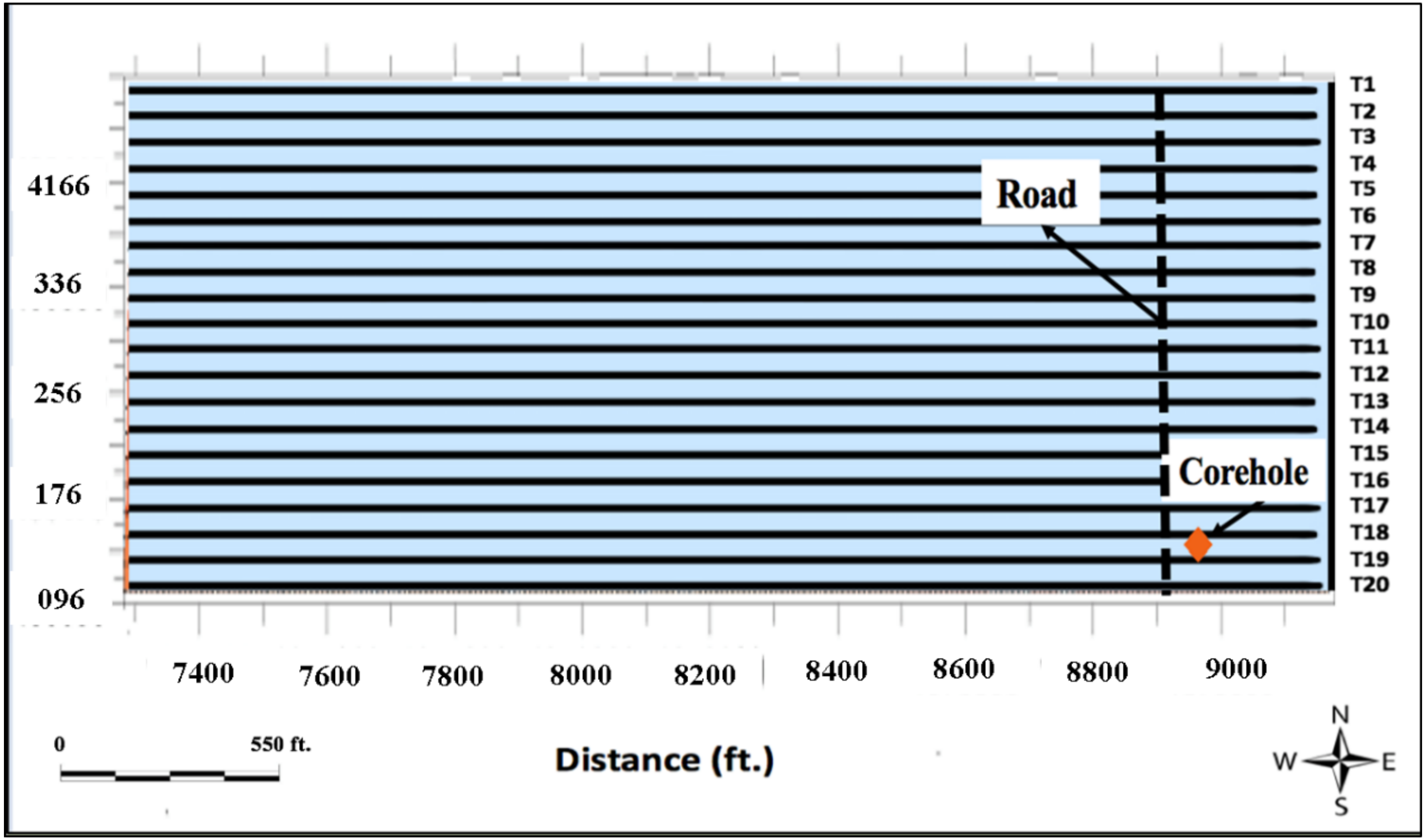


Figure 8.1. Corehole location that drilled in the study area.

9. GEOPHYSICAL STUDY

Various techniques were demonstrated in this study to characterize, image, and evaluate the potentially karst development and possible collapse sinkhole in the location. Data were acquired by ERT method along parallel west-east oriented separate traverses. The reason of this traverses orientation was because the dominant orientation of the joint sets was trended north-south. ERT data were acquired to image the subsurface, map the variations of the top of rock, map the variations in soil thickness, characterize joint sets and possible sinkholes, monitoring the groundwater flow patterns beneath the surface, and study the properties of rock and soil. 2D and 3D ERT data profiles were processed to determine the characters of possible solutional sinkhole.

9.1. ERT SURVEY

ERT is considered as effective geophysical tool in sinkholes investigation (Wightman et al., 2008). Similarly, Dobecki and Upchurch (2006) recommended that using ERT by combinations with boring data is considered as great technique in karst features investigation. Data were acquired in the location by using superstring system. Twenty west-east oriented of ERT traverses used in the study. ERT traverses were spaced at 20 feet intervals; acquiring data to the depth of approximately 160 feet covering a length of approximately 1800 feet. The data processing steps were discussed in (Section 7.3) which used to generate the 2D and 3D ERT resistivity profiles. Picking the values of resistivity which correspond mostly to 125 ohm-m is the basis on the 3D ERT profiles to be the representation of the interpreted top of rock. Interpretation showed that the bedrock is shallow, porous, and high permeable fractured rock. Dry soil is characterized by resistivity values greater than 125 ohm-m (higher resistivity). Moist soils and moist fractured rock with moist clay-fill are represented by low resistivity values less than 125 ohm-m. Interpreted mostly dry and possibly more intact rock are represented by resistivity values greater than 600 ohm-m. Resistivity values less than 600 ohm-m are used to represent mostly moist and possibly more extensively fractured rock.

Some dissolution-widened zones were interpreted by ERT profiles along the site. They oriented north-south with west-east widening. By interpreting the 2D and 3D ERT profiles, the zones of low resistivity and high moisture content had been detected. This is considered an important result for this study site.

9.2. 2D AND 3D ERT DATA

ERT is routinely used in Missouri to image the shallow subsurface in karst terrain because undisturbed soil, carbonate rock, clay in-fill, and air-filled cavities are generally characterized by very high resistivity contrast (Ismail and Anderson, 2012). Twenty oriented parallel west-east 3D ERT data spaced at 20 feet with a length of 1800 feet were acquired to image the subsurface features. Each ERT profile extends to a depth of approximately160 feet.

9.2.1. Bedrock Topography. Data acquired by ERT method and drilling boreholes for the rock in the location indicated that rock is pervasively fractured. The interpreted top of weathered rock corresponds to 125 ohm-m resistivity contour value on the ERT profile (Figure 9.1). Therefore, the low resistivity zones imaged in ERT profile are illustrated mainly due to the presence of moisture and due to high clay content.

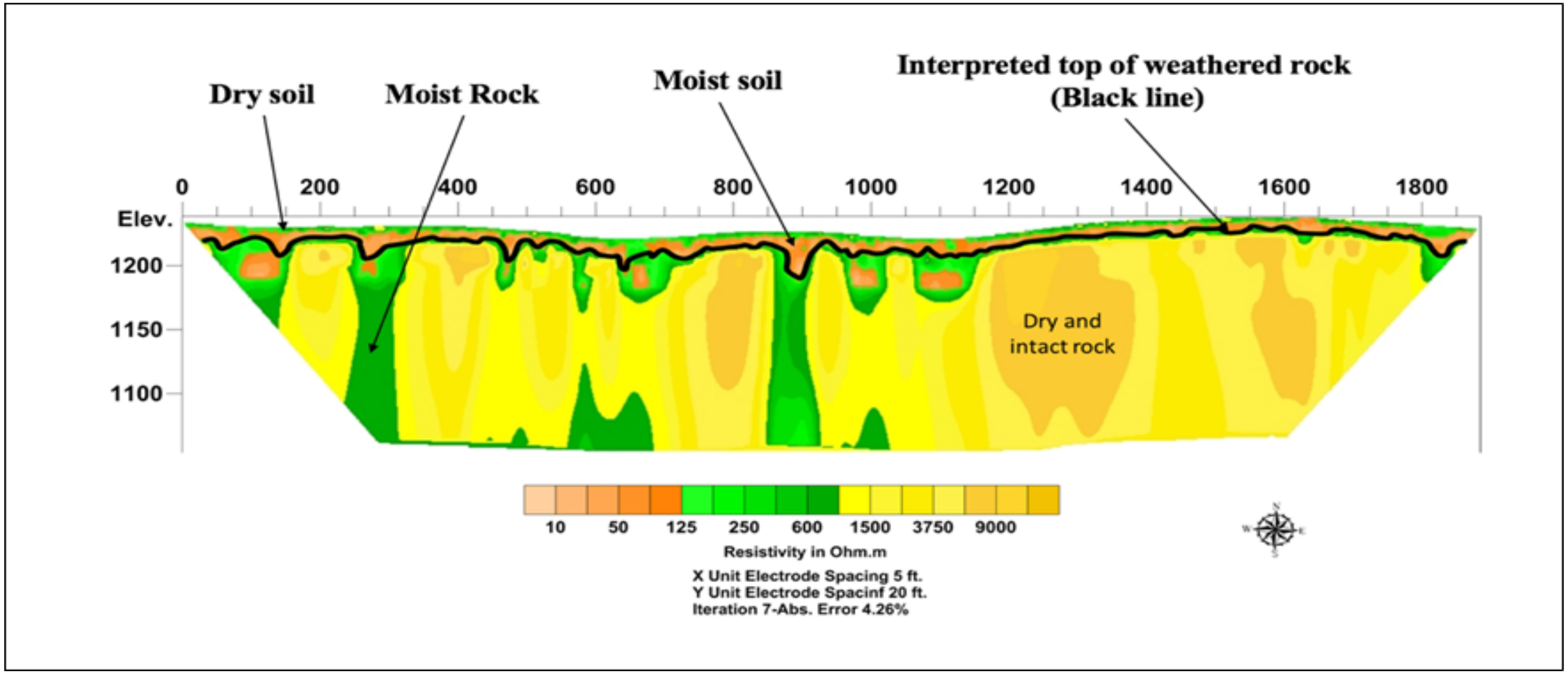


Figure 9.1. Interpreted west-east oriented 3D ERT profile in the study area indicating the interpreted top of weathered rock (highlighted black line) corresponds to (125 ohm-m) contour interval. Dry soil corresponds to resistivity values (>125 ohm-m) contour interval. Interpreted mostly dry and possibly more intact rock are correspond to resistivity values (>600 ohm-m) contour interval. Resistivity values (<600 ohm-m) represent the interpreted mostly moist and possibly more extensively fractured rock. Elevations and distances are in feet.

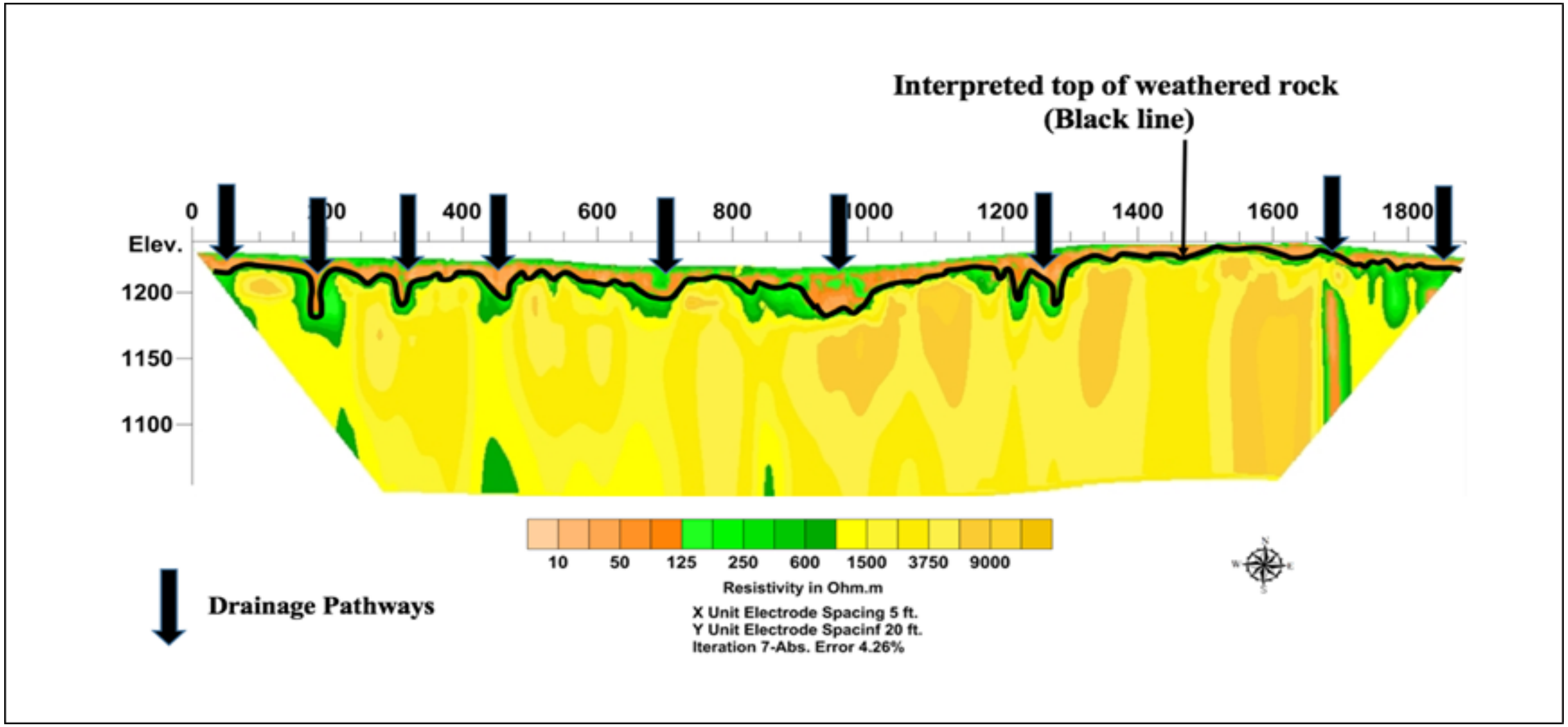


Figure 9.2. Interpreted west-east oriented 3D ERT profile in the study area indicated the interpreted top of weathered rock corresponds to 125 ohm-m contour interval with prominent direction of drainage pathways along the site. Elevations and distances are in feet.

The data acquired indicated that rock beneath subsurface is pervasively and intensely fractured. Rock conductivity increases where intensely fractures detected beneath the surface of drainage pathways and the zones where clay present. Typically, the conductivity of rock increases where moisture content is high and moisture in the porous permeable fractured rock as a result reduces the values of resistivity (Figure 9.3) and (Figure 9.4).

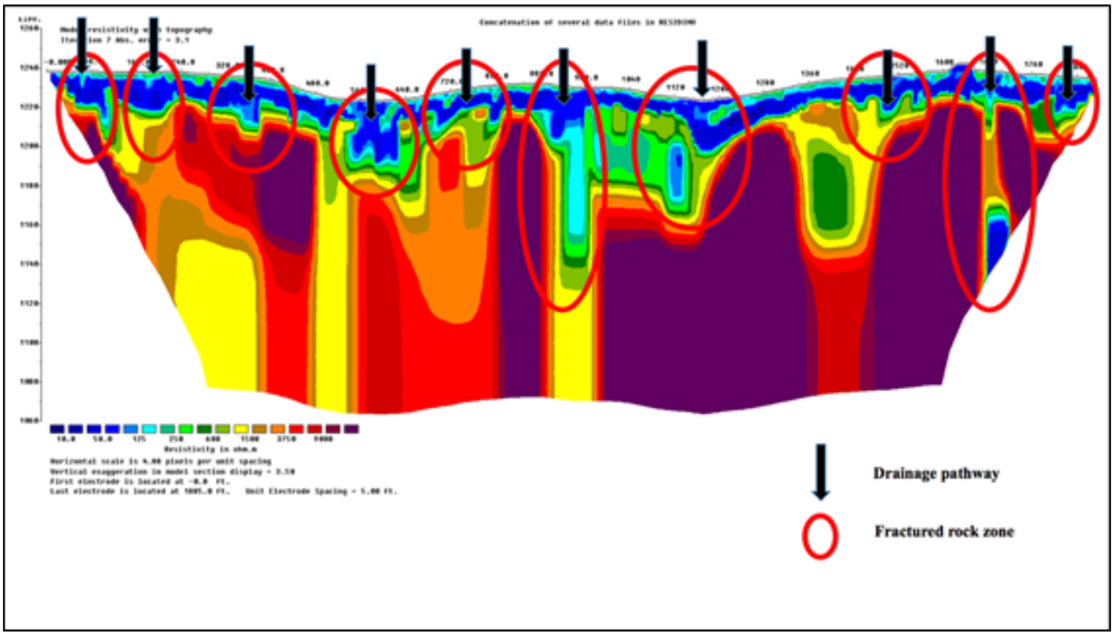


Figure 9.3. Uninterpreted west-east oriented 2D ERT profile in the study area imaged the low resistivity zones where intensely fractures detected beneath the surface of drainage pathways. Elevations and distances are in feet.

Aerial images of the site showed that the surface drainage system has multi-pathways (Figure 9.5). Maps based on ERT data interpretation represent ground surface elevation, elevation of top of rock and soil thickness in the study area. Ground surface elevations that extracted from ERT profiles varies from approximately 1215 to 1244 feet. The elevation of top of rock varies from 1150 to 1235 feet and the soil thickness in the location which also represents the depth to top of rock varies approximately from 5 to 35 feet. (Figure 9.6) and (Figure 9.7) show surface elevation and top of rock elevation contour maps correlated to the surface drainage pathways patterns in the site. Variations of top of rock elevation indicate variations in moisture content which reflected the variations in dissolution rates of intensely fractured rock beneath the surface.

The acquired data indicated that the surface topography is irregular and describes as a mirror of the bedrock surface related to the significant correlation with surface drainage pathways (Figure 9.8) and (Figure 9.9). Surface was interpreted to be dissected by weathering and so the top of rock throughout the site.

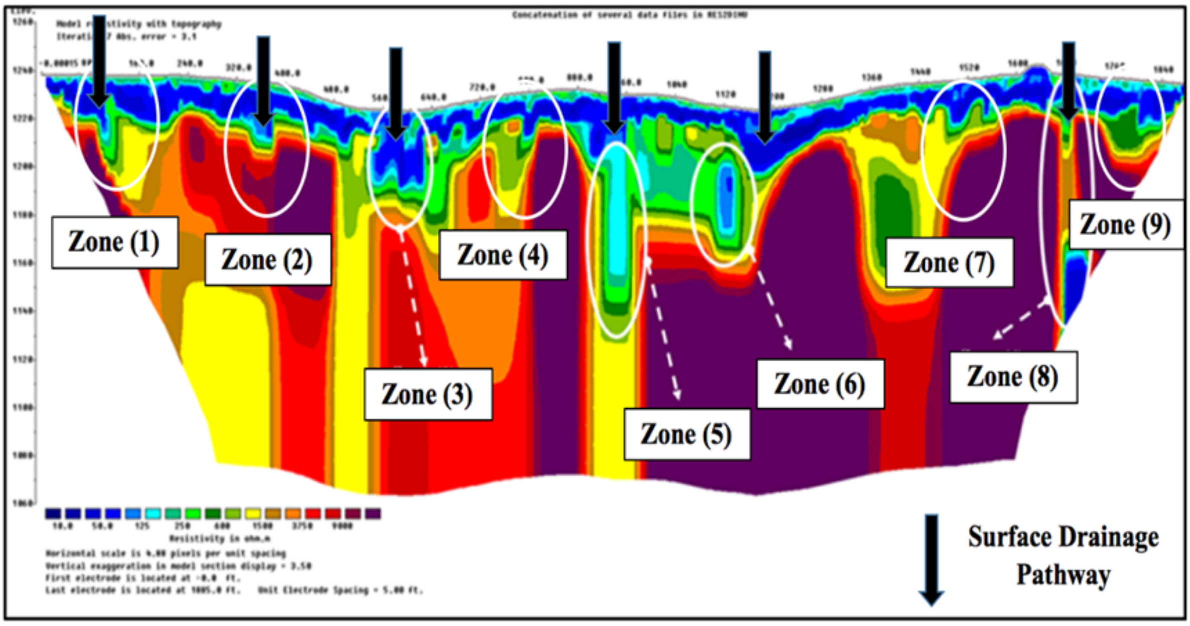


Figure 9.4. Uninterpreted west-east oriented 2D ERT profile in the study area indicated the low resistivity zones (1, 2, 3, 4,… and 9) mostly beneath the surface of drainage pathways. Other zones of low resistivity not related to surface of drainage pathways are marked.

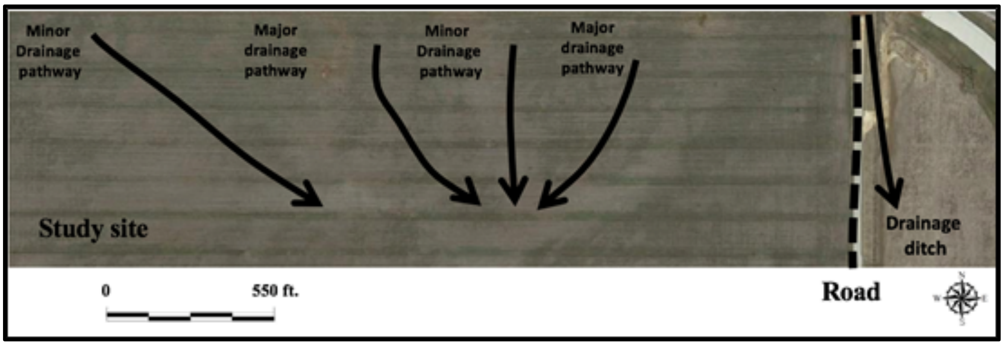


Figure 9.5. The surface drainage patterns in the study site. (Google Earth).

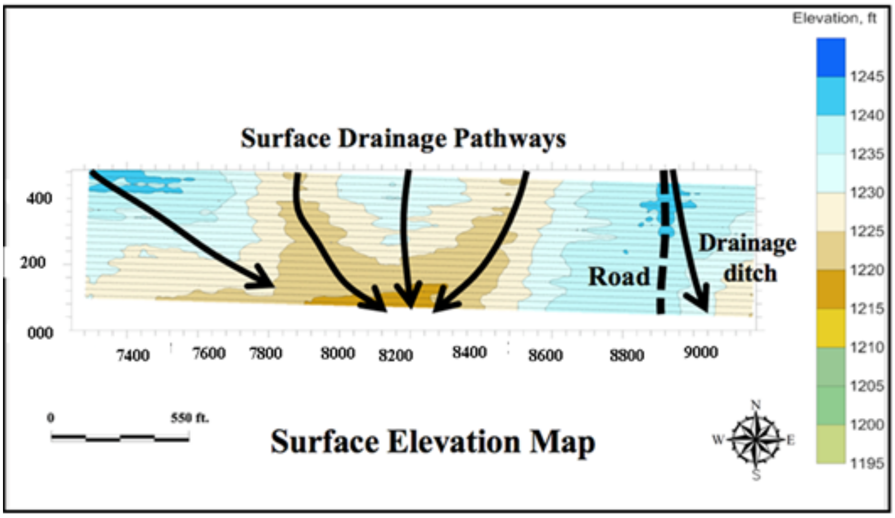


Figure 9.6. Surface elevation contour map correlated to the surface drainage pathways patterns at the site. Elevations and distances are in feet.

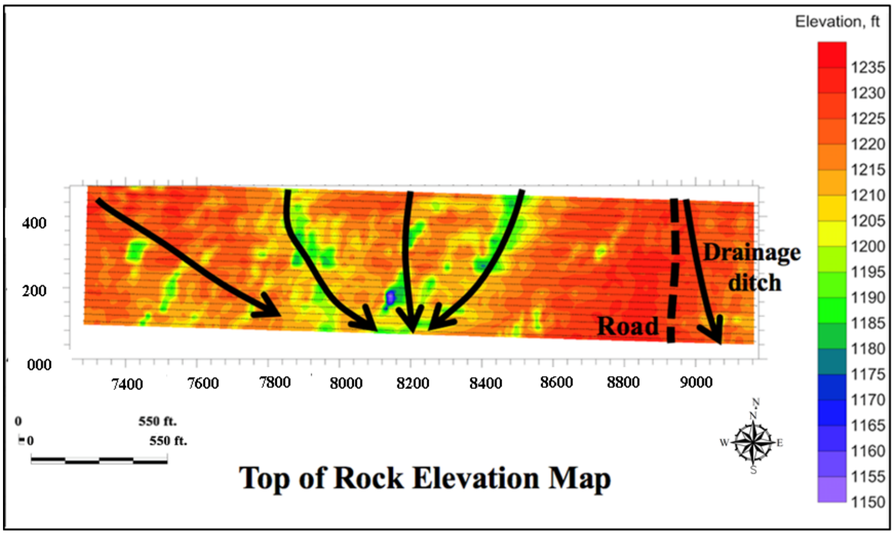


Figure 9.7. Top of rock elevation contour map correlated to the surface drainage pathways patterns at the site. Elevations and distances are in feet.

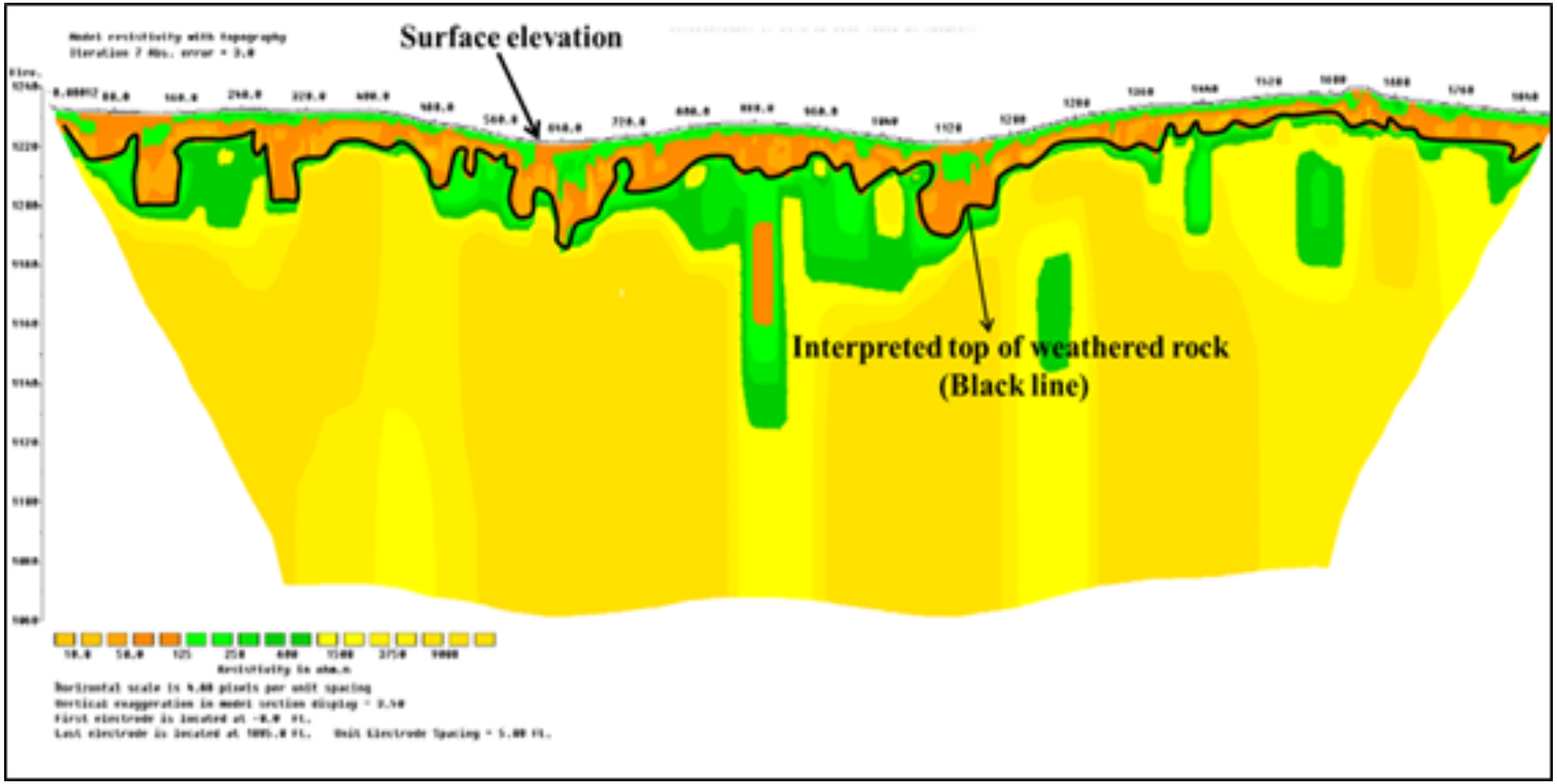
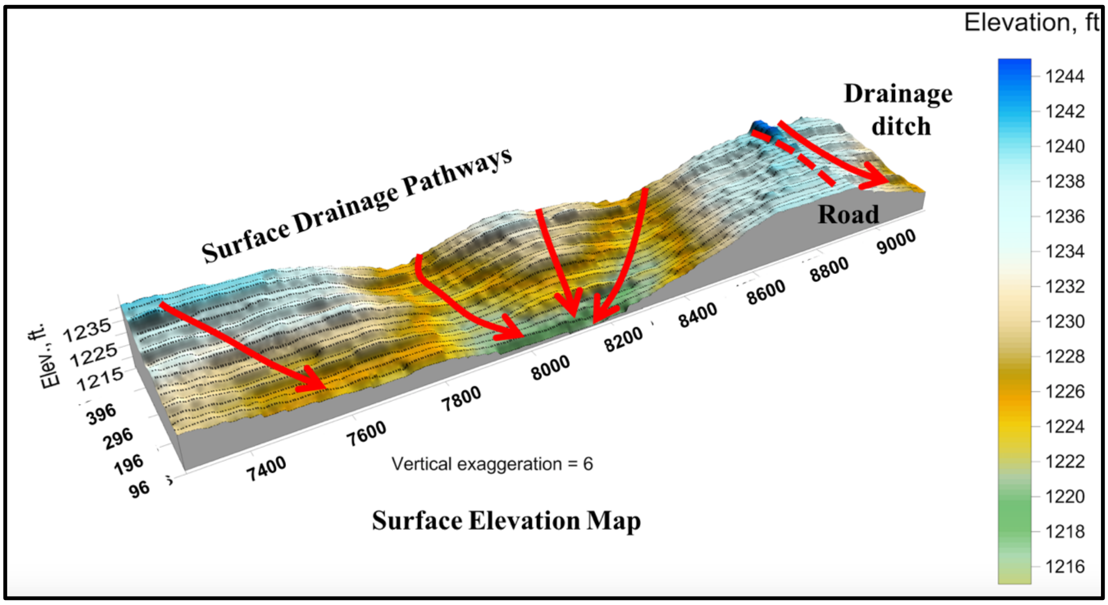


Figure 9.8. West-east oriented 2D ERT profile with interpreted top of weathered rock correlated to surface topography. Elevations and distances are in feet.



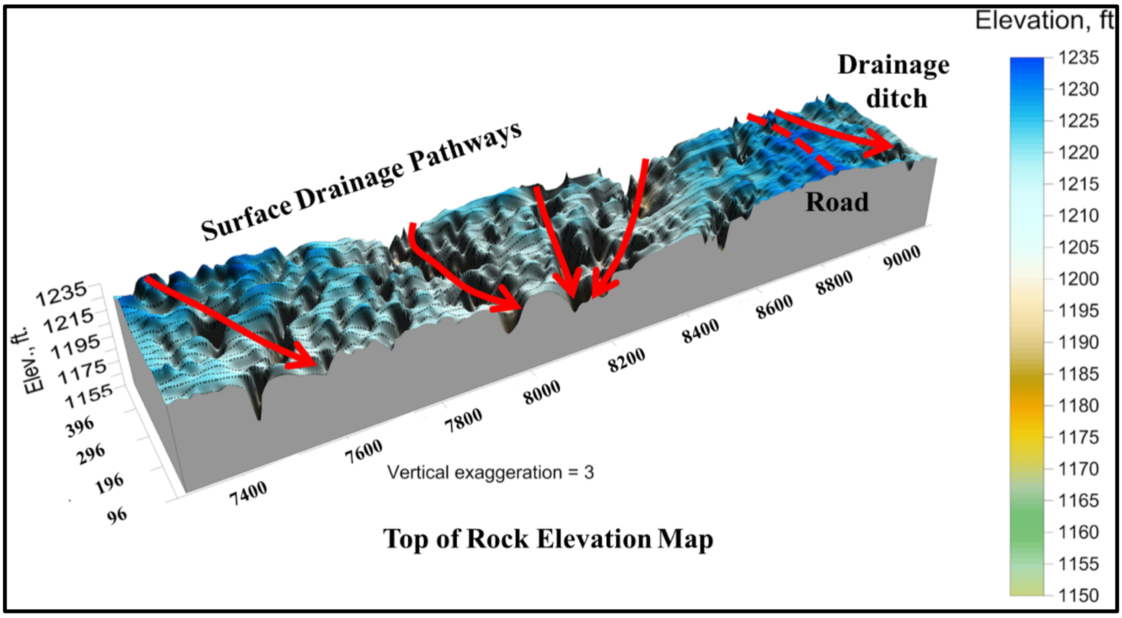


Figure 9.9. (a) Surface elevation contour map correlated to the surface drainage pathways patterns (red arrows). (b) top of rock elevation map correlated to the surface drainage pathways patterns (red arrows). Elevations and distances are in feet.

9.2.2. Soil Mapping. Relatively thin soils are present throughout the study location, the ERT profiles show the soil thickness which vary between 5 feet and approximately 35 feet (Figure 9.10). The shallower part of soil has higher resistivity values which indicated dryness. Deeper section characterized by lower resistivity values which means that it is moist which enable identifying the soil/rock contact. Because of piping of the fine-grained soils and clay, the thinner (fewer fines) are available for piping and the denser are less permeable soils.

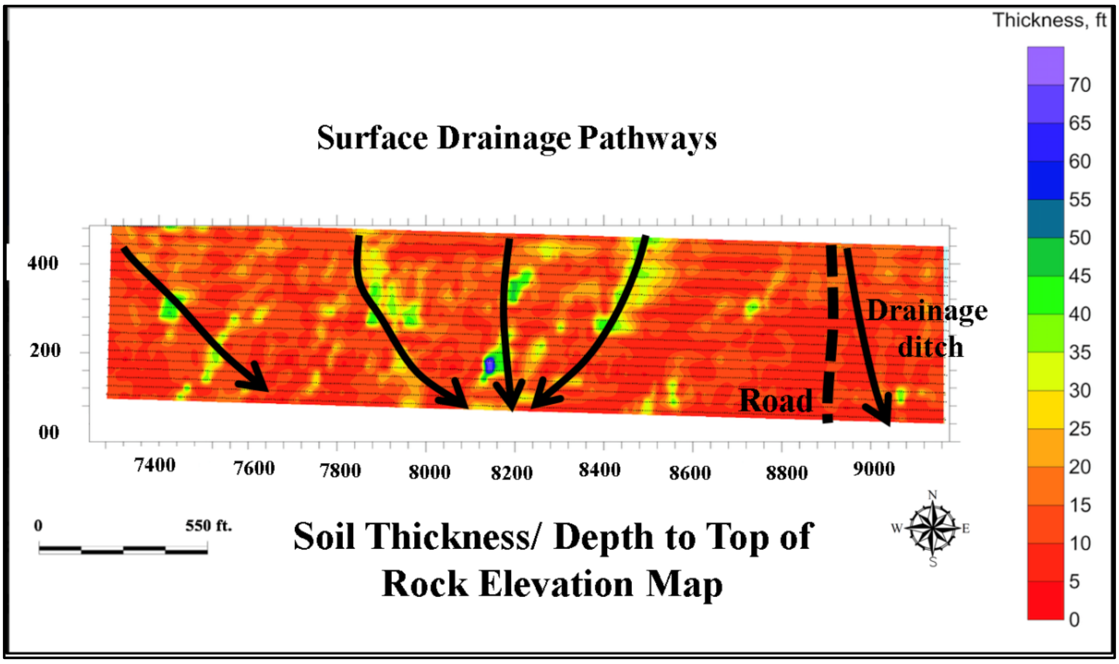


Figure 9.10. Soil thickness contour map. Elevations and distances are in feet.

9.2.3. Joints and Fractures. The parallel 20 west-east ERT indicated that the rock is pervasively fractured which characterized by low values of resistivity as a result of moisture presence related to surface drainage seepage. Resistivity values vary anomalously on some ERT profiles which related to the lateral variations of moisture and clay content throughout the sight (Figure 9.11).

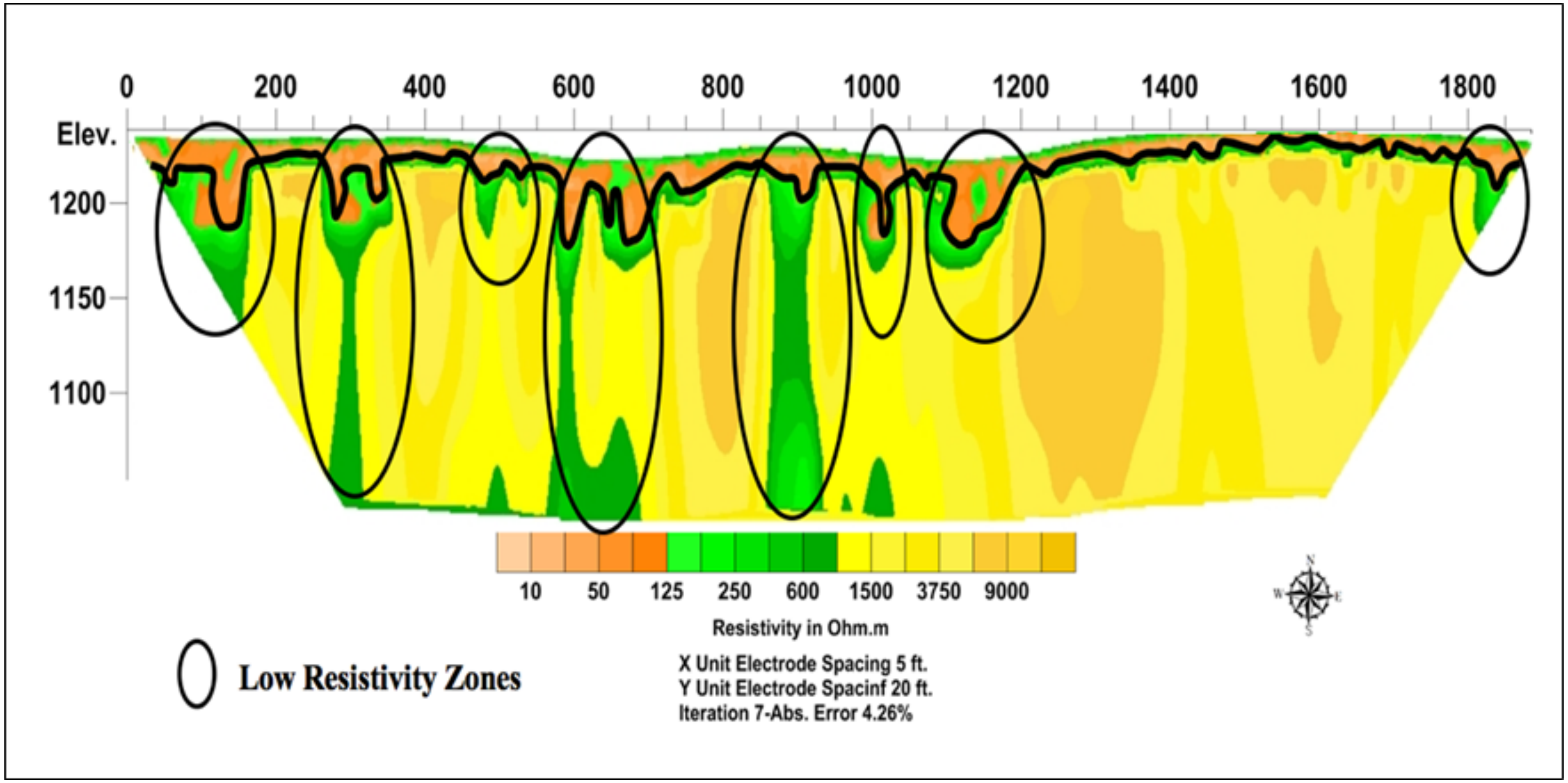


Figure 9.11. West - east oriented 3D ERT profile with interpreted top of weathered rock. Sections labelled by black ovals show the fractured zones that characterized by low resistivity values corresponding to moisture presence related to surface drainage seepage. Elevations and distances are in feet.

ERT profiles in (Figure 9.12) show the development of dissolution process within the intensely fractured rock. More pervasively widening increasing with presence of piped clay that causes broadening in the drainage seepage with depth, all these observations which related to the increasing of moisture concentrations at depth, as a result, increased the conductivity and decreased the resistivity values. Typically, the largest widths of the dissolution that often characterize by low resistivity appear where the drainage pathways present. On the other hand, interpretation of data acquired in karst terrain should consider the possible effects of ground surface topography, rather than simply identifying all low resistivity features as being related to karst. Low resistivity values in soils and shallow rock in zones not related to drainage pathways may illustrated as presence of interpreted prominent joint sets or old drainage pathways.

Based on the imaged 3D ERT profiles and values of resistivity, dissolution decreases with depth regarding to moisture decreasing farther from surface seepage. Two or more seepage directions on ERT profiles were marked. The depth slices sequence in (Figure 9.13) show that higher moisture content dictates the zones of lower resistivity values indicated by the directions of drainage pathways.

Typically, resistivity values vary significantly from low to high with depth, which correlated to the seepage directions and can be illustrated as changing in flows direction, laterally or downward through the fractures. The patterns indicated to be both horizontally and vertically; this definition can be used to monitor the seepage direction and the groundwater flow system (Figure 9.14).

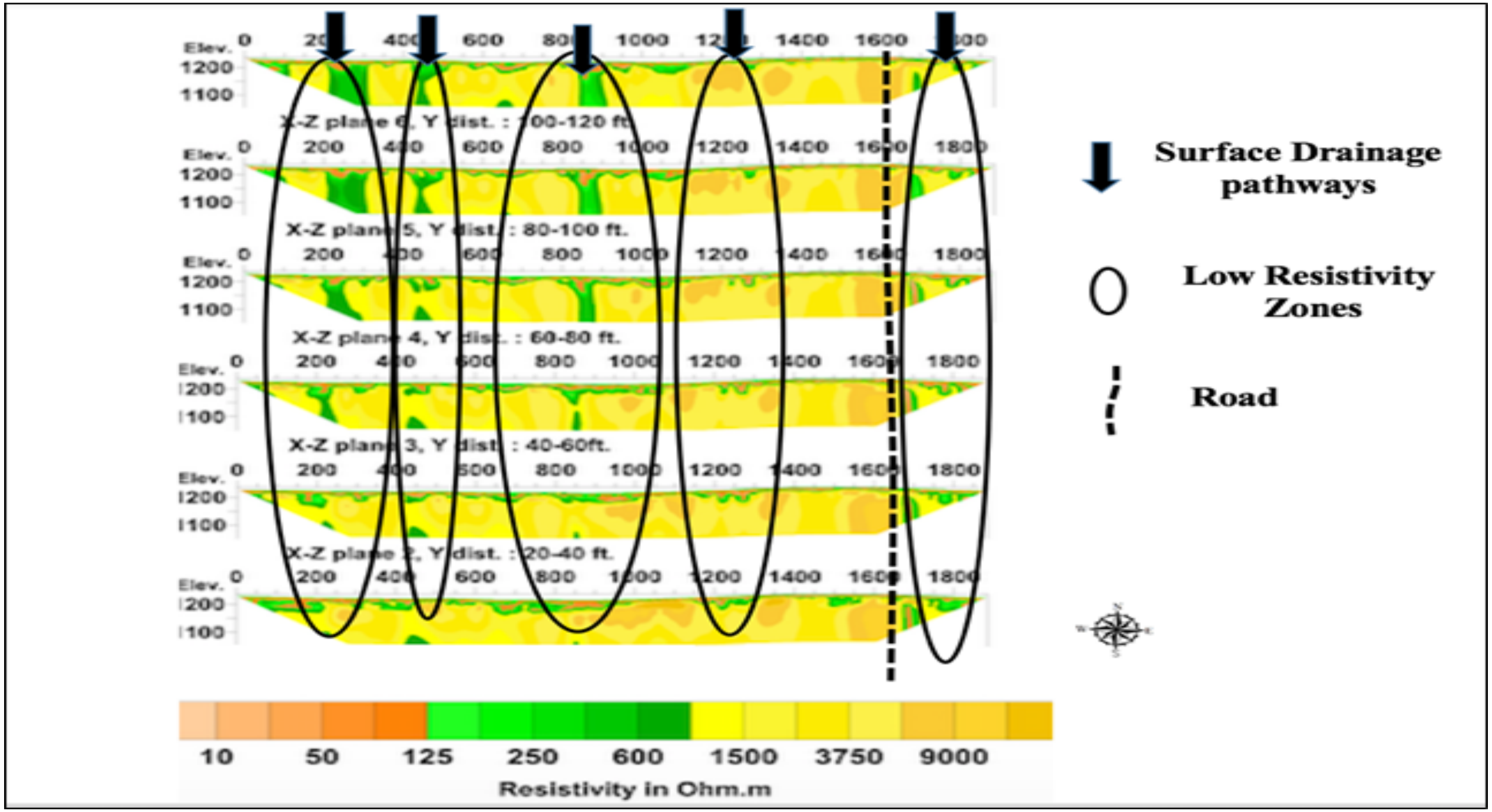


Figure 9.12. W-E oriented 3D-ERT profiles with the location of development dissolution through the intensely fractured rock characterized by low resistivity values. Elevations and distances are in feet.

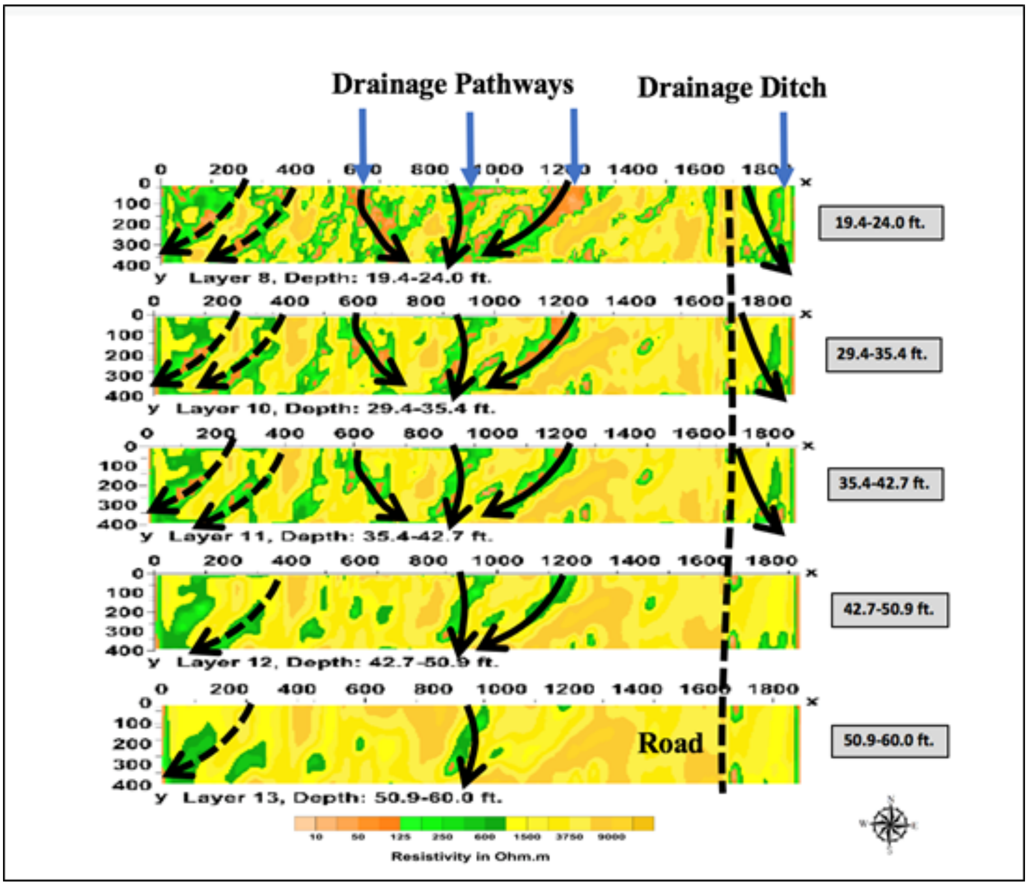


Figure 9.13. A sequence of horizontal depth slices for the study area extracted from the 3D ERT data indicates the seepage pathways directions correlated to lower resistivity values. Elevations and distances are in feet.

Depressions in the area are characterized by lower resistivity values, reflecting higher conductivity; which can be illustrated that the drainage seepage pathways through fractured rock widened with depth where moisture content are higher and the solution-widening is more extensive.

9.2.4. Air-filled Cavities. No potential air-filled voids were identified on the acquired ERT data.

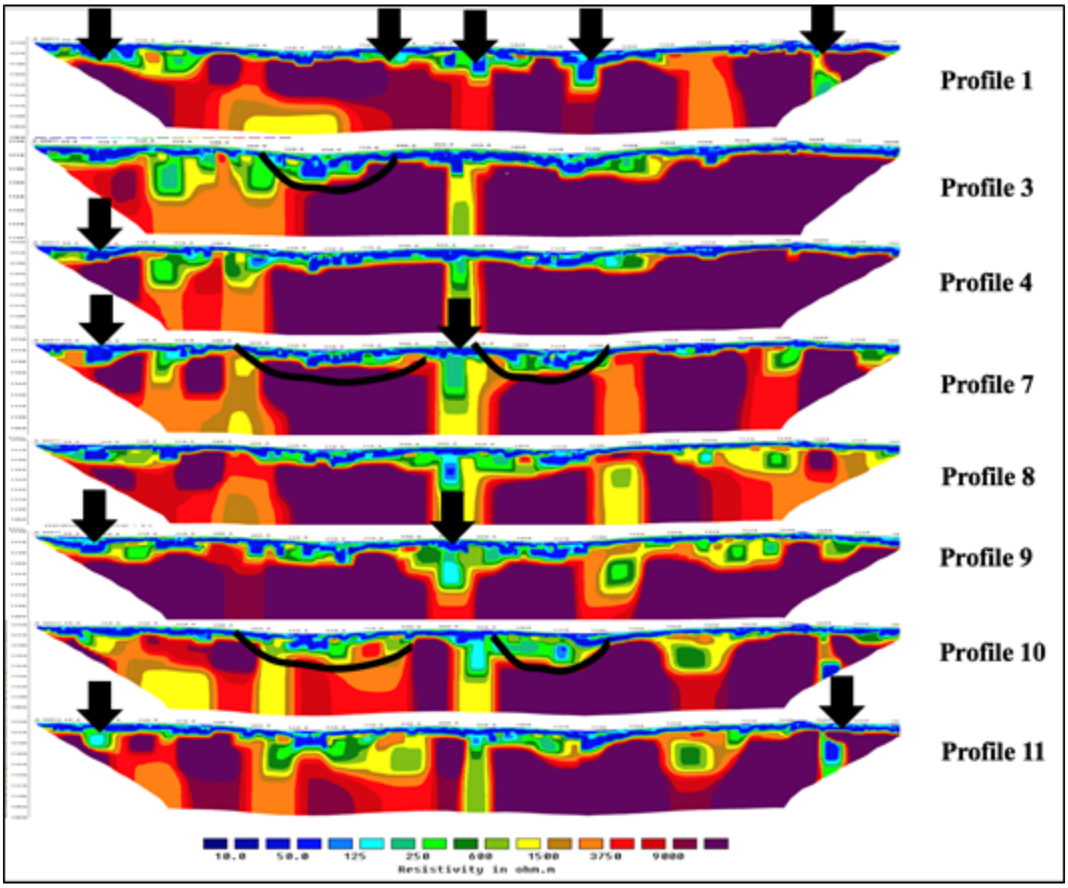


Figure 9.14. The horizontally (black lines) and vertically (black arrows) seepage pathways changing in direction correlated to variations in resistivity values represented in W-E oriented 2D ERT profiles. Elevations and distances are in feet.

10. CONCLUSIONS

Combining engineering geophysics with conventional geotechnical engineering yield to truth results about the site characterizations of site. Data were acquired in the site demonstrated that zones of anomalously low resistivity in karst terrain can be caused by the downward seepage of groundwater flowing along natural and man-made surface drainage pathways.

The data acquired indicated that rock beneath subsurface is pervasively fractured. Rock conductivity increases; where intensively fractures detected (zones of solution-widening joints), beneath the surface of drainage pathways, the zones where clay present and typically, the conductivity of rock increases where moisture content is high.

It is concluded that the resistivity of soil and rock beneath natural and man-made drainage pathways is frequently anomalously low because greater volumes of moisture seep into the subsurface along surface flow pathways than elsewhere in the study area.

Data based on ERT analysis determine that variations in the moisture content of soil and shallow rock are related to ground surface topography with the exception of soil and rock in proximity to interpreted prominent joint sets.

The results of this investigation demonstrate that not all zones of anomalously low resistivity in karst terrain are related to sinkholes and solution-widened joints. Interpretation for acquired ERT data in karst terrain should consider the possible effects of ground surface topography, rather than simply identifying all low resistivity features as being related to karst processes.

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