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Detection of Bedrock Fractures and Joints Beneath Cover: Geophysical Approaches to an Engineering Geology Problem

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DETECTION OF BEDROCK FRACTURES AND JOINTS BENEATH COVER: GEOPHYSICAL APPROACHES TO AN ENGINEERING GEOLOGY PROBLEM

by

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A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy Geosciences Western Michigan University June 2018

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This research used geophysical methods to detect the presence of sub-vertical failure planes, their direction(s), and their frequency in bedrock beneath soil or glacial drift overburden. Azimuthal measurements using the seismic, electrical resistivity (ER), and electromagnetic conductivity were made to evaluate which techniques might provide the best indication of the bedrock joints, faults, or shear zones. Measurements were made at multiple sites near each of three locations: Jackson, Alpena, and Grand Ledge, Michigan. The first two are former limestone quarries and the third is underlain by sandstone. Seismic measurements began with one or two linear refraction spreads, used to establish thickness of overburden and identify the S waves. The Circular Array Seismic Survey (CASS) was done by placing the 24 geophones around a 10 or 15m radius circle (15 degree intervals), with the shot point in the center, measuring arrival times of the P and S waves. The EM-31 conductivity was used to quickly determine that there were no wires or pipes in or near the survey circle, as well as to profile along the diameters of the circle at 12 different azimuths. Electrical resistivity measurements included linear and azimuthal square arrays. The linear array consisted of expanding 4-electrodes in the fashion used in Schlumberger array, which constitutes a Vertical Electrical Sounding (VES) to determine the resistivity layering and, similar to the linear array in the seismic refraction method, gave a second or
independent measure of the depth to bedrock, water table, or other discontinuity when interpreted. The azimuthal square array was used for the resistivity measurements in the same circle of the CASS, with the diagonal of the square being the circle diameter. This array was rotated to 12 unique azimuths at 15° intervals. Reference measurements of the strikes of failure planes were made using a Brunton compass and photographs at adjacent bedrock exposures. Verification of results was done by comparing the geophysical results and the measured strikes and dips of the nearby exposures of the joint systems. Computer software analyses of the results showed coincidence of the tests results with the strike measurements in some areas, whereas others did not. Some of the methods are very sensitive to variations in thickness and water saturation of the overburden. These effects, as well as lateral resistivity gradients in the bedrock and overburden can apparently cause false indications of fracture systems.
DEDICATION

This work is dedicated to the souls of my mother and sister who passed away before it was finished. May their souls rest in peace.

Muthanna Yousif Yaqoob Aldiney
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Muthanna Yousif Yaqoob Aldiney
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CHAPTER I

INTRODUCTION

The Problem of Detecting Hidden Joints and Fractures

1.1 Why Detecting Joints is a Problem

Prior to civil construction, site studies must be done to assess the soil and underlying rock conditions. This assessment is essential to the construction’s cohesion because discontinuities, like joints, represent planes of weakness that might jeopardize the safety of the construction. The most common and trusted technique to make this assessment is to drill holes, or borings, to extract samples. However, for the case of sub-vertical failure planes in the rock, this type of sampling rarely encounters the problematic zones, as the borings are also vertical. Informed bidding on projects that require water retention, such as dam, canal, or dike projects, can be fatally flawed if the presence of these vertical failure planes is not known. This research will review non-invasive geophysical methods to detect (prior to excavation) the presence of sub-vertical failure planes and their direction(s).

1.2 Significance of Research

Engineering Geology is devoted to the investigation, study and solution of the engineering and environmental problems which may arise as the result of the interaction between geology and the works and activities of man as well as to the prediction and the development of measures for prevention or remediation of geological hazards (The International Association of
Identification of bedrock joints is important in characterizing suitable mining and rock excavation methods. The natural size of rock blocks governs quarry management; therefore, any variation in joint characteristics would be important for block size assessment (Sousa, 2010). Fracture detection also plays a role in the stability of mines and tunnels (Stephansson et al, 1979). Identification of bedrock joints helps in designing the best settings for explosives in order to maximize production of the proper cuts of rocks for different purposes, whether blocks for mining or building, or large slabs for flooring, or facing. It also helps indicate subsurface fluid migration, which is useful for hydrogeological studies including surface water and groundwater analysis, as for example the control of water in open quarries and hazard-waste management in disposal areas where fractured bedrock might be a risk of migration of waste from disposal areas to household or municipal wells (Lewis and Haeni, 1987). Joint identification is also useful in studying local tectonic stress. The joint pattern may be used to determine past directions of principal tectonic stress. Detecting and measuring the orientation and distribution of discontinuities in rock cuts using scanline or advanced techniques such as LIDAR is important in assessing the stability of rock masses, however, this only investigates visual discontinuities leaving the hidden subsurface features neglected (Aqeel, 2012). Engineering geologists, civil and mining engineers frequently deal with rock joints and their characterization when investigating joint origin in rock masses. However, a specific description that would characterize the jointing would be difficult due to the three-dimensional nature and limitation of exposure of rock joints (Dershowitz and Einstein, 1988). Thus, probing rock joint occurrence and orientation beneath cover initiated the interest of the current study.
1.3 Selection of Methodology

Common methods used for conducting such studies may require information analysis from outcrop exposures and borehole logs. These methods are only applicable on outcrop exposures or drill samples and can be expensive, or unavailable. The most expensive and destructive method would be to remove all the soil or overburden with heavy equipment, followed by washing or brushing away the remaining soil so that the joint pattern could be seen and measured.

Recording and interpretation of geophysical profiles, such as seismic and electrical resistivity (ER), have been shown to be suitable and non-destructive methods to provide an indication of the presence of bedrock joints and their directions. These methods can be an economical alternative to the direct methods in areas of intense vegetation cover and areas covered by soil. This research proposes to use seismic recordings and electrical resistivity to locate sub-vertical bedrock joints at a number of locations within several hours driving distance of Kalamazoo, where bedrock is near the surface or even exposed at part of the site.

A series of geophysical tests were to be made at several locations where bedrock is concealed, and then physical measurements (as with a Brunton compass) and photographs made to document the orientations and spacings of the sub-vertical failure planes at the adjacent bedrock exposure locations. Verification of results would be done by making a correlation between the geophysical results and the measured strikes and dips of the joint systems in the study areas.
2.1 Engineering Aspects of Joints and Fractures

Implications of photogeologic linears in the South Long Lake Area, Alpena and Presque Isle Counties, Michigan were studied by Kimmel (1973). Photogeologic linears studied were classified into geologic fracture trace, which is a photolinear extending continuously for less than a mile across the earth’s surface representing local bedrock joints and fractures, and geologic lineament, which is also a lineament but extending continuously or discontinuously for at least one mile representing major fracture zones. The study covered an area of 48 square miles in Alpena and Presque Isle Counties of Michigan State that shows linears in the upper Middle Devonian Traverse Group of northern Michigan, which consists of limestones and shales covered by less than one foot thick of glacial cover. The purpose of the study was to geologically study linears in the area in detail and suggest its origins and relationship with the stratigraphy of the Traverse Group. The methodology included geological mapping of four photomosaics and individual aerial photographs of the study area, statistical analysis of the distribution on the linears and field observation. Ten conspicuous photolinears were named and chosen to be studied in detail. Statistical study of the photolinears in Kimmel (1973) concluded that there are two major sets of photolinears and that both sets are prominent throughout Alpena and Presque Isle Counties. Both sets were found to be approximately 90° apart with one set trending northwest-southeast, having the longest photolinears, and the other trending northeast-southwest. The mean azimuths and the mean lengths of the photolinears were found unrelated. Groundwater solution associated with underground drainage system and jointing in the limestone bedrock have played
a role in the formation of photolinears in addition to the collapse of Salina Salt in the studied area.

Characterization of rock joint geometry with joint system models was approached by Dershowitz and Einstein (1988) to describe the assemblage of geometric joint characteristics in a rock mass. They described rock mass geometry as an entity by emerging traditional disaggregate characterization, in which a typical distribution is represented by major joint characteristics, joint orientation, joint location or spacing, joint size or trace length and aperture, with aggregate characterization, in which joint characteristics are captured through the formulation of joint system models. Dershowitz and Einstein (1988) dealt only with visible joints, but joints beneath cover were not considered, whereas the current study emphasis is on concealed joints.

Mavko et al. (2005) approached the detection and characterizing of natural fractures in rocks by making an integrated strategy in which they integrate geological data, geophysical (log and seismic) data, and theoretical rock physics models linking fractures, background rock properties and observable seismic attributes. An example of integrated geological data would be the occurrence of fractures in prior geologic models, also known as a priori probability density functions (PDFs), which help geologists predict where fractures are likely to be before analyzing the quantitative seismic information, offering multiple likely fracture hypotheses. In their study, they used field visual observation of the fracture system and interpolated it to deep inside the rock structure by integrating seismic readings, including a decrease in P- and S-wave velocities, a change in Poisson’s ratio, an increase in velocity dispersion and wave attenuation. They also incorporated PDFs to adjust models’ approximations and natural variability of the rock properties of the modeled rock along with field data and well logs up to 1 mile in depth. Mavko et al. (2005) were restricted to one geophysical method (seismic), whereas the present study
incorporated the electrical resistivity with the azimuthal and Vertical Electrical Sounding (VES) in addition to the seismic refraction method in the azimuthal array and in-line array, and the electromagnetic method in the radial scanning arrangement and grid scanning arrangement.

Spatial fracture intensity (fracture area per by volume) in a site of fractured andesite in LanYu Island of Taiwan was modeled by Lee et al. (2011) using spatial data of fractured networks from Dershowitz et al. (1998), such as orientation, size, intensity, and location. The objective of their study was to assess the safety of a potential low-level and intermediate-level radionuclide waste disposal proposed for their study area. In order to evaluate the utility of modeling groundwater flow, they utilized three models to describe the discrete spatial fractures in synthetic fractured media: Enhanced Baecher’s model, the Levy–Lee Fractal model, and the Nearest Neighborhood’s model.

2.2 Physical Properties of Jointed and Fractured Rock

Crack induced velocity anisotropy in igneous rocks of the White Mountains, New Hampshire was studied by Park and Simmons (1982). Their study approached the velocity of compressional wave expressed as a function of direction in elastic media. In theory, they solve for the problem of a single thin circular crack embedded in an isotropic medium for the long wavelength limit. To create an effective anisotropic medium, they embedded saturated cracks in an uncracked media. Later, they embedded medium dry cracks in this effective anisotropic. To determine velocity anisotropy, they conducted surveys to measure velocity along nine lines in different azimuths spaced at 20°. These surveys were at sites near outcrops of previously mapped joints and had overburden of less than 3 m thick. A 12-channel analog recording system (SIE RS-44) along with geophones spaced 6 m apart were used for the recording of the seismic
signals. The signal was initiated by a 70 kg weight drop system and a 7 kg sledgehammer. Signal travel time were later picked and analyzed using the time term method. The joints at the nearby outcrops were measured and displayed using rose diagrams. They concluded that the in-situ measurement of the compressional wave velocity of the igneous rocks in the White Mountains showed anisotropy. They also found an approximate correlation between crack parameters derived from data using weak anisotropy theory and the mapped joint sets. They noted that preferred microcrack orientation might possibly contribute to the lack of better agreement with the anisotropy of mapped joints. They noted that the crack models did not exactly fit at three of their four sites and attributed this observation to the inhomogeneity that could partially be causing the velocity fluctuations. Their study also found that in order to yield a unique solution for crack parameters, it is better to use inversions from both synthetic data and compressional or shear wave velocities. They displayed their in-line survey results in rose diagrams showing different lines with different lengths representing the velocity of each line in the azimuthal survey. In the present study, a different approach was made to detect joints by designing a survey array named Circular Array Seismic Survey (CASS) in which the impact spot was in the center of the survey circle and its result was later displayed on a rose diagram showing the arrival times of the seismic waves at azimuth intervals of 15 degrees.

Kahraman (2001) investigated how the sound velocity varied with the number of joints and studied the relation between the number of joints and sound velocity for rocks by making field measurements using a Schmidt hammer (a device to measure the elastic properties or strength of concrete or rock, mainly surface hardness and penetration resistance) and testing samples with artificial discontinuity planes in the laboratory. The present study also investigated how joints affect sound velocities. Du et al. (2002) presented estimates of the S-wave velocity
and the crack density at which fractured reservoirs begin to play an important role in oil exploration by using an azimuthally anisotropic model of transverse isotropy with a horizontal axis of symmetry, known as horizontal transverse isotropic (HTI) media to describe fractured reservoirs that contain parallel vertical cracks. Of course, this is a very different technique used in deep seismic reflection surveys for oil reservoirs with near-vertical wave incidence and not applicable to the surface refraction technique with largely horizontal ray paths proposed for use here.

Martí et al. (2006) used P and S-waves to make high resolution seismic tomography to characterize the physical properties of a site in an abandoned uranium mine and make a three-dimensional reconstruction of the fracture networks and their surroundings. The mine is called the Ratones mine, which is one of several uranium mines located in the Albala Granitic pluton in the southwestern Iberian Peninsula in Europe. The method included picking P- and S-wave travel times from a three-component geophone positioned sequentially at a range of depths. A Vibroseis truck occupied shot points at two different radii, 75 m and 150 m, and at 45-degree azimuth intervals from the top of the borehole. The shock energy was recorded by a three-component borehole geophone deployed every 10 m of depth. The authors refer to this as an offset and azimuth variable seismic profile (OVSP), in this case, acquired in a 500 m deep vertical borehole. Poisson’s ratio was considered in their study to account for the non-uniqueness of the P-wave velocity interpretation in terms of rock types. The study concluded that low velocity anomalies were consistent with fractured and altered zones mapped in the study area, and Poisson’s ratio showed high values and low values due to variations in pore space, fracturing, and fluid content. Again, the depth scale of this survey far exceeds what is proposed here for shallow engineering studies.
Payne et al. (2007) described the acquisition and interpretation of broadband (100–4000 Hz) seismic data collected at a borehole test site where extensive hydrological investigations had previously been performed, including in situ estimates of permeability. The Payne et al. (2007) study was conducted on a test site located approximately 10 kilometers north of Beverley in Yorkshire, NE England. The site consists of a homogeneous Cretaceous chalk rock, whose discontinuities due to fractures and bedding planes were already well characterized. The outcrop of this rock showed planes obviously bedded in a horizontal orientation and had a vertical frequency of approximately one per meter. Also observed was a set of steeply dipping joints that extend across most of the rock face showing little displacement in the bedding planes across these joints. This chalk unit acts as an important aquifer. Their seismic data was collected over three boreholes that formed an isosceles triangle using hydrophones and a sparker source. They observed that a zone of high fracture permeability was associated with high values of seismic attenuation of P-waves and attempted to model the seismic attenuation and separate the attenuation due to scattering from intrinsic mechanisms. They concluded that measuring rock permeability in terms of seismic attenuation through means of modeling was not possible because more exact parameters were missing in the modeling process. Payne et al. (2007) studied the attenuation of seismic waves with fractures through modeling and using hydrophones. They concluded that more information is needed to get better results. The present study differed than Payne et al. (2007) in that the azimuthal seismic work was done in surface environment. Several factors including quality of the geophones “plant” or coupling at the surface causes amplitude to vary. Thus, attenuation of seismic waves with fractures was not feasible, especially with single geophones. However, to further study the detection of fractures beneath cover and back up the
resolution of the results obtained collectively, more geophysical methods with linear and azimuthal arrays were integrated in the present study.

Kahraman et al. (2008) evaluated the possibility of determining the fracture depth in rock blocks from P-wave velocities in addition to physical properties of rocks by making laboratory measurements on samples of igneous, sedimentary, and metamorphic rocks from different sites such as rock processing plants, quarries, and natural outcrops in the Nidge, Kayseri, and Konya areas of Turkey. The samples had approximate dimensions of 250 × 150 × 200 mm. Eight repeated measurements of P-wave velocities were run over a sawed fracture parallel to the measurement in each sample with the depth of the fracture being increased each time a measurement was run. The space between the emitter and receiver of the P-wave was kept constant at each measurement. An inverse linear relationship was found from the correlation of the P-wave velocity with the fracture depth of each rock type. They found that the depth of a cut fracture can be estimated from P-wave velocity and recommended to further study the relationship of P-waves velocities and fractures filled with water or another material and investigate the field validity of the method. Results obtained from laboratory conditions in Kahraman et al. (2008) did not reflect the effect of field conditions like fracture filling material or moisture in fractures on measurements of P-wave velocities.

Detecting and modeling subsurface fracture systems in geothermal fields of volcanic rocks of approximately 3 km thick using shear-wave splitting of natural and induced earthquake waves was studied by Tang (2009). Tang’s study analyzed polarizations and time delays of split shear-waves that have been distorted by the anisotropy of the medium through which the seismic waves have propagated in the Krafla and Hengill geothermal fields in Iceland and found that split shear-wave polarizations coincide with the crack system. One of Tang’s study areas was
located inside the Krafla caldera where there is a shallow crustal magma reservoir with an upper boundary at a depth of approximately 3 km, having dimensions of approximately 2-3 km in N-S and 8-10 km in E-W, and being about 0.75-1.8 km thick. Most of the events recorded in the study were events had hypocenters between 1-2 km depth, where deformation of rocks within the near-surface, dike injections, or strike-slip motion along the divergent plate boundary most likely formed the fractures at this depth. The seismic array deployed consisted of twenty stations of three-component seismographs continuously recording the seismic activity in the region surrounding an injection well located 1 km north of a power plant in the area. Tang (2009) concluded that the orientation of the polarization of fast shear-waves along a general E-W direction is consistent with the observed prevalence of a crack system oriented approximately N-S, and the observation of changes in the normalized time delays reflects the influence of fluid injection on the fracture systems. The Tang (2009) study shared similarities with the present study in terms of utilizing seismic methods to detect subsurface fracture systems but differed in terms of depth of these fractures. It also observed the influence of fluid injection on the fracture systems and how it alters the seismic wave arrival times recorded by geophones. The present study aimed at detecting shallow fracture systems buried by several meters of soil, while Tang’s study targeted fractures 1-2 kilometers deep. The methodology was also different from the present study.

2.3 Geophysical Techniques That Have Been Applied

Use of surface and borehole geophysical surveys to determine fracture orientation and other site characteristics in crystalline bedrock terrain was studied by Hansen et al. (1995). In their study, seismic refraction, azimuthal square-array direct current resistivity, borehole radar,
and ground-penetrating radar geophysical surveys were conducted where chlorinated hydrocarbons had been detected in waters from wells completed in fractured crystalline bedrock in Uxbridge and Millville, Massachusetts from August through December 1993. The purpose of their study was to detect the predominant orientation of fractures or fracture zones that may result in significant anisotropy in ground-water-flow characteristics in bedrock, which geophysical methods can indicate and suggest a preferred direction of ground-water flow. In the azimuthal seismic-refraction technique, they collected data from eight seismic lines oriented at equal angular intervals of 22.5° around a common center point at a site. In each line, 24 geophones with 1.5 m spacing were used. Five sets of time-distance data were collected for each line after striking (with a sledge hammer on a plate in the ground) two shots located 1.5 m and 7.6 m from each end of the geophone lines and one shot in the center of the line totaling five shots in each line. Their seismic data analyses were made using the SIPT computer program. In their electrical resistivity square array technique, they used four electrodes driven into ground to form a square configuration from which all their measurements were assigned to the center point of the square. For each square, three apparent resistivity measurements were taken. Two measurements were perpendicular to each other and parallel to the sides of the square, whereas a third was taken diagonally across the square. The two perpendicular measurements provided information on the directional variations of the surface resistivity, whereas the diagonal measurement served as a check on the accuracy of the two perpendicular measurements. For each complete set of azimuthal-profiling data, the array was rotated in equal angular increments of 15° around a common center point. For vertical (depth) variations in apparent resistivity, they expanded the array symmetrically about the center point in increments of the square-array side length by the root of two, making each array sampling a cube of earth with dimensions
approximately equal to the array’s side length spacing. Fracture strike was later on determined graphically by plotting each apparent resistivity for a given size square with its azimuth, in which the principal fracture strike direction was assumed to be perpendicular to the direction of maximum resistivity. Borehole radar surveys included single-hole directional and cross-hole tomography in selected wells, and allowed interpretation of strike, dip, and borehole intersection depth of planner discontinuities. Surface GPR surveys were mostly conducted along roads and managed to show horizontal and sub horizontal fractures or fracture zones at depths up to 15 m in unconsolidated deposits and (30-45) m in bedrock in several locations. Their study managed to identify the orientation of fractures in the area and found that it consists of two primary fractures with probably moderate to high- intersect angle. It also suggested a possible minor secondary fracture set. Fracture porosity, aperture, and depth to bedrock were also determined from the readings of the geophysical methods used in their study. The seismic array in their study was different than the one used in the present study as their technique was to rotate linear arrays about a point in the center, while the array in the present study was circular, with a shot point in the center of the circle.

In a study made by Yeguas et al. (2011), shot data recorded by eight seismic arrays during an active source seismic experiment carried out at Deception Island (Antarctica) in 2005 was analyzed. That study estimated the apparent slowness and propagation azimuth of the first wave arrival of seismic records for what was interpreted as a shallow magma chamber and shallow rigid bodies based on wave propagation properties that allow the seismic wave to favor travelling in high velocity material rather than low velocity material. This behavior of the seismic waves was captured in an experiment designed to obtain a high-resolution, 3-D P-wave velocity model of their study area. They used many seismometers, both on land and on the
seafloor, with an air gun as their active source. The shooting was every 60 s (~150 m) while cruising along a 0.5 km grid. Data was then analyzed from eight selected arrays that were deployed at the most accessible sites in the area using the Zero Lag Cross Correlation (ZLCC) method, in which a grid search is performed in the apparent slowness space that is intended to maximize the array-average cross-correlation of the aligned waveforms. After selecting an adequate set of parameters including filtration, time window, and apparent slowness grid, this time-domain method allowed wave fronts propagating across the array to simulate plane wave fronts and be represented by their apparent slowness vectors, or alternatively by their apparent slowness and propagation azimuths. Yeguas et al. (2011) also analyzed seismic wave arrival times to determine subsurface geologic features using the same principal the present study considered, which is wave propagation properties that allow the seismic wave to favor travelling in high velocity material rather than low velocity material. On the other hand, their approach was different than of the present study in terms of array and scale. They recorded seismic arrival times during an active air gun shooting program while cruising along a 0.5 km grid, while the present study adopted a stationary data acquisition while shots were made by a sledge hammer in the center of 20-30 m diameter circles where geophones were fixed at their perimeter in intervals of 15 degrees.

The following includes work done using various 4-electrode galvanic contact resistivity methods, as well as electromagnetic induction (EM) methods. Some references also involve ground-penetrating radar (GPR) or even less-common methods such as magneto-telluric and controlled-source audio magneto-telluric (CSAMT), all of which can be applied at different azimuths.
Effects of anisotropy on square array resistivity measurements were studied by Habberjam (1972). A terminology was used to describe the mean of the readings of the electrical resistivity measurement for both the alpha and beta orientations in the square array which was azimuthal inhomogeneity ratio (AIR). It was noted that this resistivity mean was less sensitive to orientation than the Wenner resistivity when detecting vertical planes, but on the other hand, it was highly dependent on the orientation of the array. It was discussed that when measuring in areas of dipping strata where anisotropic exists, a large value of AIR was observed when the square array configuration was oriented parallel to the strike and dip of the formations. This observation prompted Habberjam (1972) to investigate the azimuthal inhomogeneity ratio in relation to anisotropy and the effect of orientation on the mean resistivity. The study was conducted on Precambrian and Ordovician rocks of complex geology where extensive folding and thrusting caused steep dipping and pronounced metamorphism in addition to igneous intrusion and numerous dykes. These rocks are found in an outcrop in an area in the Northwest half of an island called Anglesey, Northwest of Wales in the Irish Sea. The square array was situated on a plane surface in an anisotropic half space and where there were bedding planes dipping at an angle. Two techniques were used for estimating the average mean resistivity, one was where the electrical strike direction was known and the second was where the strike was unknown. The study showed that resistivity measurements using the square array configuration are less affected by orientation relatively to the collinear array and that this only applies where non-severe anisotropy occurred. The present study also took into consideration the effects of anisotropy on electrical resistivity measurements using the square array orientation, but also utilized the Vertical Electrical Sounding to supplement the results obtained from the square array.
Behavior of fractures in hard rocks, a study by surface geology, and radial VES method was studied by Mallik et al. (1983). The objective of their study was to apply the radial VES method to help understand the behavior of fractures in hard rocks at depths. A correlation of the general fracture trends of the rocks from surface geology with those determined by radial VES methods to obtain information about the subsurface rock types was also attempted. Their study took place at Manbazar in the Purulia district of West Bengal, India, which has an undulating topography of granitic terrain and is underlain by older granites, amphibolites, and metabasics. Measurements of the attitude of the predominant joint sets have been made in more than a hundred rock outcrops, which were later plotted as a contour diagram of poles of joint planes plotted on an equal area net. The radial VES was conducted in five locations using the Schlumberger configuration along azimuths of E-W, N-S, NE-SW and NW-SE making a polygon diagram that represented the outlining of the VES lines in each location of their study area. Their polygon diagrams generally showed an ellipse indicative of the anisotropic nature of the formation, in which the major axis of the ellipse gives the strike direction of the fracture. This was done after taking into consideration the Paradox of Anisotropy (which affects in-line arrays), which is the apparent resistivity $\rho_t$, measured normal to its strike direction, is less than $\rho_s$, measured along the strike direction, although the true resistivity $\rho_t$, normal to its stratification, is greater than that parallel to the plane of stratification, $\rho_s$ (Bhattacharya and Patra, 1968). For an isotropic homogeneous formation, this polygon will assume a circular shape. However, any deviation from a circle to an ellipse is indicative of anisotropic nature of the formation. The major axis of the ellipse, which can fit any such anisotropy polygon, gives the strike direction of the fracture. Their results showed that the measurements from the radial VES surveys were in good agreement with those determined from the exposed rocks in their study.
area. Using the same concept of a polygon assuming a circular shape in an isotropic homogeneous formation, a square array was used in the current study instead of radial VES to determine joint sets beneath surface. The square array is not affected by the Paradox of Anisotropy.

Similar to Malik et al. (1983) study, Okopoli and Igwe (2013) studied the electrical resistivity anisotropy in fracture delineation and characterization in the Iwaro-Ayepe area, southwestern Nigeria on ancient Gneiss- migmatite complex with ages ranging from mainly Liberian (2800 Ma) to Pan African (600 Ma). Five locations were mapped in their study area, with each comprising four Radial Vertical Electrical Sounding (RVES) carried out along N-S, W-E, NW-SE, and NE-SW. Several polygons plotting the azimuthal resistivity sounding and their corresponding electrode spacing were made for each location. After qualitative and quantitative interpretation of geological and geophysical data namely the strike direction, foliation planes, joint direction and radial vertical electrical sounding, a clear subsurface fracture orientation was brought out.

Taylor and Fleming (1988) applied a rotating Wenner array about a fixed point measuring apparent resistivity as a function of azimuth to study anisotropy, directional connectivity, and porosity of fracture systems in bedrock and clayey till at 60 sites throughout Wisconsin in several lithologies, including gabbro, basal till, dolomite, and fine-grained glacial sediment. They based their research on the fact that a jointed rock is by definition electrically anisotropic and basic resistivity theory must be extended to include anisotropic cases, taking in consideration in their calculations the “Paradox of Anisotropy”, which causes the in-line arrays to show maximum apparent resistivity in the direction of minimum true resistivity (the direction of the fractures) (Telford, 1990). Their results were separated into three categories; the first
showed that the major axis of the apparent resistivity, represented by an ellipse, was coincident with the direction of greatest joint connectivity. Thus, the method indicated the joint set and its orientation very well. The second showed that the major ellipse axis was closely parallel to the mean strike of a prominent joint set, which meant that joint lengths exceeded the electrode spacing. The third showed the major ellipse axis represented the greatest connectivity direction when mean joint lengths were less than the electrode spacing, or when preferred joint orientations were poorly developed. Taylor and Fleming (1988) applied a rotating Wenner array about a fixed point to measure the apparent resistivity as a function of azimuth to study anisotropy, while the present study adopted the square array about a circle center to eliminate the effect of the Paradox of Anisotropy on the readings of the electrical resistivity to detect subsurface vertical fracture planes and display their orientations in a rose diagram.

Lane, Haeni, and Watson (1995) used azimuthal square-array direct-current resistivity soundings to detect fractures in a crystalline bedrock underlying glacial drift in the Mirror Lake watershed in Grafton County, NH. Note that with the square array, the “Paradox of Anisotropy” is avoided, and the direction of minimum apparent resistivity coincides with the fracture direction. They used six square arrays rotated by 15 degrees, which gave 12 unique directional resistivity measurements (180 degrees). An additional six directions are not done, as those positions would give redundant measurements. The avoidance of the Paradox of Anisotropy by using the square array in their study validates the choice of using the square array in the present study to detect joints beneath cover. Variation of saturation in connected rock pores and cracks affects rock electrical conductivity; hence, variation of apparent resistivity of rock under application of pressure was studied by Hao et al. (2002). They experimented on samples from a magnetite quartzite rock using a compressed uniaxial test cell, in which several loading-
unloading cycles were done, and salt solution was injected into cracks of the sample, resulting in a series of true resistivity tomographic measurements that revealed microscopic structure explaining the reason for the changes of apparent resistivity. Their results validate the observations of effects of water saturation on the readings obtained in the present study. Using electrical resistivity and ground penetrating radar (GPR) imaging, a study of factors controlling storage and percolation of ground water for hydrogeological purposes of a fractured bedrock aquifer in crystalline terrains located in Caićara farm, near Ecuador city, in NE Brazil was conducted by da Silva et al. (2004). They obtained data from geophysical profiles using the Schlumberger array done approximately orthogonal to a creek. The study area was a hard rock terrain where soil cover was up to 8 m thick and where high resistivity contrast usually occurred between fresh rock and saturated zones. Some GPR profiles were also obtained over the dry quartz-sand soil. They did not make azimuthal measurements, but instead were able to make contour maps from their profile data and thus interpret the positions and orientations of the major fault zones and lithologic boundaries. There was some experimenting done in the present study with GPR in the Jackson location, but results showed low penetration, therefore, they were later discarded.

Near-surface cavities and subsurface voids were studied by Cardarelli et al. (2010) to estimate cavity size and evaluate the overburden thickness. They assessed the risk of collapse by using electrical resistivity tomography and seismic refraction tomography data, which were integrated in a joint interpretation process for cavity location in the city of Rome. Similar to the present study, Cardarelli et al. (2010) integrated electrical resistivity and seismic refraction methods to determine discontinuities in rocks beneath surface, but they focused on near-surface cavities and subsurface voids, while the present study focused on joint sets beneath cover.
Electrical resistivity tomography (ERT), also known as electrical resistivity imaging, a geophysical technique used for imaging sub-surface structures from electrical measurements made at the surface with a programmable multi-electrode array, was used by Zhu et al. (2009). This technique is considered a reliable tool for environmental and engineering site investigation, such as detection of pollution, hydrogeological investigations, and active landslide investigations. Zhu et al. (2009) used this technique for detecting and imaging subsurface structures like water-saturated buried faults in Zibo City, Shandong province, China, to better understand the seismic activity beneath that region. Their resistivity data was acquired along two survey lines over the Zhangdian-Renhe fault, which is an active, northwest-trending normal fault with a left-lateral strike slip component, and extending about 50 Km. The fault is buried under an overburden of Quaternary strata ranging in depth from several meters to 100 m. The bedrock underlying the overburden is mainly composed of strongly and medium weathered sandstone, medium weathered mudstone, and conglomerate. Their study concluded that a fault should only be interpreted when the low resistivity zone extends from the deep to the near-surface terrain, while a near-surface low resistivity zone that does not extend to the deep should not be interpreted as a fault. The electrical resistivity method is reliable in detecting faults and fractures through measuring resistivity in fractures and faults that are saturated in water. This principle is also applied in the present study and the near-surface resistivity for detection of fractures or joints has been investigated.

Use of the azimuthal resistivity technique for determination of regional azimuth of transmissivity was studied by Carlson (2010). The purpose of the study was to determine the trend of joint fractures and indicate which would be the dominant set if more than one set were present. The study also proposed the exploitation of joint properties studied locally in studies
done on a regional scale. The study was conducted at 17 sites in Milwaukee County in Wisconsin. The method included conducting 26 azimuthal resistivity surveys at 17 different sites of Silurian-Devonian dolomite with less than 15 m of overburden. The results were then analyzed (using Gopher resistivity-modeling program) and compared with numerous direct observations of joints at 24 sites throughout southeastern Wisconsin and with transmissivity results from 14 multiple-well-aquifer tests conducted in nearby Mequon, Wisconsin. After determination that a site was free of wires and pipes, one or two Wenner array resistivity soundings were conducted at each site. The second resistivity sounding was conducted perpendicular to the first using similar electrode spacings. Apparent resistivity was measured along 12 azimuths by rotating 15° about a fixed center point relative to due north. The study took in consideration the effect of the Paradox of Resistivity noted by Taylor (1982), and Taylor and Fleming (1988) studies in which the results would show an ellipse displaying highest apparent resistivity in the direction of the joint trend, whereas the lowest apparent resistivity was displayed perpendicular to the joint trend. Results showed two apparent resistivity ellipses, one with major axis oriented northeast-southwest and another oriented northwest-southeast. A third result showed two peaks of apparent resistivity that were approximately 90° from each other. The first result was interpreted as a dominant joint set running NE-SW; the second was a dominant joint set running NW-SE, while the third result meant that there were two significant joint sets in the study area. The Carlson (2010) study concluded that azimuthal resistivity surveys are a useful and reliable method for determining the orientation of a pair of regional joint sets within the Silurian-Devonian dolomite in Milwaukee County in Wisconsin. Another conclusion was that results from azimuthal resistivity surveys are similar to those from multiple-well-aquifer tests, in terms of determination of two possible trends of preferred flow of water through two dominant
sets of joints, which are roughly perpendicular to each other. The study also found that the average of results from azimuthal resistivity surveys closely match results for joints orientation and maximum of transmissivity. The study also noted that the trend of horizontal anisotropy of hydraulic transmissivity in the studied area was determined better using azimuthal resistivity surveys compared with direct observations of joint orientation, and that the surface azimuthal electrical resistivity survey method can also be successfully used for regional-scale geotechnical and hydrogeological studies. The present study shares the same principle of determining dominant joint set with electrical resistivity but using the square array. These results, unaffected by the Paradox of Resistivity, will show an ellipse displaying highest apparent resistivity in the direction perpendicular to the joint trend, whereas the lowest apparent resistivity is displayed parallel to the joint trend. However, the present study has taken in consideration the water content or moisture of the joints and its effects on the results. Use of 2D azimuthal resistivity imaging in delineation of the fracture characteristics in the Dammam aquifer within and outside of the Abu-Jir fault zone, central Iraq, was studied by Al-Zubedi and Thabit (2016). The Dammam aquifer is a confined aquifer and a productive hydrogeological unit that is highly fractured. Forming this aquifer are variable carbonate rocks of different ages and thicknesses. Their ages range from Paleocene - early Eocene to Lower - Upper Eocene (with thickness ranging from 70 m to 121 m), and Lower Miocene (with thickness ranging between 10 m to 20 m). The unit is covered by an overburden of 1 m - 2 m in thickness. Their readings were conducted in 11 locations distributed within and outside of the Abu-Jir fault zone. In each location they employed a Wenner–Schlumberger array along four lines with 45° interval between each line (N-S, E-W, NE-SW, and NW-SE), symmetric about a common center point. Each line consisted of 60 electrodes with interval spacing of 10 m between electrodes and measurements.
were taken with a SYSCAL pro+ instrument. They opted for the Wenner-Schlumberger array after running the modeling software RES2DMOD and processed the inversion of their readings with software RES2DINV version 3.59, using its robust inversion option. They concluded that the Wenner-Schlumberger array was the most suitable electrode array when both vertical and horizontal structures were present in the subsurface. They also concluded that their 2D azimuthal resistivity technique was very successful in marking out the subsurface fracture extension in all directions. The Al-Zubedi and Thabit (2016) 2D azimuthal resistivity technique differs from the technique adopted in the present study because their study is time and labor consuming in addition to covering only four azimuths out of the 180 degrees possible.
CHAPTER III

METHODOLOGY

3.1 Introduction

For detecting sub-vertical failure planes in joint systems and their orientation beneath thin cover, this research has adopted geophysical methods using digital instruments, and classical Brunton compass strike and dip measuring method for measuring joint systems in exposed areas. The geophysical methods chosen for the current study were the seismic refraction method, the electrical resistivity method (ER), and the electromagnetic (EM) method. Surveys of these methods played two roles in the investigation. In one role, survey applications were used to directly detect any anomaly that can lead to a potential occurrence of a sub-vertical failure plane in the joint system beneath cover. On the other hand, the other role was to check the suitability of the measurement site by verifying that the surveyed area was clear of any foreign object that might interfere with the other survey readings. In this case, the seismic refraction method, and electrical resistivity were used for the detection of potential sub-vertical planes in the joint systems beneath cover of the study area, while the electromagnetic method was used to verify the absence of metallic conductors buried in the soil. Linear and azimuthal arrays for the chosen methods surveys were used serving different aspects of the detection of vertical planes beneath cover. In the seismic refraction method, a Circular Array Seismic Survey (CASS) approach is suggested.
3.2 Seismic Refraction Method

3.2.1 Principle

The seismic refraction method was used to produce acoustic waves, Primary or Compressional Waves (P-waves) and Secondary or Shear Waves (S-waves,) that were sent into the subsurface by hammering on a steel striker plate. Travel times of these waves from source to receivers were recorded to indicate any geophysical boundaries in the subsurface. A delay in travel time for waves at a certain azimuth indicated that fractures or joints may have been crossed, or that the overall rock texture is anisotropic.

Seismic waves are sound waves that are refracted or bent by layers within the ground. These layers have different elastic properties (e.g., rigidity) and densities. The P-wave is the seismic wave most often employed in seismic prospecting, but S-waves are sometimes also used. The P-wave is composed of alternating compressions and dilatations in the direction of propagation, and S-wave is composed sinusoidal waves with particle motion perpendicular to the propagation direction. The velocity of P- and S-waves passing through a homogeneous, isotropic, and perfectly elastic rock or soil is as follows:

\[
V_p = [(K + 4/3G)/\rho]^{1/2} \quad \text{Equation (3-1)}
\]

\[
V_s = [G/\rho]^{1/2} \quad \text{Equation (3-2)}
\]

Where: \( V_p \) = P-wave velocity,

\( V_s \) = S-wave velocity,

\( K \) = Bulk modulus,

\( G \) = Rigidity modulus, and

\( \rho \) = Density.
These expressions illustrate the dependence of P- and S-wave velocity on elastic constants (bulk modulus and rigidity modulus) and the density (Ahmed, 2002). Equations 3-1 and 3-2 can be found in Burger (1992).

Analysis using the time-intercept method (the simplest method) is conducted by plotting first arrival times on a forward and reversed time-distance graph, measuring slopes, and intercept times, and then computing layer velocities and thicknesses.

3.2.2 Hypothesis

The hypothesis here is that the amplitudes of the P-waves would be decreased if the wave crossed joints that were air-filled, and less so for water-filled joints. The travel time of S-waves would be increased, and amplitudes of S-waves would be decreased by crossing air or water-filled joints along their paths.

3.2.3 Survey Arrays

The seismic refraction method was employed in two arrangements (and with a sledgehammer source), a linear array, and an azimuthal array.

3.2.3.1 Linear Seismic Array

In the linear seismic or in-line seismic array, 24 geophones were used for standard reversed refraction (plus a mid-shot) measurements using first P-wave arrivals. This was done at each proposed site to determine thickness of overburden and absence of appreciable bedrock topography. It was also used to identify the arrival times of later phases, such as Vertically Polarized Shear (SV) and Surface Waves (the last is not included in the current study). The first
arrival data were inverted to obtain thickness of the soil or glacial/alluvial overburden, and hence depth to the target bedrock. Seismic velocities of these upper layers and the bedrock were also determined in this step. With this information, the appropriate minimum geophone distance from the shot point (radius of ring) was determined for the next step.

3.2.3.2 Azimuthal Seismic Array

In the azimuthal seismic array or Circular Array Seismic Survey (CASS), 24 geophones were deployed in a circular pattern, with one geophone at every 15 degrees of azimuth. This nicely optimizes the use of a 24-channel system and a pair of 12-channel spread cables with at least a 5 m take-out spacing. The impact or shot point was at the center of the circle. Vertical geophones record Vertically Polarized S-waves (SV), while horizontal geophones record Horizontal Polarized S-waves (SH). Illustration of the CASS is shown in Figure. 3-1. The ring radius was generally chosen to be more than twice the crossover distance, to allow sufficient separation of the different waves at the constant distance of the ring geophones from the shot point. For the current study, all the ring radii were either 10 or 15 meters, with the separation of the takeouts on the spread cable defining the upper limit. In the current study, the terms azimuthal seismic or CASS will be used when referring to this array.
With a vertical hammer blow, a wavefront was generated consisting of three main groups of waves, P-waves, S-waves, and Surface Waves (the last is not included in the current study). The wavefront responded differently to the presence of fractures along the travel path. Where fractures existed, the wavefront was delayed, and where fractures did not exist or were less frequent, the wavefront was not delayed, as shown in Figure 3-2.

Figure 3-1: Diagram showing the Circular Array Seismic Survey (CASS) of 24 geophones with spacing of 15° azimuth spread on the perimeter of a circle with a fixed radius.
Figure 3-2: Diagram showing a wavefront traveling in different speeds after impact in the azimuthal array of 24 geophones with spacing of 15° azimuth evenly distributed on the perimeter of a circle with a fixed radius and an impact point in the center, also referred to as the Circular Array Seismic Survey (CASS).

3.2.4 Equipment

The seismic surveys in this research were conducted using equipment provided by the Geosciences Department at WMU. These systems were all digital and had the capacity to record large amounts of data in internal memory. The main system used for the seismic survey was the Geometrics RX-24 Seismograph, with spread cables for up to 5 m geophone spacings, impact trigger, ancillary wires, and battery. Spread cables were deployed such that Channel 1 was the North position, and channel numbers increased clockwise around the circle. Refraction data processing was done using SIP software installed in the geophysics computer lab in the Geosciences Department at WMU. Filtering and further examination of later phases was done using Interpex IXSEG2SEGY. Results were displayed in an azimuthal circle (rose diagram) by using program AZPLOT.
3.2.5 Error Analysis

In the rose diagrams, a percentage of difference between the maximum and minimum values of picked times values are reflected in the diagram or ellipse outline. In this case, each ring of the rose diagram from outer to inner represents an increment of the difference percentage value. The bigger the difference the higher anisotropy is measured.

3.3 Electrical Resistivity Method

3.3.1 Principle

The electrical resistivity recording measures the resistivity (3-D resistance) of the rock material when an electrical direct current (low frequency or commutated DC) passes through it. The current is transmitted between electrode pairs and the potential drop is measured between another electrode pair (Dahlin, 2001). A decrease in current, in the vicinity of the potential-measuring electrodes, indicates a diminished electrical conductivity in the rock material, therefore the electrical resistivity method is regarded as superior theoretically to most other electrical methods because it yields quantitative results by using a controlled source of specific amplitude and geometry (Telford, 1990). Measured resistivity is referred to as apparent resistivity and is commonly expressed as Ω-m (Ohm-meters). The apparent resistivity is the resistivity value of an equivalent uniform half-space that creates the measured potential difference at the earth’s surface. Anomalous zones resulting from inhomogeneities in the ground, such as conductive layers, can be inferred because they distort the normal potentials (potentials arising from current flowing through a uniform half-space). In Vertical Electrical Soundings (VES), electrode spacing is slowly increased about a center point and the apparent resistivities
are measured and plotted as a function of electrode spacing. Inversion programs can (non-uniquely) invert the apparent resistivity vs. electrode spacing to models of true resistivity vs. depth.

3.3.2 Hypothesis

It is hypothesized that open space in rock joints would interrupt electricity current flow in dry conditions and would enhance it in wet conditions. In general, moist fissures conduct electricity better than tight, low-porosity bedrock, so the electrode pattern most aligned with the direction of fissures should show the lowest electrical resistivity.

3.3.3 Survey Arrays

The electrical resistivity system was also deployed in two different arrays. The first was linear or in-line, and the second was azimuthal.

3.3.3.1 Linear Array

This array consists of expanding 4-electrodes, in this case using the Schlumberger array, which constitutes a Vertical Electrical Sounding, (Dahlin, 2001). This was done to determine the resistivity layering and, similar to the seismic refraction method, gave a second or independent measure of the depth to bedrock, water table, or other discontinuity when interpreted. Using this information, the proper minimum electrode spacing to reach the bedrock for the next step (the azimuthal ring survey) could be determined. If the interface determined by resistivity corresponded to the base of the soil layer, its depth should be very similar to that determined by
the seismic refraction method. In the current study, the term Schlumberger VES will be used when referring to this array.

3.3.3.2 Azimuthal Array

Just as in the seismic refraction method, and using the same circles, an azimuthal resistivity survey was done using the square array, rotating about a common center point, as illustrated in Figures. 3-3, 3-4, and 3-5. The square array was the array of choice for the azimuthal work. For this array, A and B represent the current electrodes, and M and N the voltage electrodes. The same 15-degree interval that was used for the seismic work was used here. The electrode spacing “a” was chosen to be considerably larger than the overburden thickness as determined by the VES interpretation and by the seismic refraction method. After the 3 readings corresponding to these 3 figures were completed, the electrodes were rotated 15 degrees clockwise, and another set of 3 readings were taken. This continued until the 6’th position, a 90 degree total rotation from the initial configuration. This set of readings provided the reciprocal measurements that could be compared with the measurements of the initial orientation, thus providing a measure of quality control (QC). The square electrode array was used to measure directional anisotropy (which is assumed to be caused by a dominant fracture pattern or patterns). The square array is preferred for azimuthal studies because it does not suffer from contrary indications caused by the Paradox of Anisotropy, as linear arrays do (Busby, 2000). In the current study, the terms azimuthal resistivity or rotating square array will be used when referring to this array.
Figure 3-3: Square array as used in the azimuthal ER method at zero rotation, or S-N azimuth in the alpha (α) configuration.

Figure 3-4: Square array in the azimuthal ER method measured in the beta (β) configuration, which is the W-E or 90° measurement.

Figure 3-5: Square array in the azimuthal ER method at 0 rotation, but measured in the gamma (γ) configuration (which is simply an error check, as well as a measure of anisotropy). In an isotropic medium the result should be zero.
3.3.4 Calculations

The electrical resistivity calculations for the square array were computed by using the following equation:

\[
\rho = \frac{2\pi a}{(2-2\sqrt{2})} \frac{V}{I} \quad \text{Equation (3-3)}
\]

Where: \(\rho\) = Electrical resistivity (rho) in Ohm-m,

\(a\) = Side of square

\(V\) = Voltage in mV,

\(I\) = Current in mA

3.3.5 Equipment

The electrical resistivity surveys in this research were conducted using equipment provided by the Geosciences Department at WMU. This system was digital and had the capacity to record large amounts of data in internal memory. The main system used for the electrical resistivity survey was the Iris Syscal R-2 Electrical Resistivity System, with 250 Watt power converter, cables, electrodes, and battery. Data processing was done using software installed in the geophysics computer lab in the Geosciences Department at WMU, such as SCHLINV6 and RHOAZ.

3.3.6 Error Analysis

In the electrical resistivity readings, the QC reading is taken when rotating the square array in the 180° position, which verifies the reading taken in the first array direction at N. This helps reduce the anisotropy effect, therefore, big difference in electrical resistivity reading will show a sharp ellipse shape towards a preferred direction or directions representing a major
anisotropy effect versus a subtle difference will yield a rather round or circular diagram shape indicating strong isotropy. The QC procedure might also indicate human error in field or laboratory work which provokes an investigation to the source or cause of error.

3.4 Electromagnetic Survey

The electromagnetic survey was utilized in this research as a screening method to look for buried metallic objects that, if present, would mean that a site would be unsuitable for further work with electrical resistivity methods. It was also used in azimuthal fashion at some sites to test it as another tool for measuring electrical anisotropy.

3.4.1 Principle

In this method, continuous-wave or transient electromagnetic fields are propagated in and over the earth. When a survey is conducted, inductive coupling occurs between the transmitter, receiver, and buried conductor in the EM field situation. This results in a trio of electric circuits coupled by electromagnetic induction. Source energy in a few EM ground systems may be introduced into the ground by direct contact. However, inductive coupling is generally used and invariably the signal is received at the detector by induction (Telford, 1990). Subsurface electrical measurements obtained by the electrical resistivity method are expressed in terms of resistivity, in contrast with the measurements obtained by the EM method, which reports its results in terms of conductivity expressed in milli-Siemens per meter (mS/m) (Ahmed, 2002). Most EM instruments work by transmitting an alternating current from a coil that is referred to as the transmitter (Tx) and then received by another coil, referred to as the receiver (Rx). The Tx and Rx are separated from each other by a fixed distance. When the alternating current is passed
through the Tx at a known frequency, a time-varying magnetic field, known as the primary magnetic field, is produced. This magnetic field induces small time-varying electric currents (eddy currents) in the earth, which in turn generate their own secondary magnetic field. The receiver coil senses both the primary and secondary magnetic fields. EM units are commonly operated in many different geometries, the most common being the horizontal dipole mode, and the vertical dipole mode. In the horizontal dipole orientation (vertical loops), the magnetic field vector at the TX is horizontal, whereas in the vertical dipole orientation (horizontal loops), the magnetic vector points up and down (Ahmed, 2002), Figure. 3-6.

**Figure 3-6:** Vertical and horizontal dipole field configurations for inductive electromagnetic technique, after Friedel et al. (1990).

Ground conductivity, also referred to as apparent or terrain conductivity, is measured by computing the difference between the amplitudes and phases of the primary and secondary fields. This calculation is done when induction numbers are much less than unity and the magnitude of the secondary magnetic field becomes directly proportional to the ground conductivity. The apparent conductivity is given by the following expression:
\[ \sigma = \frac{4}{\omega u s} \frac{H_s}{H_p}, \text{ Equation (3-4)} \]

Where: \( \omega \) = angular frequency, \( 2\pi f \),

\( u \) = permeability of free space,

\( s \) = intercoil spacing,

\( H_s/H_p \) = ratio of secondary magnetic field to primary magnetic field, and

\( \sigma \) = apparent conductivity

3.4.2 Equipment

The electromagnetic surveys in this research were conducted using equipment provided by the Geosciences Department at WMU. The system used was the Geonics EM31-MK2. It reads ground conductivity (quadrature-phase) and magnetic susceptibility (in-phase) measurements directly from an integrated DL600 data logger (which can be easily removed from the console for data transfer). Apparent conductivity is measured in milliSiemens per meter (mS/m) and the in-phase is expressed as the ratio of the secondary to primary magnetic field in parts per thousand (ppt). The inter-coil spacing is 3.66 m and operating frequency is 9.8 kHz. Data processing was done using software installed in the geophysics computer lab in the Geosciences Department at WMU, such as Microsoft’s Excel and Golden’s Surfer.

3.5 Physical Measurement

Physical measurements documenting the orientations and spacing of the sub-vertical failure planes at the adjacent bedrock exposure locations were done by using a Brunton compass, and photography. These measurements were later used to compare with or verify the results from
the instrumental measurement by making a correlation between the geophysical results and the measured strikes and dips of the observable joint systems in and near the study areas.
4.1 Introduction

The study areas were determined based on three factors; location, geological setting, and fieldwork feasibility. The locations chosen depended upon logistics and permission for access to specific properties. The areas immediately surrounding abandoned rock quarries are ideal for this type of work. Active quarries have excessive seismic and electrical noise, as well as scheduling, liability, and security problems. Geological setting and lithology were also taken in consideration, where commonly jointed rocks such as sandstone and limestone were preferred. Fieldwork included site choosing in location to determine in-situ measuring feasibility, and site preparation such as clearing roads to sites and clearing extra vegetation on sites.

4.1.1 Location of Study Areas

Two test areas in inactive quarries were chosen: one near Jackson, and the other north of Alpena, both in Michigan. Another location was selected near a river gorge in Grand Ledge, Michigan. The study area locations are shown in Figure 4-1.
4.1.2 Geological Setting of Study Areas

Geologically, the study areas fall in the Michigan Basin, which geographically includes all of Michigan’s southern peninsula and part of its northern peninsula and parts of Wisconsin, Illinois, Indiana, Ohio, and Ontario. Structurally, the Michigan Basin is a slightly ellipsoidal autogeosyncline, which was relatively isolated from the adjacent basinal areas by tectonic elements that exhibited positive relief (Shideler, 1969). The Michigan basin has a radius of 482 km and is nearly 5 km in depth, and it is suggested that it was formed by episodes of irregular basin-centered subsidence separated by periodic regional tilting due to effects of Appalachian orogenic activity (Howell and van der Pluijm, 1990). The basin is bounded on the north by the Canadian Shield, on the east and southeast by the Algonquin and Findley Arches, on the southwest by the Kankakee Arch, and on the west and northwest by the Wisconsin Arch and Wisconsin Dome (Ells, 1969), as shown in Figure 4-2.
Figure 4-2: Total thickness of Phanerozoic sedimentary rocks in the Michigan basin region. Contours in kilometers. Star is location of the well that was used for subsidence analysis (after Haxby et al., 1976; Nunn and Sleep, 1984, in Howell and van der Pluijm, 1990).

A rift valley of Keweenawan age (about 1100 m.y.) having a strongly positive gravity anomaly and flanking lows, crosses the basin from Northwest to Southeast (Hinze, Kellogg, and O'Hara, 1975). Distant from the rift valley axis, the basement is composed of granitic and metamorphic rocks of about 1200-1500 m.y. in age (Hinze, Kellogg, and O'Hara, 1975); (Van Schmus, 1976). Faulting and alkaline igneous activity occurred in the North Bay region of Ontario and eastward in early Cambrian time, some 565 m.y. ago (Doig, 1970). Basin subsidence occurred at different rates in a time span of 500 m.y. creating a sediment column of Phanerozoic sediments (shallow water sediments) (Sleep and Sloss, 1978). The subsidence rate averaged about 10-20 meters per million years throughout the geological history, with the exception of the Late Silurian and Early Devonian, when the rate was more than 100 meters per million years (Wilson, Budai, and Sengupta, 2001). The present characteristic shape of the Michigan basin is exhibited by strata of Middle Ordovician age, 462 m.y. Cambrian and the extremely eroded Lower Ordovician sediments underlie the basin. On the other hand, the youngest sediments that
record the subsidence are of Pennsylvanian age, 300 m.y. ago (Nunn, 1981). The dominant lithologies of the Michigan basin are limestone and dolomite or interbedded limestone, dolomite, argillaceous limestone or dolomite and shale. Sandstone is not widely spread throughout the basin. Carbonate-evaporite cycles, including salt deposits make up the thick series of the Silurian Salina Group. Anhydrite can be found in thin beds in the center of the basin (Nunn, 1981).

Throughout geologic time, the Michigan basin has received various sediments from sources in surrounding areas depending on the amount of orogenic activity. The widely varying thickness of sedimentary units from one area of the Michigan basin to another was highly dependent on the shifting and truncation of units, which in turn have affected the thickness and distribution of Pennsylvanian rock units (Venable et al., 2013). In the center of the Michigan basin in Midland County, the Pennsylvanian units are over 213 m in thickness, whereas in Jackson County near the sub crop limit in the southern part of the basin, the units are 9 m or less (Cohee, Macha, and Holk, 1951). Outcrops showing complete sections of Pennsylvanian units and associated contacts with underlying Mississippian strata do not occur, thus most knowledge of the relationships of these two systems is derived from subsurface studies (Ells, 1979). In the Lower Peninsula, where preglacial valleys are overlain by moraines, glacial deposits can reach up to 365 m in thickness, whereas they may be absent in other areas (Ells, 1979).

4.1.3 Fieldwork at Study Areas

4.1.3.1 Site Suitability Investigation

Fieldwork included choosing sites where the ground was even and not contaminated with foreign objects in the subsurface, like metal, that might affect or obscure the instrumental
measurements. Detection of joints beneath the surface started by experimenting with Ground Penetrating Radar (GPR) at one site, but results were shortly dismissed due to poor resolution of sub-vertical joints. Further investigation of the suitability of a site was done by several techniques. Thickness of overburden (depth to hard rock) was obtained with an in-line seismic refraction array of vertical geophones. This was usually applied with 1-meter geophone spacing and hammer shot points off each end. These data were used to calculate the depth to hard rock, as well as P-wave seismic velocities of the soil and rock layers. Using these data, the optimal radius of the azimuthal circle was determined, so as to provide refracted arrivals distant at least 3 times the cross-over distance (on the T-D diagram). The vertical geophones were replaced with transverse horizontal geophones and the reversed refraction profile was repeated with horizontal hammer blows. In this way, the first shear wave arrival time could be identified on these horizontally polarized (SH) records. With that knowledge, the first SV arrivals could then be identified on the previous vertical refraction records, and hence on the azimuthal seismic records where there was a constant shot-geophone distance. This exercise was also used to verify that the thickness of the soil over rock was suitable, ie, in the range of approximately 1-3 meters. Finally, the seismic refraction was essential to confirm that the rock surface (the refractor) was horizontal or parallel to the land surface.

To further verify that the subsurface was suitable for these azimuthal measurements, at least one electrical resistivity in-line VES measurement using the Schlumberger array (Schlumberger VES) was made along at least one azimuth. In most cases, the large contrast in resistivity between the porous soil and the low-permeability rock beneath produced a VES curve (log of measured resistivity vs. log of current electrode spacing) that could be readily interpreted
(inverted) to give the depth to bedrock, as well as the resistivity of the soil and of the underlying rock.

A final site suitability measurement was made at some sites using the EM induction method (Geonics EM-31). This could be used along either parallel lines over the proposed site, or radial lines of the azimuthal setup. Any buried wire, cable, metallic pipe, or conduit would clearly show a strong anomaly, whereas a ‘clean’ site would show very little lateral variation.

4.1.3.2 Instrument Setting at Sites

Seismic, electrical resistivity and electromagnetic surveys were conducted in most of the sites chosen. For surveys conducted with azimuthal arrays, a circle of appropriate diameter was surveyed with a transit, with angular spacing of 15 degrees and azimuths marked on stakes clockwise relative to magnetic north. For seismic measurements, vertical geophones were inserted in the ground at the stakes marking the circle. A sample of the circle layout is shown in Figure 4-3.

![Figure 4-3: Markers on azimuths spaced 15 degrees around a circle with geophones shown at Rockport Site 1.](image-url)
Measurements of wave arrival times were acquired by making vertical hammer blows on a metal sheet laid flat on the ground at the center of the circle. A sample of the hammer blowing is shown in Figure 4-4.

![Figure 4-4: Vertical hammer blows applied on a metal plate to produce a seismic wave at Rockport Site 1.](image)

For azimuthal ER measurements, the square array was used rotating clockwise on the same circle to acquire the measurements around 180 degrees. In the seismic in-line array, 24 geophones inserted in the ground with spacing 1 m were used for standard reversed refraction method.
4.2 Jackson Quarry

4.2.1 Location of Jackson Quarry

The Jackson Quarry location is 68 miles east of Kalamazoo, Michigan, and 3.7 miles NE of Jackson, Michigan. This small, inactive limestone quarry belongs to a private owner, and most of the quarry is filled with water. Instrumental (geophysical) measurements were conducted at sites around the western side of the quarry where the ground was relatively flat, and soil or transported overburden cover was present. Additionally, strikes and dips of sub-vertical fractures were measured with the Brunton compass on available exposures around the flooded quarry. There were four sites chosen for instrumental measurements and three for joint measurements. The instrumental sites were marked with numbers, while the joint sites are marked with letters as shown in Figure 4-5.

Figure 4-5: Google satellite image of the Jackson Quarry location showing instrumental sites marked in numbers and joint measurement sites marked in letters.
Site coordinates where geophysical measurements were made and at the Jackson Quarry location are shown in Table 4-1, while coordinates where joints were measured are shown in Table 4-2.

Table 4-1: Site coordinates for instrumental measurements at the Jackson Quarry.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (ft)</th>
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<tbody>
<tr>
<td>Jackson Site 1</td>
<td>42°19'14&quot;N</td>
<td>84°22'46&quot;W</td>
<td>929</td>
</tr>
<tr>
<td>Jackson Site 2</td>
<td>42°19'12&quot;N</td>
<td>84°22'49&quot;W</td>
<td>927</td>
</tr>
<tr>
<td>Jackson Site 3</td>
<td>42°19'27&quot;N</td>
<td>84°22'50&quot;W</td>
<td>919</td>
</tr>
<tr>
<td>Jackson Site 4</td>
<td>42°19'24&quot;N</td>
<td>84°22'50&quot;W</td>
<td>921</td>
</tr>
</tbody>
</table>

Table 4-2: Site coordinates for joint measurements at the Jackson Quarry.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jackson Site A</td>
<td>42°19'23&quot;N</td>
<td>84°22'49&quot;W</td>
</tr>
<tr>
<td>Jackson Site B</td>
<td>42°19'18&quot;N</td>
<td>84°22'49&quot;W</td>
</tr>
<tr>
<td>Jackson Site C</td>
<td>42°19'16&quot;N</td>
<td>84°22'45&quot;W</td>
</tr>
</tbody>
</table>

4.2.2 Geological Setting of Jackson Quarry

The Jackson Quarry area is dominated by the Bayport limestone, which is of Chesterian (Late Mississippian) and Morrowan (Early Pennsylvanian age (Towne, 2013)), and overlays the Michigan Formation (Newcombe, 1933). The Michigan Formation and the Bayport limestone units vary greatly in thickness, which is attributed to uplift along the Findley and Kankakee Arches that isolated the basin from neighboring depocenters during Late Mississippian time (Cohee, 1979). Lack of reported Chesterian fossils after the deposition of the Bayport limestone and before the Saginaw Formation is attributed by Newcombe (1933) and Cohee (1979) to the post-depositional tectonic uplift that produced the discontinuous nature of the Bayport limestone. However, Vugrinovich (1984) suggests that the Bayport limestone was deposited in the Middle Mississippian, (Chesterian) based on lithological interpretations derived from wire-line logs, core-cuttings, and comparisons with similar strata in the Illinois basin. Thickness of the Bayport limestone unit varies from 10 to 100 ft. (Lasemi, 1975; Lilienthal, 1978; Vugrinovich, 1984).
Previous studies covered the Bayport limestone in outcrops in the Wallace Stone Quarry in Huron County; the Parma Quarry in Jackson County; and Bellevue Quarry in Huron County. Studies from Bacon (1971); Vugrinovich (1984); and Ciner (1988) describe the lithology of the Bayport formation in the outcrops as a heterolithic mixture of cherty and fossiliferous limestone, dolomite, siltstone, and sandstone. Two facies within the Bayport limestone have been reported by Lasemi (1975): (1) a brown tan dolomite he attributes to a tidal flat origin, and (2) a gray fossiliferous limestone.

4.2.3 Field Work at Jackson Quarry

Several exploration trips were made to Jackson Quarry in May and June 2010 after acquiring permissions from the owner of the quarry. On May 19, 2010, fieldwork started at Site 1 (southern side of the quarry) experimenting with GPR and Schlumberger VES. Results from GPR were later dismissed due to poor image resolution from wet ground from rain two days earlier, and inability to show sub-vertical joints. Weather conditions for fieldwork days at the Jackson Quarry are shown in Table 4-3.

<table>
<thead>
<tr>
<th>Date</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/19/2010</td>
<td>Sunny, 75°F, nice, wet ground from rain 2 days earlier.</td>
</tr>
<tr>
<td>6/08/2010</td>
<td>Cloudy, rained 2 days before. Some standing water.</td>
</tr>
<tr>
<td>9/24/2010</td>
<td>Cloudy, 75°F, nice, moist soil from much rain 2 days earlier.</td>
</tr>
</tbody>
</table>

On June 8, 2010, an azimuthal circle of 20 m diameter was marked at Site 1, in which the azimuthal ER survey was conducted. Another azimuthal circle, but of 20 m diameter was established at Site 2 (south of site 1) where the azimuthal ER survey was conducted.

On September 24, 2010, the in-line seismic survey was conducted at Site 3 as the first step in the seismic characterization of the site. Later on, an azimuthal circle of 20 m diameter
was established on Site 3 (northwestern side of the quarry) where both the azimuthal ER and azimuthal seismic surveys were conducted. On the same day, the in-line seismic survey was first conducted at Site 4. After that, a standard azimuthal circle, this time with 30 m diameter, was established at Site 4 (Western side of the quarry). Utilizing this circle as at the previous sites, the azimuthal ER and azimuthal seismic surveys were conducted at Site 4. A summary of the field activities arranged by date and site at the Jackson Quarry location are shown in Table 4-4. Each method conducted at the given date is marked by a “X” sign. Summaries of field activities conducted on other locations are also presented in tables using the same fashion as the Jackson Quarry location.

Table 4-4: Field activities arranged by date and site and at the Jackson Quarry.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Circle Diameter (m)</th>
<th>Azimuthal Seismic</th>
<th>In-Line Seismic</th>
<th>Schlumberger VES</th>
<th>GPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/19/2010</td>
<td>Jackson Site 1</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6/08/2010</td>
<td>Jackson Site 1</td>
<td>20</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jackson Site 2</td>
<td>20</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/24/2010</td>
<td>Jackson Site 3</td>
<td>20</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jackson Site 4</td>
<td>30</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Joint and fracture plane measurements of strike and dip were taken at different outcrops using the Burton compass, Figure 4-6.
4.3 Rockport Quarry

4.3.1 Location of Rockport Quarry

The Rockport Quarry is about 10 miles north of Alpena, MI. The location is about 300 miles northeast of Kalamazoo. This long-abandoned limestone quarry, about 300 acres in area, and its surroundings was managed by the Michigan Department of Natural Resources (MI DNR) as the Rockport Recreational Area. In 2012, the quarry and 4,237 acres of surrounding land and former deep-water port became the Rockford State Park (Michigan Nature Association, 2012). Instrumental measurements were conducted at different locations in and near the quarry. The instrumental measurement sites were chosen in areas where the ground was even, had overburden cover, and was easy to access as the area was heavily covered with vegetation and had narrow paths sometimes filled with standing water or mud. Additionally, strikes and dips of
sub-vertical fractures were measured with the Brunton compass on available exposures around the western side of the quarry. There were five sites chosen for instrumental measurements and three for joints. The instrumental sites were marked with numbers, while the joints sites are marked with letters as shown in Figure 4-7.

Figure 4-7: Google satellite image of the Rockport Quarry location showing instrumental sites marked in numbers and joint measurement sites marked in letters.

Site coordinates where geophysical measurements were made at the Rockport Quarry location are shown in Table 4-5, while coordinates where joints were measured are shown in Table 4-6.

Table 4-5: Site coordinates for instrumental measurements at the Rockport Quarry.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockport Site 1</td>
<td>45°12′15″N</td>
<td>83°23′24″W</td>
<td>620</td>
</tr>
<tr>
<td>Rockport Site 2</td>
<td>45°12′26″N</td>
<td>83°23′47″W</td>
<td>672</td>
</tr>
<tr>
<td>Rockport Site 3</td>
<td>45°12′27″N</td>
<td>83°23′50″W</td>
<td>673</td>
</tr>
<tr>
<td>Rockport Site 4</td>
<td>45°11′58″N</td>
<td>83°23′12″W</td>
<td>580</td>
</tr>
<tr>
<td>Rockport Site 5</td>
<td>45°11′51″N</td>
<td>83°22′54″W</td>
<td>610</td>
</tr>
</tbody>
</table>
Table 4-6: Site coordinates for joint measurements at the Rockport Quarry.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockport Site A</td>
<td>45°12′25″N</td>
<td>83°23′45″W</td>
</tr>
<tr>
<td>Rockport Site B</td>
<td>45°12′12″N</td>
<td>83°23′49″W</td>
</tr>
<tr>
<td>Rockport Site C</td>
<td>45°12′10″N</td>
<td>83°23′49″W</td>
</tr>
</tbody>
</table>

4.3.2 Geological Setting of Rockport Quarry

The Rockport Quarry, which is located in Alpena County in Michigan, is one of several Middle Devonian outcrops lying in the eastern end of an arcuate belt of outcrops extending across the northern end of Michigan’s southern peninsula (Fagerstrom, 1971). Rocks of the arcuate belt form one of eleven formations that make up the Middle Devonian Traverse Group. The lithology in the Rockport Quarry location consists of the Rockport Limestone Formation, overlying the Bell Shale, gradationally (Cookman, 1976). The Bell Shale is the basal formation of the Traverse Group (Ehlers and Kesling, 1970). The Rockport Quarry Limestone is reported to have thicknesses commonly ranging from 15 to 18 meters (Cookman, 1976). Stratigraphically, the Rockport is comprised of facies of intertonguing laterally contemporaneous shallow subtidal to supratidal carbonate platform, all situated in mosaic form (Cookman, 1976). Extensive biolithites, composed of laminate to tabulate stromatoporoid sheets interlaminated with subordinate organic-mud packstone, make up the basal Rockport strata. In the higher section at the Rockport quarry, a subtidal back-shoal biolithite-micrite transition facies containing calcareous algae locally capped the stromatoporoid sheets that are interlaminated with subordinate organic-mud packstone (Cookman, 1976). In the shales of the Ferron Point Formation, that overlies the Rockport formation, there is an increase in carbonate content making it difficult to trace the Rockport formation down dip to the south-west. However, in the subsurface to the northwest, the Rockport is highly fossiliferous (Hake and Maebius, 1937).
Interbedded with shales lithologically similar to the Bell Shale, the Rockport becomes more shaley near the center of the Michigan Basin, whereas in the quarry itself, the limestone contains chert, which becomes darker to the west (Jodry, 1957). There are two facies in the Rockport Quarry Limestone that are recognized based on “mud” content; the first is the "argillaceous" or "bituminous" facies, and second is the micrite facies (Warthin and Cooper, 1943; Kelly and Smith, 1947; Ehlers and Kesling, 1970). In the Rockport Quarry, the limestone of the micrite facies is about 3 m thick, which makes up about 30 percent of the exposed Rockport section (Cookman, 1976). Within the less fissile layers of the Rockport Quarry Limestone, such as the micrite facies, long vertical fractures within the Rockport strata with dilation up to 2 mm usually occur. The cracks often pass through two less fissile layers separated by a thinner more fissile layer, usually shale. Thus, the cracking happened late or post-compaction. Filling the cracks is a pore-filling medium crystalline polygonal sparry calcite (Cookman, 1976). With an increase of overburden (glacial overburden cannot be excluded), a decrease in the thickness of the Rockport Quarry Limestone occurred, initiating fracturing of the Rockport Quarry Limestone into equant polygons probably partially due to inhomogenous strain and support properties within the underlying Bell Shale and overlying Ferron Point Formation (Cookman, 1976). Dolomite in the Rockport Quarry Limestone is secondary and minor, as dolomitazation replaces pore-filling sparry calcite (Cookman, 1976).

4.3.3 Field Work at Rockport Quarry

After acquiring the necessary official permissions from The Department of National Resources of Michigan, fieldwork in the Rockport Quarry started on August 12, 2011. The first site chosen was on an even area on the northeastern side of the quarry bottom, with a thin rubble
covering. The usual in-line seismic refraction and Schlumberger vertical electrical sounding surveys (N60E) were first conducted to characterize the seismic and electrical properties of the surficial soil and underlying rock layers. An azimuthal survey circle 20 m in diameter was then established on Site 1. This circular setting was used for seismic, electrical resistivity, and electromagnetic measurements. The azimuthal electrical resistivity survey was then conducted. Rain started at 3:00 pm, which ended the fieldwork for that day and halted the work for the next day. Weather conditions for fieldwork days at the Rockport Quarry sites are shown in Table 4-7.

Table 4-7: Weather conditions at the Rockport Quarry.

<table>
<thead>
<tr>
<th>Date</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/12/2011</td>
<td>Sunny, 75°F</td>
</tr>
<tr>
<td>8/14/2011</td>
<td>Cloudy, rained heavily on the previous day.</td>
</tr>
<tr>
<td>8/15/2011</td>
<td>Sunny, 75°F</td>
</tr>
</tbody>
</table>

On August 14, 2011, work was done on Sites 2 and 3, which were both north and outside of the quarry pit. At Site 2, an azimuthal circle measuring 14 m in diameter was established, limited by the open ground space available at the site (surrounded by woods). Utilizing this circle, electrical resistivity and electromagnetic surveys were conducted at Site 2. The azimuthal electrical resistivity survey was conducted along the circle’s 14 m diameter lines rotating clockwise at 15 degree intervals relative to magnetic north. This process was repeated until reaching the 180-degree marker on the circle circumference. The azimuthal electromagnetic survey was conducted early, as the site did not appear to be pristine. The azimuthal electrical resistivity measurements backed by the azimuthal electromagnetic survey revealed a severe apparent anisotropy, which led to the judgment that this site was contaminated with metals, as it is an intersection of old roads. Hence, no more work was done at Site 2. Moving to the west of Site 2, Site 3 was chosen as relatively flat ground with minor brush in the forest that was later
cleared using a machete. It apparently seemed untouched except for a bulldozed logging trail. It clearly seemed to be on a boulder moraine. A standard azimuthal survey circle of 20 m diameter was established on Site 3. The azimuthal electrical resistivity survey then was conducted.

On August 15, 2011, the azimuthal electromagnetic survey was done on the previously established circle back at Site 1 along the 20 m diameter lines and in the same fashion as in Site 2. Using the same settings and techniques as in Site 1 and 2, the azimuthal electromagnetic survey was then conducted at Site 3. The in-line seismic survey and Schlumberger vertical electrical sounding were conducted along a diameter at azimuth N60E. The azimuthal seismic survey was then conducted. Site 4 was chosen near the center of the quarry. A standard azimuthal circle of 20 m diameter was established at the site. This site has only 5-20 cm of crushed limestone debris and some black soil developed below the surficial gravel. Azimuthal ground penetrating radar was experimented with at Site 4, but results were later dismissed due to poor image resolution of the measurements. This experiment used the 100 MHz Tx antenna at the center and Rx antenna behind the stakes on the circle. For each station, the two antennae were rotated so that their long axes were always parallel. The Schlumberger vertical electrical sounding survey was conducted along the N45E radial and expanded out to 46.41 m to take advantage of the large open space. Along the same N45E radial, the in-line seismic was conducted. The azimuthal electrical resistivity survey followed by the azimuthal seismic survey was then done at Site 4. At Site 5 (at the southeastern side of the quarry), an azimuthal circle of 20 m diameter was established at which the azimuthal electrical resistivity survey was conducted. This was followed by the Schlumberger vertical electrical sounding survey. A summary of the field activities arranged by date and site at the Rockport Quarry location are shown in Table 4-8.
Table 4-8: Field activities arranged by date and site at the Rockport Quarry.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Circle Diameter (m)</th>
<th>Azimuthal</th>
<th>In-Line Seismic</th>
<th>Schlumberger VES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Seismic</td>
<td>ER</td>
<td>EM</td>
</tr>
<tr>
<td>8/12/2011</td>
<td>Rockport Site 1</td>
<td>20</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>8/14/2011</td>
<td>Rockport Site 2</td>
<td>14</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rockport Site 3</td>
<td>20</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/15/2011</td>
<td>Rockport Site 1</td>
<td>20</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rockport Site 3</td>
<td>20</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rockport Site 4</td>
<td>20</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rockport Site 5</td>
<td>20</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Joint and fracture plane measurements of strike and dip using the Brunton compass were taken along the western wall of the quarry, an example of which can be seen in Figure 4-8.

Figure 4-8: Vertical joint planes in the Rockport Quarry.
4.4 Grand Ledge

4.4.1 Location of Grand Ledge

The Grand Ledge location is also in Michigan. The location is about 76 miles NE of Kalamazoo. Instrumental (geophysical) measurements were conducted at sites located in different parts of the location along the Grand River. The instrumental measurement sites were chosen in areas where the ground was level and had natural soil or overburden cover. Some sites were in parks like Oak Park and Fitzgerald Park. Another was located on the lawn of an apartment complex called Riverwalk Apartments situated on the riverwalk south of the Grand River. Additionally, strikes and dips of sub-vertical fractures were measured with the Brunton compass on available exposures along the southern and northern cliffs of the deeply incised Grand River. There were five sites chosen for instrumental measurements and three for joints. The instrumental sites were marked with numbers, while the joints sites are marked with letters as shown in Figure 4-10.

Figure 4-9: Google satellite image of the Grand Ledge location showing instrumental sites marked in numbers and joint measurement sites marked in letters.
Site coordinates where geophysical measurements were made at the Grand Ledge location are shown in Table 4-9, while coordinates where joints were measured are shown in Table 4-10.

Table 4-9: Site coordinates for instrumental measurements at the Grand Ledge location.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Ledge Site 1</td>
<td>42°45'25&quot;N</td>
<td>84°45'25&quot;W</td>
<td>843</td>
</tr>
<tr>
<td>Grand Ledge Site 2</td>
<td>42°45'32&quot;N</td>
<td>84°45'10&quot;W</td>
<td>844</td>
</tr>
<tr>
<td>Grand Ledge Site 3</td>
<td>42°45'3/&quot;N</td>
<td>84°45'12&quot;W</td>
<td>840</td>
</tr>
<tr>
<td>Grand Ledge Site 4</td>
<td>42°45'34&quot;N</td>
<td>84°45'42&quot;W</td>
<td>869</td>
</tr>
<tr>
<td>Grand Ledge Site 5</td>
<td>42°45'34&quot;N</td>
<td>84°45'42&quot;W</td>
<td>869</td>
</tr>
</tbody>
</table>

Table 4-10: Site coordinates for joint measurements at the Grand Ledge location.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Ledge Site A</td>
<td>42°45'27.85&quot;N</td>
<td>84°45'21&quot;W</td>
</tr>
<tr>
<td>Grand Ledge Site B</td>
<td>42°45'18.97&quot;N</td>
<td>84°45'18&quot;W</td>
</tr>
<tr>
<td>Grand Ledge Site C</td>
<td>42°45'32.20&quot;N</td>
<td>84°45'31&quot;W</td>
</tr>
<tr>
<td>Grand Ledge Site D</td>
<td>42°45'29.54&quot;N</td>
<td>84°45'15&quot;W</td>
</tr>
</tbody>
</table>

4.4.2 Geological Setting of Grand Ledge

In the Lansing area, the glacial deposits range from 3 m to 60 m thick (Stuart, 1945). In and around outcrops in Grand Ledge, the uppermost sandstone units are capped with a thin layer of glacial material (Venable et al., 2013). The Grand Ledge location is situated over the Saginaw Aquifer, which ranges from less than 30 m to more than 91 m in thickness, and consisted of the Saginaw confining unit, which is overlain by the above range of thickness of sandstone (Westjohn and Weaver, 1996b). Regional aquifer studies assume that the sandstones are hydraulically connected. Fine-grained facies of the Saginaw Formation provide the basal confining unit of the Saginaw Aquifer. These units are primarily shale, but may also contain thin, discontinuous sandstone, siltstone, coal, and limestone beds (Westjohn and Weaver, 1996b). Sandstone dominates the upper part of the Pennsylvanian system, while larger portions of shale
occur in the lower portions (Westjohn and Weaver, 1996b). In the Grand Ledge location, the sandstone forms the ledges, or bluffs, of the Grand River and its tributaries in the northern part of Eaton and the southern part of Clinton Counties (Hudson, 1957). According to Kelly (1936), the sandstone in Grand Ledge is considered post-Saginaw and a member of the Grand River Group. Kelly (1936) named the sandstone in Grand Ledge “Eaton Sandstone”. The true stratigraphic relation of the Eaton Sandstone to other sandstones, such as the Woodville, Ionia or other strata of this group outcropping elsewhere, has not been determined. To also be noted, its exposures have not been found outside the Grand Ledge area (Hudson, 1957) in spite of the Grand River and Saginaw Formations covering an area of at least 48,697 square km extending 233 km in a north-south direction and 209 km east-west, (Wanless and Shideler, 1975). The Eaton sandstone is porous, buff-colored sandstone, having a maximum thickness in outcrop of 15 m. The lower contact of this formation with the channel shale of the underlying Saginaw group is highly undulating, and the elevation of this contact varies between 242 m to 252 m above sea level, while the upper surface of the Eaton is bounded by glacial drift (Kelly, 1936). Hudson (1957) supported Kelly’s (1936) interpretation of the origin of the sandstone in Grand Ledge to be of continental origin. Hudson (1957) also found that there is a northern depositional direction dominating in the area. Kelly (1933), being one of the first to study the stratigraphy and depositional environments of the Pennsylvanian section in Michigan, favored a cyclothem approach to correlation of units. The cyclothem term was first used by Wanless and Weller (1932) to informally describe geologic units associated with unstable shelf or interior cratonic basin conditions in which alternating periods of transgressions and regressions deposited variable types of sedimentary materials. Kelly’s (1933) work on the Grand Ledge shows correlation diagrams having the Grand River Formation capping Saginaw units. Venable et al. (2013)
suggest that Kelly (1933) based his notion of the division of the Grand River Formation and Saginaw units on the observance of a thin conglomerate bed, or else a large cutbank feature exposed at the Lincoln Brick Park quarry. The conglomerate bed lies along the Sandstone Creek trail at the base of the ~7.6-m-thick massive sandstone unit that forms the plateau on which most of Fitzgerald Park rests (Venable et al., 2013). According to Davis and Bredwell (1975), the Grand Ledge is composed of exposed fine-grained, quartz-bearing sandstone, which is interbedded with thin shales or shale pebbles. Overlying the sandstone is a 2 m thick plant-bearing, grey siltstone, which is overlain by a 2–4 m coarsening upward sequence. Marking the base of the sequence is black, brittle, fissile shale with sandy laminae (Martin, 1982). A soft, blue-gray, Lingula-bearing shale marks the sequence grading vertically, which then coarsens into an alternating unit of shale and very fine-grained (1 mm thick) sandstone laminae. Moving towards the top, sandy content increases until the shale bands finally disappear from the sequence. Sand content, as well as mica, increases in the overlying layers where root-penetrated coarse siltstone or very fine sandstone lies (Martin, 1982). At the top of the sequence, the roots become more abundant until under-clay and coal is encountered, and after 0.9 meters of lignite or bituminous-grade coal, the sequence above is covered by talus (Martin, 1982). According to Davis and Bredwell (1975), the upper 4–6 m sequence is composed of primarily coarse-grained siltstone containing two 30 cm coal beds.

4.4.3 Fieldwork at Grand Ledge

The first trip was made to the Grand Ledge location after permission was acquired from the Riverwalk Apartments Complex office. Measurements at the Grand Ledge location were
taken on several trips made to the location. Weather condition for the fieldwork days at the Grand Ledge location are shown in Table 4-11.

Table 4-11: Weather conditions at the Grand Ledge location.

<table>
<thead>
<tr>
<th>Date</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/12/2012</td>
<td>Sunny, 75°F.</td>
</tr>
<tr>
<td>6/15/2012</td>
<td>Sunny, hot, clear sky.</td>
</tr>
<tr>
<td>6/22/2016</td>
<td>Partly cloudy, 80°F, Nice.</td>
</tr>
</tbody>
</table>

On June 12, 2012, Site 1 was chosen on the western side of the complex in an open, even area. An azimuthal circle of 20 m diameter was established at the site after clearing the site of occasional bushes using a machete. To examine the suitability of the site and establish the thickness of the soil cover, the Schlumberger VES array was done at azimuths of N60E and N150E. To further verify the layering, the in-line seismic survey was done along a diameter of this circle. Azimuthal ER, EM, and seismic surveys were conducted utilizing this circle.

On June 15, 2012, fieldwork started at Sites 2 and 3 at Oak Park on the northern bank of the Grand River. Once again, for site screening purposes, the Schlumberger VES in East-West and North-South azimuths were conducted at Site 2, and similarly at N60E and N150E azimuths at Site 3. An in-line seismic survey was also done at Site 3 to confirm the suitability of this site. An azimuthal circle of 20 m diameter was established at Site 3. Then the azimuthal ER and the azimuthal seismic surveys were conducted at Sites 2 and 3.

On June 22, 2012, fieldwork started at Site 4 at Fitzgerald Park (NW of Site 1). A standard azimuthal circle, this time with 30 m diameter, was established at Site 4 and an azimuthal ER survey was conducted on it. On the same site, an electromagnetic survey was conducted on a 30 m by 30 m grid with spacing of 1 m between the grid lines to screen the area for possible electrically conductive objects. This grid EM survey backed by the azimuthal ER
survey revealed a strong linear anomaly crossing the area. It was clear that a metal water pipe, wire, or conduit was crossing the site area, which halted further investigation at Site 4. An alternate area was selected about 20 meters to the northwest to continue the investigation as Site 5. At this site, another azimuthal circle of 30 m was surveyed and staked. Site screening involved the Schlumberger VES survey along S-N and W-E azimuths. Then both the azimuthal ER azimuthal seismic surveys were conducted at site 5. A summary of the field activity arranged by date and sites is shown in Table 4-12

Table 4-12: Field activities arranged by date and site and at the Grand Ledge location.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Circle Diameter (m)</th>
<th>Azimuthal Grid EM</th>
<th>In-Line Seismic</th>
<th>Schlumberger VES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Seismic</td>
<td>ER</td>
<td>EM</td>
</tr>
<tr>
<td>6/12/2012</td>
<td>Grand Ledge Site 1</td>
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<td>Grand Ledge Site 5</td>
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Joint and fracture plane measurements of strike and dip using the Brunton compass were taken in different sites, one of which is shown in Figure 4-12.
Figure 4-10: Vertical joint planes at the Grand Ledge location.
CHAPTER V

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter, results from both instrumental and joint measurements for Jackson Quarry, Rockport Quarry, and Grand Ledge locations are displayed and discussed. Furthermore, examples of steps and procedures used in the digital processing of the data from the instrumental measurements are shown in the following sections.

5.2 Digital Processing of Data

Using programs and software in the geophysics lab at the Geosciences Department of WMU, raw data from the instrumental measurements were processed through several methods like formula calculations, seismic wave arrival time picking, inversion, and plotting.

5.2.1 Seismic Data Digital Processing

For the linear array, a 24-channel field record was printed by the field instrument for each of the three shot points, near end, midpoint, and far end. An example is shown in Figure 5-1. The digital file for each recording was in the form of a binary industry standard SEG-2 format DAT File, which was downloaded from the instrument to the computer, then processed in SIP software. In this software, frequency filtering, gain adjustments, and picking of first arrival times of the Primary Wave (P) at each of the 24 geophones was done, Figure 5-2. The time picks were saved as a PIK File, Figure 5-3. The PIK File (text file) was used in the next module of the SIP software for Time-Distance plotting, layer velocity calculation, and Depth Model plotting. For
the Circular Azimuthal Seismic Survey (CASS), the same procedures applied to the linear array digital processing were applied except that in this case the PIK File was used in program AZPLOT for displaying the azimuthal plot of arrival times.

Figure 5-1: Field print of seismic record from an in-line array of 24 vertical geophones with shot point 1 m offset from first geophone at Site 1 at Grand Ledge.
Figure 5-2: First break picks of DAT File of seismic waves from the record of Figure 5-1, as displayed in the SIP program. Note that much of the latter part of the record has been truncated in order to obtain better resolution of the initial arrival times.

Figure 5-3: PIK File (text) showing time picks of the first breaks from SIP (Figure 5-2) for the in-line array at Site 1 at Grand Ledge. The poorly resolved arrival at geophone 9 has been set to zero.
5.2.2 Electrical Resistivity Data Digital Processing

For the Schlumberger Vertical Electrical Sounding (VES), an ASCII (text) DAT File was downloaded from the Syscal instrument to the computer. Data from this file was entered into an Excel spreadsheet to calculate the apparent resistivity. Values of the calculated apparent resistivity were then entered manually into program SCHLINV6 to display the apparent resistivity as a function of current electrode half-spacing (AB/2) in log-log format. Then an initial layer model (thicknesses and resistivities) was entered to begin the iterative inversion process. The result, after adjusting the initial “seed” thicknesses and resistivities, is a layered subsurface model that best fits the observed VES data, as shown in Figure 5-4.

![VES Data Table]

Figure 5-4: Example of the apparent resistivity VES plot as a function of current electrode half-spacing in log-log format at Site 1 in Grand Ledge. The horizontal axis begins at 1 m. Asterisks indicate initial model values that were fixed or constrained by the user.
For the azimuthal electrical resistivity survey using the square array, a text file was also downloaded from the instrument to the computer and transferred to an Excel spreadsheet to calculate the apparent resistivity. The calculated values were then manually entered into program RHOAZ, for the azimuthal display.

5.2.3 Electromagnetic Data Digital Processing

Binary data from the EM-31 instrument was downloaded to the computer and converted to a G31 File (a text file in GEONICS format), which was processed in an Excel spreadsheet to add the coordinates of each reading according to the type of survey (radial or grid shape). After the coordinates were entered, the data was exported as a Comma Separated Variable (CSV File), which could then be used in the graphic software SURFER to be gridded and displayed as a contour map of the spatial distribution of conductivity (milliSiemens/meter).

5.2.4 Joints Data Digital Processing

Strike and dip data from joints measured were entered manually in Stereonet software version 9.9.1 created by Allmendinger, (2016). This software produced Rose Diagrams, which are stereographic plots of joint orientations and dips in a hemispherical view with intensity of joint occurrence highlighted in black. Annotations of geographical orientation were later added on the joint figures using Paint software.

5.3 Instrumental and Joint Measurements Results and Interpretation

Data retrieved from measuring instruments have been processed using standard calculation methods and software. This resulted in the following figures, which are shown
according to the study area locations, and the methodology conducted at these locations. The slowness of arrival times was picked in the direction or directions of the average slowest values (largest arrival times) and displayed as two-sided black arrows on a rose diagram with a marking of Δ referring to the difference in time. The lengths of the arrows represent the difference in time with the longest representing the slowest time, normalized to 100. The same applied to the electrical resistivity where maximum electrical resistivity was displayed as two-sided black arrows pointing in the direction or directions of the maximum resistivity on a rose diagram also marked with Δ. The length of the arrows represents the resistivity maximum where shorter arrows represent resistivity relatively lower than the longer arrows. These interpretive figures are displayed alongside the instrumental azimuthal plots to show how they were derived. Later on, the interpretive figures along with the strike and dip Stereographs are plotted on the location map to show the instrumental reading values in their geographical distribution with relation to the strike and dip orientation of joints near that location. However, with seismic waves, only maps with P-wave (not S-wave) interpretive figures and associated strike and dip Stereographs are displayed to reduce figure count. For seismic picked times, changes in outline of the diagram representing the reading will be considered very subtle in the first six percentage difference values. Such small difference may not represent a geological effect on readings, but rather human subjectivity when picking the arrival times. However, in the electrical resistivity readings a sixth reading is taken when rotating the square array in the 180° position, which verifies the reading taken in the first array direction at N. This helps reduce the anisotropy effect, therefore, big difference in reading will show a sharp ellipse shape towards preferred direction representing a major anisotropy effect versus a subtle difference will yield a rather round or circular diagram shape indicating strong isotropy.
5.3.1 Jackson Quarry Instrumental Measurements and Interpretation

At the Jackson location, instrumental measurements were restricted to the seismic refraction, and the electrical resistivity methods.

5.3.1.1 Site 1

At this site, electrical resistivity surveys using the in-line VES Schlumberger array, and azimuthal response using the rotating square array were conducted. The square array was rotated in increments of 15 degrees from 0 (N) clockwise to 180 degrees. The results of the Schlumberger VES inversion show a weak or subtle 3-layer case that fit the field data very closely, 1.30% rms fit. It also shows a first layer of slightly higher resistivity which might represent a coarse rubble overburden layer, Figure 5-5.

![Figure 5-5: Inversion results of Vertical Electrical Sounding (Schlumberger VES) using program SCHLINV6 showing a 3-layer case at Site 1 of the Jackson Quarry.](image)
The result of the azimuthal survey is shown in Figure 5-6. In a rose diagram, three maximum resistivity peaks were picked at N10W, N75W and N35E for later display purposes. From the azimuthal survey figures, a percentage of difference between maximum and minimum values are calculated and discussed. Azimuthal displays were normalized by removing a constant background to show the variable portion for better display resolution. The normalization value (percentage removed) is shown in the center of the azimuthal diagram. An error percentage or noise estimate for the azimuthal diagrams readings is also discussed.

Figure 5-6: A) Azimuthal plot of the electrical resistivity using the rotating square array with radius of 10 meters at Site 1 of the Jackson Quarry, using program RHOAZ for display. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates an 8% difference between the minimum and maximum resistivities at 80% display normalization. B) Interpretive summary diagram showing two maximum resistivities of roughly the same value that were picked at N10W, N75W and N35E directions.

5.3.1.2 Site 2

An electrical resistivity survey using the rotating square array was conducted at this site and its result is shown in Figure 5-7A, which shows a 15% difference in resistivity when
normalized to 85 to show the difference in resistivity. The maximum resistivity was picked at its peak at N45E, Figure 5-7B.

![Figure 5-7: A) Azimuthal plot of the electrical resistivity with the rotating square array with radius of 10 meters at Site 2 of the Jackson Quarry, after data processing using program RHOAZ. The plot indicates a 15% difference between the minimum and maximum resistivities when display is normalized at 85%. B) Maximum resistivity picked at N45E.](image)

5.3.1.3 Site 3

At this site, seismic refraction surveys using the linear and azimuthal arrays were conducted. Also conducted was the electrical resistivity survey using the rotating square array.

5.3.1.3.1 Seismic Refraction Surveys

The linear array deployed across this site resulted in a Travel-time or Time-distance graph showing two layers different in velocity, Figure 5-8. Layer assignments were input manually to program SIP to designate the deepest layer that was encountered by a given raypath.
Note that the boundary from layer 1 to 2 is gradational. This indicates a gradient change in P-wave velocity starting at around 2-3 m.

Figure 5-8: Program SIP Travel-time graph of the raw arrival times of the Primary Wave (P-wave) at 24 geophones (Geo.) with shot points (SP) at locations A, B, and C showing two different layers at Site 3 of the Jackson Quarry.

The Travel-time inversion yielded a depth model with velocity in layer 1 \( V_1 = 216 \) and layer 2 \( V_2 = 1661 \) meters/sec. The velocity \( V_2 \) is typical of a limestone formation. The depth at the velocity change is approximately 1.5 m, Figure 5-9. An important result for the subsequent azimuthal work is that the boundary between soil and rock is horizontal and without undulations.
Figure 5-9: Program SIP inversion depth model from the linear array seismic refraction method showing a refraction boundary between 2 different layers at Site 3 of the Jackson Quarry. $V_1 = 216$ and $V_2 = 1661$ meters/sec. The depth at the velocity change from soil to rock is approximately 1.5 m.

Azimuthal plotting for the P-wave azimuthal survey was done using program AZPLOT in full 360 degree mode. The seismic refraction result for the primary wave (P) from the Circular Array Seismic Survey (CASS) at Site 3 in the Jackson Quarry location is shown in Figure 5-10.
To help reduce effects of heterogeneity (small local variations), which might occur in the ground and affect the propagation of the seismic waves; and to enhance the expected 180 degree periodicity due to joints (vs the 360 degree periodicity due to a sloping surface or lateral inhomogeneity), an averaging technique was used. In this technique, all seismic plots were converted to a 180 degree mode. To do this, time values in opposite directions were averaged, and then projected across the center to form a symmetric plot to be displayed in the 180 degree plotting fashion. P-wave averaged arrival times were approximately 7% slower at about N15W and N45W, as shown in Figure 5-11.
Figure 5-11: A) Azimuthal plot of Primary Wave (P) normalized averaged arrival time from the Circular Array Seismic Survey (CASS) in the seismic refraction method with radius of 10 meters at Site 3 in the Jackson Quarry. Azimuthal plotting was done using program AZPLOT. Averaged 180 degree data set shown. B) Slowest times picked at N15W and N45W.

Shear Wave averaged arrival times using vertical geophones (SV) from the CASS at Site 3 in the Jackson Quarry location are shown in Figure 5-12, where the maximum slowness of the shear wave was indicated at N8E. The direction of the slowest shear wave showed a significant deviation from that of the P-wave. This might be caused by a change of fracture direction at greater depth, as the two waves do not necessarily follow the same paths.
Figure 5-12: A) Azimuthal plot of the Shear Wave (SV) normalized averaged arrival time using vertical geophones from the Circular Array Seismic Survey (CASS) in the seismic refraction method with radius of 10 meters at Site 3 in the Jackson Quarry. Azimuthal plotting was done using program AZPLOT. Time averaging is displayed in a 180 degree plotting fashion. B) Slowest time marked with arrow in N8E direction.

5.3.1.3.2 Electrical Resistivity Survey

The azimuthal electrical resistivity survey using the rotating square array was conducted, with the result shown in Figure 5-13. In this case, a broad maximum resistivity direction at N30W, N60W, and N90E was picked. This compares with a P-wave maximum slowness of arrival time near N20W (slow P-wave direction in Figure 5-11), although parts of the broad lobes on these two figures are overlapping.
Figure 5-13: A) Azimuthal plot of the normalized electrical resistivity using the square array with radius of 10 meters, at Site 3 of the Jackson Quarry. The plot indicates a 9% difference between the minimum and maximum resistivities normalized to 91% for maximum enhancement. B) Maximum electrical resistivity was picked at N30W, N60W, and N90E directions.

5.3.1.4 Site 4

Seismic refraction surveys with the linear and azimuthal arrays were conducted. Also conducted was an azimuthal electrical resistivity survey, using the square array rotated in 15 degree increments to 180 degrees.

5.3.1.4.1 Seismic Refraction Surveys

At this site, the linear (in-line) seismic refraction survey using a 1 meter geophone interval and 3 hammer impact points was conducted. This was followed by the azimuthal seismic survey with the hammer point at the center of a 15 meter radius circle. The linear refraction array yielded a travel-time graph of 2 layers with different $V_p$, Figure 5-14, but no low velocity soil
layer, as was typical of most other sites. The graph shows a very gentle change in velocity at cross-over distances of 12-14m, which corresponds to a depth of 2.5m. This change in velocity from an intermediate to higher velocity indicates a lack of an overburden layer at the site, which is most probably the case because the site appeared to have only a very thin gravel veneer. It seemed as if the area was compacted and flattened by excavation or loading vehicles, Figure 5-15.

Figure 5-14: Program SIP Travel-time graph of the raw arrival times of the Primary Wave (P-wave) at 24 geophones (Geo.) with shot points (SP) at locations A, B, and C showing 2 different layers at Site 4 of the Jackson Quarry.
The Travel-time graph yielded a depth model with velocity of layer 1 \( (V_1) = 1100 \), layer 2 \( (V_2) = 1911 \) meters/sec, and depth to the transition of about 2.5 meters, Figure 5-16. This cross section indicates an approximately planar bedrock surface whose depth does not change across the diameter of the circle. Both Travel-time graph and depth model are quality control criteria for subsequent azimuthal surveys, as significant undulations, channel-forms, or a sloping surface would mimic the effects of fractures on the directional surveys.
Figure 5-16: Program SIP inversion depth model from the linear refraction array data, showing a boundary between 2 different layers at Site 4 of the Jackson Quarry. \( V_1 = 1100 \) and \( V_2 = 1911 \) meters/sec.

The azimuthal seismic results for the Primary Wave (P) and the first Shear Wave using vertical geophones (SV) from the Circular Array Seismic Survey (CASS) at Site 4 in the Jackson Quarry location are shown in Figures 5-17, and 5-18. The P-wave graph showed two maximum slowness of arrival times at N40E and N25W with N40E slightly dominating over the other direction. On the other hand, the shear wave showed a single peak at N60W.
Figure 5-17: A) Normalized averaged arrival times of the Primary Wave (P) vs azimuth from the Circular Array Seismic Survey (CASS) with radius of 15 meters at Site 4 in the Jackson Quarry. This is a 180 degree rotation plot. B) Interpretive figure showing two slowness directions of P-wave picked at N25W and N40E directions.

Figure 5-18: A) Normalized 180 degree plot of averaged arrival times of the Shear Wave (SV) vs azimuth from the Circular Array Seismic Survey (CASS) with radius of 15 meters at Site 4 of the Jackson Quarry. B) Interpretive figure showing direction of SV picked at the N60W direction.
5.3.1.4.2 Electrical Resistivity Surveys

The electrical resistivity survey using a 15 meter radius square array rotated in 15 degree increments was conducted. The result of the azimuthal survey is shown in Figure 5-19. A 20% difference is resistivity was found with maximum at N45W.

![Figure 5-19: A) Azimuthal graph of normalized electrical resistivity using the square array with radius of 15 meters, at Site 4 of the Jackson Quarry. Note that the 15 m radius results in a square array electrode separation “a” of 21.21 meters. The plot indicates a 20% difference between the minimum and maximum resistivities. B) Maximum electrical resistivity was picked at the N45°W direction.](image)

The azimuthal resistivity shows clear anisotropy of 20% with the direction of the maximum resistivity at N45W. By contrast, the P-wave anisotropy had two slowness directions of only 8% at N25W and N40E directions (Figure 5-17), but the S-wave anisotropy had one clearly defined slow direction 9% at the N60W direction (Figure 5-18), which matched the direction of maximum resistivity. This difference in slowness of primary wave compared to shear wave is an indicative of change of physical properties in layers within depth.
5.3.2 Jackson Quarry Joint Measurements and Interpretation

Measurements of strike and dip for joints at Sites A, B, and C of Jackson Quarry were plotted on stereographs by using Stereonet Software as shown in Figures 5-20, 5-21, and 5-22.

Figure 5-20: Stereograph showing projection of strike and dip of joints at Site A of the Jackson Quarry, 7 measurements were included in this diagram.

Figure 5-21: Stereograph showing projection of strike and dip of joints at Site B of the Jackson Quarry, 5 measurements were included in this diagram.
In an outcrop at the location of the abandoned Jackson Quarry, two distinct rock layers showed different degrees of weathering, Figure 5-23. Such layering can have a major impact on the seismic and electrical resistivity readings. Having more void space from dense fractures in the upper part of the rock formation will diminish seismic velocities and yield a maximum slowness direction perpendicular to the direction of major fracture planes. Similarly, these open fractures (if dry) can hinder the flow of electrical current, giving a maximum resistivity in a direction perpendicular to these planes. On the other hand, if the voids were filled with water, or at least moisture, they will still retard the P-wave and interrupt the shear wave. In this case the P-waves will propagate slower in liquid than in rock, producing a slow direction in a direction perpendicular to the void direction on the azimuthal plot. Shear waves will not pass through voids filled with air or water. Joints at Jackson Quarry mainly showed two sets of preferred directions, roughly N45W and N70W, with the angle between joints ranging from 25°-45°, Figure 5-24.
Figure 5-23: Outcrop in Jackson Quarry location showing two distinct rock layers with different weathering and fracture density.

Figure 5-24: Collage of pictures of joint set having two preferred directions, roughly N45W and N70W at Jackson Quarry location.

P-wave interpretation plots along with stereographs of strike and dips of joints at the sites of Jackson Quarry were all combined and geographically plotted on a Google map image of the
area, Figure 5-25. The same was applied to the electrical resistivity interpretative figures and joint sites of the Jackson Quarry location, Figure 5-26.
Figure 5-25: Slowness of P-wave (ΔP) directions in comparison to joint orientations in the Jackson Quarry location.
Figure 5-26: Azimuthal diagrams showing directions of maximum electrical resistivity ($\Delta R$) in comparison to joint azimuths in the Jackson Quarry location.
5.3.3 Rockport Quarry Instrumental Measurements and Interpretation

5.3.3.1 Site 1

In this site, seismic refraction, and electrical resistivity surveys, with both the linear and azimuthal arrays were conducted. Also conducted was the electromagnetic conductivity survey as a precautionary measure to detect buried metallic objects (which would disqualify a site for any further electrical measurements). In the absence of metallic conductors, this azimuthal EM survey is also a measure of anisotropy or conductivity changes with direction over the Site.

5.3.3.1.1 Seismic Refraction Surveys

The linear array at Site 1, with a 1 meter spacing of vertical geophones and three shot points, showed a Travel-time graph, Figure 5-27, which yielded a depth model (Figure 5-28) with P-wave velocity of layer 1 \((V_1) = 156\) and layer 2 \((V_2) = 982\) and layer 3 \((V_3) = 2228\) meters/sec. The very low velocity surface layer is very thin, less than a meter, while the intermediate layer is about 3 meters thick. The depth to the transition surface between the first and second limestone layers was undulating at depths ranging from 10-60cm; this confirms field observations on the quarry walls of an irregular boundary at this site. The transition surface between the second and third layers also undulated between depths of 2.5-5m. Undulating layer boundaries like this means that one could anticipate more scatter in azimuthal seismic data (and possibly also in the resistivity) in this site.
Figure 5-27: Travel-time graph of the raw arrival times of the Primary Wave (P) from the SIP inversion program showing 2 refraction boundaries and 3 layers at Site 1 of the Rockport Quarry. The different end arrival times of the two end shots indicates a problem in first-break picking and leads to the scatter in the next figure.

Figure 5-28: Depth model from the SIP inversion program showing refraction boundaries between 2 layers at Site 1 of the Rockport Quarry. $V_1 = 156$, $V_2 = 982$, and $V_3 = 2228$ meters/sec.
The azimuthal seismic refraction survey results for the Primary Wave (P) from the Circular Array Seismic Survey (CASS) at Site 1 in the Rockport Quarry location are shown in Figure 5-29. The directional change in the P-wave velocity was only 7%, with the slowest direction at N75W and N45E directions.

Shear wave arrival times were measured twice, once with vertical geophones (SV), and again with horizontal geophones and horizontal source impact (SH). The SV anisotropy is shown in Figure 5-30. The SV anisotropy diagram shows a maximum of 4% directional variation, without a clear-cut dominant direction. The Shear Wave anisotropy measured with horizontal geophones (SH) is shown in Figure 5-31. It shows a 6% azimuthal change, with no single dominant direction. Both have their minimum (fastest direction) at 120° azimuth and maximum (slowest directions) at N-S, N45E and N90E directions. The shear-wave results are thus very
similar for the two wave polarization directions, as is expected, but this experiment was done partially to verify that the SV waves were being correctly identified on the vertical component seismograms.

Figure 5-30: A) Azimuthal plot (180 deg) of normalized averaged arrival times for Shear Wave (SV) from the CASS with radius of 10 meters at Site 1 of the Rockport Quarry. B) Interpretive figure showing direction of slowest SV at N-S, N45E and N90E directions.
Figure 5-31: A) Azimuthal diagram of the Shear Wave using horizontal geophones (SH) normalized averaged arrival times from the CASS using a circle with radius of 10 meters at Site 1 of the Rockport Quarry. B) Interpretive figure showing direction of slowest SH at N-S, N45E and N90E directions.

5.3.3.1.2 Electrical Resistivity Surveys

At this Site, electrical resistivity surveys using the in-line Schlumberger VES array, and the rotating square array were conducted. The result of the VES is shown in Figure 5-32, and the azimuthal data in Figure 5-33. The VES graph shows a steady gradient in electrical resistivity versus depth. It was modeled with three layers with different resistivities 17, 37, and 89 Ohm-m, with the first layer having a thickness of 1.4 m, and the second 13.5 m. The azimuthal plot showed a maximum resistivity towards the N30W direction.
Figure 5-32: Schlumberger Vertical Electrical Sounding (VES) graph, and its inversion results using program SCHLINV6 showing a 3 layer ascending case at Site 1 of the Rockport Quarry. The horizontal AB/2 scale begins at 1 m.
Figure 5-33: A) Azimuthal plot of electrical resistivity as a function of azimuth with radius of 10 meters, using the square array, at Site 1 of the Rockport Quarry. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates a 15% difference between the minimum and maximum resistivities. B) Interpretive figure showing the maximum resistivity in the N30W direction.

5.3.3.1.3 Electromagnetic Survey

At this site, an azimuthal electromagnetic survey using the Geonics EM-31 was conducted resulting in an electromagnetic conductivity map of the surveyed area, as shown in Figure 5-34. This graphic shows mainly a gradient across the measured area, with increasing conductivity in the N75E direction. As this area has a very gentle stratigraphic dip from E to W, this may simply be due to sampling a thickening wedge of a higher resistivity stratum towards the W.
5.3.3.2 Site 2

At this site, the azimuthal electrical resistivity survey with the square array, and the electromagnetic survey with the EM-31 were conducted. Results of these surveys are shown in Figures 5-35, 5-36, and 5-37. The electrical resistivity survey showed 57% difference between the maximum and minimum resistivity, which means that this area is probably underlain by some manmade electrical conductor, such as discarded wire rope, rails or other debris. This electrical survey indicated the need to investigate the site further using the electromagnetic survey, which showed two cycles ranging from 9.9-11.5 mS/m. The location of Site 2 on an apparent former crossroad or loading location might have been cause for buried conductors and thus the observed anomalous electrical resistivity/conductivity results. The small sampling circle
radius of 7 m was constrained by surrounding forest. These observations prompted cancelation for further surveys.

Figure 5-35: A) Azimuthal plot of the normalized electrical resistivity using the square array with radius of 7 meters, at Site 2 of the Rockport Quarry. Note that the 7 m radius results in a square array electrode separation “a” of 9.89 meters. The plot indicates a 57% difference between the minimum and maximum resistivities. B) Interpretative figure showing the maximum resistivity at N30W and N80W directions.
Figure 5-36: Data graph showing electromagnetic conductivity vs distance along the azimuth line N-S, at Site 2 of the Rockport Quarry. The Geonics EM-31 was used.

Figure 5-37: Data graph showing electromagnetic conductivity vs distance along the azimuth line W-E, data displayed in Excel Worksheet, at Site 2 of the Rockport Quarry.
5.3.3.3 Site 3

At this Site, in-line and azimuthal seismic refraction surveys, and electrical resistivity surveys, both linear and azimuthal were conducted. Also done was the electromagnetic survey to detect any possible buried metallic objects. This site was in a semi-open wooded area.

5.3.3.3.1 Seismic Refraction Surveys

The linear array over the surveyed Site resulted in a Travel-time graph, and a depth model with velocity of layer 1 \((V_1) = 294\) and layer 2 \((V_2) = 2608\) meters/sec, as shown in Figures 5-38, and 5-39. The boundary between the two layers is at about 1.5 m depth.

Figure 5-38: Travel-time graph of the raw arrival times of the Primary Wave (P) at 24 geophones (Geo.) with shot points (SP) at locations A, B, and C showing 2 layers at Site 3 of the Rockport Quarry. The inversion of the refraction data was done with the SIP software package.
Figure 5-39: Depth model from the 1-m spacing refraction array showing a refraction boundary between 2 different layers at Site 3 of the Rockport Quarry. Using the SIP software package, $V_1 = 294$ and $V_2 = 2608$ meters/sec.

The azimuthal seismic refraction survey results at Site 3 in the Rockport Quarry location for the Primary Wave (P), shows 10% azimuthal variations, as can be seen in Figure 5-40. The Shear Wave result using vertical geophones (SV) is shown in Figure 5-41 and shows only 7.5% variations. The Shear Wave results using horizontal geophones (SH) is shown in Figure 5-42, indicating 6% azimuthal variation. Seismic wave plots were indicative of two prominent fracture sets slightly varying in direction towards deeper areas (SV and SH). Such variation may be due to differences in joint aperture, or else filling material with depth, thus affecting the shear wave propagation differently than P-wave.
Figure 5-40: A) Azimuthal plot of Primary Wave (P) normalized averaged arrival times from the CASS using vertical geophones around circle with radius of 10 meters at Site 3 of the Rockport Quarry. B) Interpretive figure showing maximum slowness of P-wave at N22W and N68E directions.

Figure 5-41: A) Azimuthal plot of normalized averaged arrival times for Shear Wave using vertical geophones (SV) from the CASS around a circle with radius of 10 meters at Site 3 of the Rockport Quarry. This is 180 degree averaged data. B) Interpretive figure showing maximum slowness of P-wave at N60W and N60E directions.
Figure 5-42: A) Azimuthal diagram of normalized averaged arrival times of the first Shear Wave using horizontal geophones (SH). Geophone circle of the CASS has radius of 10 meters at Site 3 of the Rockport Quarry. B) Interpretive figure showing maximum slowness of P-wave at N45W and N45E directions.

5.3.3.3.2 Electrical Resistivity Survey

At Site 3, linear VES and azimuthal electrical resistivity surveys were conducted, as shown in Figures 5-43, and 5-44. The VES graph showed an increase in resistivity with depth in a three layers scenario at this site. The first layer showed a thin bed of 0.36 m thickness with 250 Ohm-m and the second layer was 8.17 m thick and had a resistivity of 581 Ohm-m. The azimuthal diagram showed a maximum resistivity at N15W direction.
Figure 5-43: Schlumberger Vertical Electrical Sounding (VES) graph, and its inversion results using program SCHLINV6 showing an ascending 3 layer case at Site 3 of the Rockport Quarry.

Figure 5-44: A) Azimuthal plot of the normalized electrical resistivity using the square array with radius of 10 meters, data plotted using program RHOAZ, at Site 3 of the Rockport Quarry. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates a 20% difference between the minimum and maximum resistivities. B) Interpretive figure showing maximum resistivity at N15W direction.
The high-resistivity direction is within 10 degrees of the maximum slowness direction for the P-wave (Figure 5-40). However, the P-wave anisotropy is only 10%, while the resistivity anisotropy is 20%.

5.3.3.3 Electromagnetic Survey

In this site, the azimuthal electromagnetic survey was conducted with the Geonics EM-31, resulting in a conductivity map of the surveyed area, as shown in figure 5-45. The electromagnetic survey showed minimal conductivity difference of 1.5 mS/m increasing from West to East. This minimal conductivity difference might indicate a slight downwards tilt in the measured layer subsurface towards the East.

Figure 5-45: Contour map of the electromagnetic conductivity at Site 3 of the Rockport Quarry showing minimal conductivity difference of 1.5 mS/m increasing from West to East.
5.3.3.4 Site 4

At this site, both in-line and azimuthal seismic refraction and electrical resistivity surveys were conducted.

5.3.3.4.1 Seismic Refraction Surveys

The linear array with 1 meter geophone spacing at Site 4 resulted in a Travel-time graph, and a Depth model with velocity of layer 1 ($V_1$) = 179, layer 2 ($V_2$) = 1413, and layer 3 ($V_3$) = 2390 meters/sec. Both are shown in Figures 5-46, and 5-47. The interpreted depth model shows a high degree of scatter, which is due to small difference between the slopes of the arrivals designated as layer 1 and layer 2 on the travel-time diagram, but mainly due to the violation of reciprocal times evident on the T-D diagram. The depth of the first transition surface shows at around 0.5 m.

Figure 5-46: Travel-time graph, from software SIP, of the raw arrival times of the Primary Wave (P), showing 3 layers at Site 4 of the Rockport Quarry.
The azimuthal seismic refraction survey result for the Primary Wave (P), at Site 4 in the Rockport Quarry location is shown in Figures 5-48. The graph shows compound peak ellipses indicating different slowness times that have been recorded. The direction of the maximum slowness time was picked at N65W, N15E and N60E directions, the latter being the dominant. The difference between the maximum slowness time and the minimum slowness time was 18%. On the other hand, the result for SV at the same site showed rather wide smooth ellipse with a 15% difference between the maximum and minimum arrival times, Figure 5-49. The average slowness direction of SV was also picked at N60E. The difference in shape between P and SV graphs indicates that P has encountered two families of fracture planes that retarded the seismic wave at shallow depth. The SV graph shows that the wave was most retarded in one direction, N60E, while the set in the N15E direction had less effect. The shear wave SV being less retarded...
than P in the N15E direction may be an indication that that fracture set is more open and/or water filled.

Figure 5-48: A) Azimuthal diagram of normalized Primary Wave (P) averaged arrival times from the CASS on a ring with radius of 10 meters at Site 4 of the Rockport Quarry. B) Interpretive figure showing maximum slowness of P-wave at N65W, N15E and N60E directions.
5.3.3.4.2 Electrical Resistivity Survey

At Site 4, electrical resistivity surveys using linear Schlumberger VES and rotating square arrays were conducted. The VES survey was expanded out to 46.41 m in the N45E direction with center about 3 m south of the azimuthal survey circle center to take advantage of the open space at this site. The VES result showed an electoral resistivity graph different than previous VES graphs, Figure 5-50. The resistivity anisotropy was also very large (87% -99%) with one lobe corresponding with the P-wave maximum slowness direction at N20E and N55E directions, Figure 5-51. This resulted in detecting a very low resistivity layer below the limestone, with resistivity of 48 Ohm-m. The thickness of the first layer as determined by VES (H = 0.52 m) is very similar to the thickness of Layer 1 as determined with seismic refraction (Figure 5-47).
Figure 5-50: Schlumberger Vertical Electrical Sounding (VES) using program SCHLINV6 showing inversion results and graph for a 3 layer case at Site 4 of the Rockport Quarry expanded out to 46.41 m in N45E direction with center about 3 m south of azimuthal survey circle center.
Figure 5-51: A) Azimuthal diagram of the normalized electrical resistivity using the square array in a circle with radius of 10 meters (i.e., “a” = 14.14 m) at Site 4 of the Rockport Quarry. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates a 46% difference between the minimum and maximum resistivities. B) Interpretive figure showing average maximum electrical resistivity in N20E and N55E directions.

5.3.3.5 Site 5

At this site, in-line and rotating square array electrical resistivity surveys were conducted. The in-line survey resulted in a VES graph, shown in Figure 5-52, that displayed a different shape from that at the previous Site 4. It starts with a medium resistivity of 216 Ohm-m in the first layer, then even lower in both layers 2 and 3. The anisotropy ranged from 60% to 84%. The rotating square array resulted in Figure 5-53, which shows resistivity azimuthal variation of 8%.
Figure 5-52: Schlumberger Vertical Electrical Sounding (VES) graph, and its inversion results using program SCHLINV6 showing a 3-layer case at Site 5 of the Rockport Quarry.
Figure 5-53: A) Azimuthal plot of normalized electrical resistivity using the square array with radius of 10 meters, data processed using program RHOAZ, at Site 5 of the Rockport Quarry. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates an 8% difference between the minimum and maximum resistivities. B) Interpretive figure showing maximum electrical resistivities at N45E, N37Eand N75E directions of relatively similar values.

5.3.4 Rockport Quarry Joint Measurements and Interpretation

Measurements of strike and dip for joints at Sites A, B, and C of Rockport Quarry were plotted on stereographs by using Stereonet Software as shown in Figures 5-54, 5-55, and 5-56.
Figure 5-54: Stereograph showing projection of strike and dip of joints at Site A of the Rockport Quarry. Included in this graph are 4 measurements.

Figure 5-55: Stereograph showing projection of strike and dip of joints at Site B of the Rockport Quarry. This graph is displaying the projection of 28 measurements of strike and dip of joints.
Field observations at a wall of the Rockport Quarry location showed flat bedded limestone layers varying in color, thickness and fracture density, Figure 5-57. The outcrop also seemed to show a very thin overburden layer at the top, where it is merely enough to support sparse vegetation. Several sites showed generally two joint sets separated by about 70 degrees and apertures ranging 0.1-0.4 cm. Kimmel’s (1973) study observed photogeologic linears in the region of the Rockport Quarry location and concluded that there are two major sets of photolinears and that both sets are prominent throughout Alpena and Presque Isle Counties. Both sets were found to be approximately 90° apart with one set trending northwest-southeast, having the longest photolinears, and the other trending northeast-southwest.
Figure 5-57: Outcrop at Rockport Quarry location showing a cross-section view of flat bedded limestone varying in color, thickness, and fracture density.

Figure 5-58: Two joint sets crossing at 70 degrees dominating the Rockport Quarry location.
P-wave interpretation plots along with stereographs of strikes and dips of joints at the sites of Rockport Quarry were all combined and geographically plotted on a Google map image of the area, Figure 5-59. The same was applied to the electrical resistivity interpretive figures and joint sites of the Rockport Quarry location, Figure 5-60. Maximum slowness of P-waves showed a general orientation whose direction is perpendicular to the joint directions. Slight variation in orientation or dominancy reflects the orientation and intensity of joints that were captured in the measured areas. Electrical resistivity maximum orientations appear to diverge from the trends of P-wave slowness. In Sites 1, 3, and 5, the electrical resistivity maximum was 70° counter-clock-wise of the P-wave maximum slowness orientation. This deviation in direction may be due to the occurrence of moisture in fractures parallel to the P-wave slowness orientation at N45E. At Site 4, the maximum resistivity deviated slightly counter-clock-wise of the dominant P-wave direction indicating a less moisture content in the fractures affecting the reading. It is worth noting that the location had rain events during the fieldwork period, which might explain the incompatibility of electrical readings with the P-wave readings in some sites at the location.
Figure 5-59: Slowness of P-wave (ΔP) directions in comparison to joints in the Rockport Quarry location.
Figure 5-60: High electrical resistivity (ΔR) directions in comparison to joints in the Rockport Quarry location.
5.3.5 Grand Ledge Instrumental Measurements and Interpretation

5.3.5.1 Site 1

At this site, both in-line and rotating seismic refraction and electrical resistivity surveys were conducted. The electromagnetic survey was initially done to verify the absence of buried metallic objects.

5.3.5.1.1 Seismic Refraction Surveys

The linear array at Site 1 resulted in a Travel-distance graph and a Depth model with velocity of layer 1 ($V_1$) = 138, layer 2 ($V_2$) = 542, and Layer 3 ($V_3$) = 1330 meters/sec, which are shown in Figures 5-61, and 5-62. The lower transition surface showed a slightly undulating form at depths ranging from 2-2.5 m.

![Figure 5-61: Time-distance graph of the raw arrival times of the Primary Wave (P) at 24 geophones (Geo.) with shot points (SP) at locations A, B, and C, from Program SIP showing 3 layers at Site 1 of Grand Ledge.](image-url)
Results of the seismic refraction method with the CASS geometry at Site 1 in the Grand Ledge location for the Primary Wave (P) and Shear Wave (SV) using the vertical geophones are shown in Figures 5-63 and 5-64, while the Shear Wave using radial horizontal geophones (SH) is shown in Figure 5-65. The P-wave anisotropy is about 8.5% and has only a single lobe oriented N30W. The SV wave anisotropy is very similar at 9% and its slowness axis is within 10 degrees of that of the P-wave. The SH wave anisotropy diagram shows what appears to be two main directions, N30W and N75W, which combine to form a single broad or composite lobe with 8% anisotropy.
Figure 5-63: A) Azimuthal plot of normalized Primary Wave (P) arrival times using vertical geophone from the CASS around a ring with radius of 10 meters, Site 1 of Grand Ledge. Data plotted using program AZPLOT. B) Interpretive figure showing a maximum slowness of P-wave picked at the N30W direction.
Figure 5-64: A) Azimuthal diagram of normalized Shear Wave (SV) arrival times from the CASS using vertical geophones around a circle with radius of 10 meters at Site 1 of Grand Ledge. Data processed using program AZPLOT. B) Interpretive figure showing the maximum slowness of SV picked at N45W direction.

Figure 5-65: A) Azimuthal plot of the normalized first Shear Wave (SH) arrival times using radial horizontal geophones in a circle with radius of 10 meters from the CASS at Site 1 of Grand Ledge. Data plotted using program AZPLOT. B) Interpretive figure showing a maximum slowness of SH picked in N30W and N75W directions.
5.3.5.1.2 Electrical Resistivity Survey

At this site, in-line electrical resistivity surveys (VES) with orientations of N60E, and N150E, and rotating square array were conducted. Results of these surveys are shown in Figures 5-66, 5-67, and 5-68. The azimuthal resistivity showed a maximum direction at N45E that was 40% greater than that at N150E. Hence, the anisotropy had a significant effect on the two VES’s, in that the N60E VES was nearly aligned with the maximum resistivity direction, and the N150E VES was in the minimum resistivity direction. Note that the average resistivity of the azimuthal measurements was 247 Ohm-m, indicating that it was influenced mainly by layer 3 of the VES’s. The total transverse resistance (T) for the two VES’s was 3229 and 3182, compatible with the higher resistivity seen at a single spacing in the NE direction for the rotating square array.

![VES Table and Graph](image)

Figure 5-66: Schlumberger Vertical Electrical Sounding (VES) expanded in the N60E direction with inversion results from program SCHLINV6 showing a 4-layer case at Site 1 of Grand Ledge.
Figure 5-67: Schlumberger Vertical Electrical Sounding (VES) curve and inversion results, expanded in the N150E direction, (perpendicular to that of the previous Figure) showing a 4-layer case at Site 1 of Grand Ledge. Inversion was done using program SCHLINV6.
Figure 5-68: A) Azimuthal plot of normalized electrical resistivity with a rotating square array having radius of 10 meters, data processed using program RHOAZ, at Site 1 of Grand Ledge. Note that the 10 m radius results in a square array electrode separation “a” of 14.14 meters. The plot indicates a 40% difference between the minimum and maximum resistivities. B) Interpretive figure with a maximum electrical resistivity picked at N45E.

Thus, the azimuthal P and S wave slowness directions are perpendicular to the azimuthal resistivity maximum at Site 1. This appears to be a contrary result. The Grand Ledge location is different from the other two in that water table is deep, beyond the range of these measurements, due to the nearby river canyon. That means that the joints may be quite dry. Following this logic, the resistivity maximum should be perpendicular to the joint set. But, that implies that the seismic slowness direction is at the same azimuth as the joints.

5.3.5.1.3 Electromagnetic Survey

At this site, the azimuthal electromagnetic conductivity survey was made, resulting in a conductivity map of the surveyed area, as shown in Figure 5-69. The electromagnetic
conductivity map shows a difference between maximum and minimum conductivity of 5 mS/m most of it due to two small, discrete high conductivity zones in the SW quadrant. There are clearly no man-made conductors through this area.

![Contour map of azimuthal electromagnetic conductivity survey results at Site 1 of Grand Ledge.](image)

**Figure 5-69:** Contour map of azimuthal electromagnetic conductivity survey results at Site 1 of Grand Ledge. The radius of the circle was 10 m, the same as that along which the electrodes were placed for the rotating square array.

5.3.5.2 Site 2

At this site, perpendicular in-line VES expansions in the S-N, and E-W directions were conducted, as shown in Figures 5-70, and 5-71. The figures showed a four layer case in both VES’s, very similar to the VES’s at Site 1 on the opposite side of the river. The inversion model for the N-S VES has a tendency toward higher composite resistivity, shown as a higher “T” value (2161) as compared with that of the E-W sounding with “T” of 1779.
Figure 5-70: Schlumberger array Vertical Electrical Sounding (VES) plot and inversion results from program SCHLINV6, showing a 4-layer case, expanded in the S-N direction, at Site 2 of Grand Ledge.
Figure 5-71: Schlumberger Vertical Electrical Sounding (VES) curve and inversion results from program SCHLINV6, showing a 4-layer case. Expansion was in the E-W direction at Site 2 of Grand Ledge. (Compare with previous Figure where expansion was in the N-S direction.)

The result of the resistivity survey with the rotating square array is shown in Figure 5-72.

The difference between the minimum and maximum resistivities is 17% and the maximum resistivity is at N15W, N45W, N15E and N55E, this agrees with the resistivity results from the VES profiles which also showed higher resistivities in the N-S direction than E-W, if compared via the thickness-weighted “T” factor.
5.3.5.3 Site 3

At this site, also on the East side of the river, in-line and azimuthal seismic refraction and rotating electrical resistivity surveys were conducted.

5.3.5.3.1 Seismic Refraction Surveys

The linear array over the surveyed site resulted in a Time-distance graph, and a depth model with velocity of layer 1 \( V_1 = 160 \) and layer 2 \( V_2 = 1277 \) meters/sec, as shown in Figures 5-73, and 5-74. The two-layer scenario with the first layer being of low resistivity and the transition surface of the two layers at around 1 m depth indicates that the first layer is an
overburden layer and the second is the sandstone layer that is being noted in the field observations.

Figure 5-73: Time-distance graph of the raw arrival times of the Primary Wave (P) at 24 geophones (Geo.) with shot point (SP) at locations A, B, and C, from program SIP, showing 2 layers at Site 3 of Grand Ledge.
Figure 5-74: Depth model from the linear array using the seismic refraction method, after inversion of data by program SIP showing a refraction boundary between 2 layers at Site 3 of Grand Ledge. \( V_1 = 160 \) and \( V_2 = 1277 \).

The seismic refraction survey results using the CASS at Site 3 of the Grand Ledge location for the Primary Wave (P), and the Shear Wave (SV) are shown in Figures 5-75, and 5-76. Orientations of P and SV slowness are both at N30W, which is also the same direction of P at Site 1, across Grand River. The P diagram showed 9% anisotropy, while the SV diagram showed only 6.3% anisotropy.
Figure 5-75: A) Azimuthal plot of normalized Primary Wave (P) arrival times from the CASS with radius of 10 meters at Site 3 of Grand Ledge. B) Interpretive figure showing a maximum slowness of P-wave picked at N30W and N20E directions.
5.3.5.3.2 Electrical Resistivity Surveys

In this site, electrical resistivity (VES) surveys with the Schlumberger array at the orientations of N60E, and N150E, were conducted, as shown in Figures 5-77, and 5-78. The figures also showed a four-layer case in both directions similar to Site 2.
Figure 5-77: Schlumberger Vertical Electrical Sounding (VES) graph and its inversion results using program SCHLINV6, showing a 4-layer case. Expansion was along the N60E orientation at Site 3 of Grand Ledge.

Figure 5-78: Schlumberger Vertical Electrical Sounding (VES) graph and its inversion results using program SCHLINV6, showing a 4-layer case. Same center location as the previous Figure, but the expansion azimuth was in the N150E direction, at Site 3 of Grand Ledge.
Results of the resistivity survey with the rotating square array are shown in Figure 5-79. This site showed a significant difference in electrical resistivity of 26% with maximum resistivity oriented in the N30W and N15E directions. The difference in resistivity does not seem compatible with the anisotropy of P-wave.

5.3.5.4 Site 4

The electrical resistivity survey using the rotating square array was done, whose result is shown in Figure 5-80. The electrical resistivity azimuthal plot shows an extreme difference between the maximum and minimum readings of electrical resistivity indicating an abnormality in the surveyed area. This abnormality prompted an electromagnetic survey to verify if the surveyed area had any buried metal objects that might be affecting the resistivity readings,
Figure 5-81. The electromagnetic survey indeed proved the presence of a linear metallic buried object thought to be a pipe line or power line serving the restroom facility near the site. Thus, Site 4 was abandoned, and Site 5 established further to the NW.

Figure 5-80: A) Azimuthal plot of the electrical resistivity from a rotating square array with radius of 15 meters, data processed using program RHOAZ, at Site 4 of Grand Ledge. Note that the 15 m radius results in a square array electrode separation “a” of 21.21 meters. The plot indicates a 68% difference between the minimum and maximum resistivities. B) Interpretive figure showing a maximum electrical resistivity picked at the N75W direction.
Figure 5-81: Contour map of electromagnetic conductivity at the initial Site 4 of Grand Ledge showing the parallel (E-W) line survey that detected a metallic object (pipe, or wire) beneath this location. The high-low-high parallel zones are characteristic of a single metallic conductor. The site was then abandoned and moved to the NW (Site 5) to avoid influences of this feature.

5.3.5.5 Site 5

At this site, in-line and azimuthal seismic refraction and rotating electrical resistivity surveys were conducted.

5.3.5.5.1 Seismic Refraction Surveys

The linear seismic array in this site resulted in a Time-distance graph, and a depth model with velocity of layer 1 ($V_1$) = 358 and layer 2 ($V_2$) = 1028 meters/sec, which are shown in Figures 5-82, and 5-83. With $V_1 = 358$ meters/sec and the transition surface at 1.5 m depth, the
two-layer scenario indicates that the first layer is an overburden layer, while the second is the sandstone seen in field observations.

Figure 5-82: Time-distance graph of the raw arrival times of the Primary Wave (P) at 24 geophones (Geo.) with shot point (SP) at locations A, B, and C, from program SIP, showing 2 layers at Site 5 of Grand Ledge.
At this site, seismic refraction surveys using the CASS were conducted. The Primary Wave (P) and Shear Wave (SV) full azimuthal results are shown in Figures 5-84 and 5-85. Result of the Shear Wave using horizontal geophones (SH) is shown in Figures 5-86. Anisotropy in the P-wave diagram was at 5.4%, SV at 10%, and SH at 9.4%. The difference in direction between the P-wave, being picked at N38W, shear waves at N83W, and anisotropy of SV and SH being higher than P is indicative of the seismic waves being affected by different layer properties with depth.
Figure 5-84: A) Azimuthal plot of normalized Primary Wave (P) arrival times from geophones in the CASS with radius of 15 meters at Site 5 of Grand Ledge. B) Interpretive figure showing two maximum slowness of P-wave picked at N38W and N45E directions.
Figure 5-85: A) Azimuthal plot of Shear Wave (SV) normalized arrival times at vertical geophones in the CASS with radius of 15 meters at Site 5 of Grand Ledge. B) Interpretive figure showing a maximum slowness of SV picked in the N85W direction.

Figure 5-86: A) Azimuthal plot of first Shear Wave normalized arrival times using radial horizontal geophones (SH) in the CASS in a circle with radius of 15 meters at Site 5 of Grand Ledge. B) Interpretive figure showing a maximum slowness of SH picked at N85W and N15E directions.
5.3.5.5.2 Electrical Resistivity Surveys

At this site, perpendicular in-line VES expansions in the S-N, and E-W directions were conducted, as shown in Figures 5-87, and 5-88.

Figure 5-87: Schlumberger array Vertical Electrical Sounding (VES) plot and inversion results from program SCHLINV6, showing a 3-layer case, expanded in the S-N direction, at Site 5 of Grand Ledge.
Figure 5-89: A) Azimuthal plot of the electrical resistivity from a rotating square array with radius of 15 meters, data processed using program RHOAZ, at Site 5 of Grand Ledge. Note that the 15 m radius results in a square array electrode separation “a” of 21.21 meters. The plot indicates a 21% difference between the minimum and maximum resistivities. B) Interpretive figure showing a maximum electrical resistivity picked at N45W and N75E directions.

5.3.6 Grand Ledge Joint Measurements and Interpretation

Measurements of strike and dip for joints at Sites A, B, C and D of Grand Ledge were plotted on stereographs by using Stereonet Software as shown in Figures 5-90, 5-91, 5-92, and 5-93.
Figure 5-90: Stereograph showing projection of one strike and dip measurement of a joint at Site A of Grand Ledge.

Figure 5-91: Stereograph showing projection of strike and dip of joints at Site B of Grand Ledge. This graph shows projection of two measurements at this site.
Seismic plots at Site 1 showed preferable maximum slowness picked at directions towards the west, as P was picked at N30W, SV at N45W, and SH at N75W. This orientation suggests that the fracture planes might be changing in direction with regard to depth or there are two or more layers with different physical properties that are affecting the path of wave
propagation with depth, or just 3 different sets of fractures that show differently to different waves at different sites.

Field observation from an outcrop on the river bank of Grand River at Site B showed visibly that this Site 1 is above two layers of sandstone with two different weathering intensities. Both layers had flat bedding. The top layer was about 1.5 m thick and showed thinner bedding with frequent fractures, while the deeper layer was thicker than the upper layer. Also, the fractures were less frequent in the lower layer, as Figure 5-94 shows. The vertical fractures had very thin aperture (0.2-0.4 cm) and crossed both layers, but they were more distorted in the upper layer, hence the change in direction and dip, Figure 5-95.

Figure 5-94: Field picture showing layers of different weathering in an outcrop on the river bank of Grand River at Site B near Site 1 at the Grand Ledge location.
Figure 5-95: Field picture showing vertical fracture planes with different direction and dip in an outcrop on the river bank of Grand River Site B nearby Site 1 at the Grand Ledge location.

Fractures at Site D (near Site 3) showed a similar situation to Site B, but fracture apertures seemed bigger in some places, probably due to effects of river erosion on its banks, Figure 5-96.
Figure 5-96: Field picture showing wide aperture of a vertical fracture planes in an outcrop on the river bank of Grand River Site D near Site 3 at the Grand Ledge location.

P-wave interpretation plots along with stereographs of strike and dips of joints at the sites of Grand Ledge were all combined and geographically plotted on a Google map image of the area, Figure 5-97. The same was applied to the electrical resistivity interpretive figures and joint measurement sites of the Grand Ledge location, Figure 5-98. Maximum slowness of P-wave seemed to show a constant perpendicular orientation relative to the vertical fracture orientations in all sites at the location. However, at Site 1, the orientation of P-wave slowness seems as if it does not match the nearby vertical fracture measurement sites, Site A and Site B. This is probably due to the effect of the weathering of the upper layer, seen in the outcrops, on the propagation path of the P-wave, or that Site 1 was over a vertical fracture of an orientation just like of that found in Site D (N60E). Another explanation might be being that Site A and Site B did not have an outcrop showing the vertical fracture measured at Site D (N60E); therefore, it is a visual illusion to the reader. Having two maximum slowness peaks from readings at Sites 5 might possibly indicate another natural feature affecting the reading such as different filling material, or multiple joint sets in different directions.
Figure 5-97: Slowness of P-wave (ΔP) directions in comparison to joint directions in the Grand Ledge location.
Figure 5-98: High electrical resistivity ($\Delta R$) directions in comparison to joint directions at the Grand Ledge location.
5.4 Discussion

Detecting vertical fractures, such as joints, beneath cover using geophysical methods is improved through application of multiple integrated methods. Many factors come together to determine if it is possible to detect the orientations of hidden fractures. The seismic linear and VES methods helped by assessing the rocks physical properties with relation to depth, as well as revealing the thickness of the soil layer. The azimuthal arrays of seismic and electrical methods helped with measuring the horizontal anisotropy. The electromagnetic method worked as a screening tool to reject sites with metallic conductors presence. Using a single method will give only a partial and ambiguous result. Similar approaches to detecting or determining fractures have been discussed. Difference and similarities of their approaches from the results reached by this investigation are discussed here.

From engineering aspects of joints and fractures, Kimmel (1973) studied photogeologic linears in the Rockport Quarry region and found that there are two major sets of photolinears and that both sets are prominent throughout Alpena and Presque Isle Counties. The two sets of lineations were orthogonal with one set trending northwest-southeast, having the longest photolinears, and the other trending northeast-southwest. The current study found similar joint sets, with azimuths 70° apart. Lee et al. (2011) studied spatial fracture intensity using spatial data of fractured networks through utilizing statistical models rather than geophysical methods, as the current study used. Physical properties of jointed and fractured rock were studied by Mavko et al. (2005). They approached the detection and characterizing of natural fractures in rocks by making an integrated strategy in which they integrate geological data, geophysical (log and seismic) data, and theoretical rock physics models linking fractures, background rock properties, and observable seismic attributes. Mavko et al. (2005) approach shared similar
methodology with the current study but only seismic methods were utilized. Park and Simmons (1982) conducted surveys to measure velocity of compressional wave expressed as a function of direction in elastic media along nine lines in different azimuths spaced at 20°. They displayed their in-line survey results in rose diagram showing different lines with different lengths representing velocity of each line survey. The current study used the Circular Array Seismic Survey (CASS) in which the impact spot was in the center of the survey circle and its result was later displayed on a rose diagram showing the azimuthal variation of the seismic wave arrival times. Mavko et al. (2005) methods were more time and labor consuming compared the the CASS used in the current study. Kahraman (2001) shared the same concept used in the current study of how joints affect sound velocities and thus can be detected by studying their time arrivals. Du et al. (2002) used azimuthally anisotropic model of transverse isotropy with a horizontal axis of symmetry to describe fractured reservoirs that contain parallel vertical cracks. Their technique was used in deep seismic reflection surveys (near-vertical ray paths) for oil reservoirs, and not applicable to the surface refraction technique (horizontal ray paths) used in the current study.

Discussed here are some previous studies that applied geophysical techniques in detecting fractures subsurface and the differences of similarities to the current study. Martí et al. (2006) used P and S-waves to make high-resolution seismic tomography to characterize the physical properties of a site in an abandoned uranium mine and made a three-dimensional reconstruction of the fracture networks and their surroundings. The depth scale of Martí et al. (2006) survey was not applicable for shallow engineering investigations like what the current study is considering. Payne et al. (2007) collected seismic data over three boreholes that formed an isosceles triangle using hydrophones and a sparker source. They observed that a zone of high
fracture permeability was associated with high values of seismic attenuation of P-waves and attempted to model the seismic attenuation and separate the attenuation due to scattering from intrinsic mechanisms. They concluded that measuring rock permeability in terms of seismic attenuation through means of modeling was not possible because more exact parameters were missing in the modeling process. The current study differed from Payne et al. (2007) in that it suggests that utilizing more than one geophysical method will give a better resolution of the fractures subsurface rather than depending on limited variables for computer modeling.

Kahraman et al. (2008) evaluated the possibility of determining the fracture depth in rock blocks from P-wave velocities in addition to physical properties of rocks. They made laboratory measurements on samples of igneous, sedimentary, and metamorphic rocks from different sites including rock processing plants, quarries, and natural outcrops. Their study was conducted in the laboratory, as such it lacked the effects of field conditions like the association of water and other material in the fractures, which the current study investigates. Detecting and modeling subsurface fracture systems in geothermal fields of volcanic rocks approximately 3 km thick using shear-wave splitting of natural and induced earthquake waves was studied by Tang (2009). The study concluded that split shear-wave polarizations coincide with the crack system. Their study was conducted on a large scale, differing from the current study where the methods used covered relatively small local scales of circular areas of 10-15m in diameter, which are feasible to certain investigations, like civil engineering and environmental. Hansen et al. (1995) used surface and borehole geophysical surveys to determine fracture orientation and other site characteristics in crystalline bedrock terrain. In their study, seismic refraction, azimuthal square-array direct current resistivity, borehole radar, and ground-penetrating radar geophysical surveys were conducted where chlorinated hydrocarbons had been detected in waters from wells.
completed in fractured crystalline bedrock. Their seismic data were collected from eight seismic lines centered about a point in the middle of the lines where the lines were separated by equal angular intervals. Their seismic approach is similar to Park and Simmons (1982) but differs from the CASS conducted in the current study in which with few shots from the center more information will be gathered than the radial array (eight seismic lines) used in Hansen et al. (1995). The electrical resistivity in Hansen et al. (1995) is similar to the azimuthal square array used in the current study, but they used the square array to measure electrical resistivity vertically by expanding the array dimensions to penetrate more deeply. To measure electrical resistivity with regard to depth, one or two VES expansions were used in the current study, which was less time consuming and covered a greater depth range than what was used in Hansen et al. (1995). The integration of different geophysical methods in Hansen et al. (1995) seemed to work in identifying the orientation of fractures in their study area; this supports the suggestion implied by the current study of integrating more than one geophysical method in an investigative study to determine fracture orientation beneath coverage. Yeguas et al. (2011) used the same principle of utilizing seismic wave propagations to determine subsurface geological features, in this case shallow magma chamber and shallow rigid bodies. They captured the behavior of the seismic waves in a 3-D high-resolution fashion. Their approach was operationally more complicated than the approach done by the current study and covered a large area of several hundred meters, whereas the current study focused on local shallow circular areas of 10-15 m in diameter and few meters in depth, which can be conducted with less time and labor. Habberjam (1972) used the electrical resistivity method with the square array to study the effects of anisotropy on the measurements and compared it with the results obtained from using the Wenner array when detecting vertical planes. Habberjam (1972) investigated the azimuthal
inhomogeneity ratio in relation to anisotropy and the effect of orientation on the mean resistivity. Habberjam (1972) used a single method to investigate a single problem, whereas the current study integrates different geophysical methods to study a problem from a horizontal and vertical perspective. Mallik et al. (1983) applied the radial VES method in the Schlumberger configuration along azimuths of E-W; N-S to help understanding the behavior of fractures in hard rocks at depths, making a polygon diagram that represents the outlining of the VES lines in each location of their study area. The polygon diagrams reflected the anisotropy beneath the surveyed area. This approach is similar to the approach used in the current study, but the rotating square array was used instead of the radial VES. Similar to Malik et al. (1983) study, Okopoli and Igwe (2013) studied the electrical resistivity anisotropy in fracture delineation and characterization. Several polygons plotting the azimuthal resistivity sounding and their corresponding electrode spacing were made for each location. After qualitative and quantitative interpretation of geological and geophysical data, namely the strike direction, foliation planes, joint direction and radial vertical electrical sounding, a clear subsurface fracture orientation emerged. Okopoli and Igwe (2013) used the azimuthal approach, but with long VES expansions rotated about a center point, whereas the current study used the azimuthal square array and plotted its results on a rose diagram to have a better understanding of the dominant electrical resistivity orientation in a local circular area of 10-15 m. Taylor and Fleming (1988) applied a rotating Wenner array about a fixed point measuring apparent resistivity as a function of azimuth to study anisotropy, directional connectivity, and porosity of fracture systems in bedrock and clayey till at 60 sites throughout Wisconsin in several lithologies, including gabbro, basal till, dolomite, and fine-grained glacial sediment. Their study utilized one geophysical method to study anisotropy in a broad area and on different lithologies, whereas the current study
investigated anisotropy in three locations chosen in the State of Michigan with only two lithologies (limestone and sandstone). The current study gave more detailed information on anisotropy and its effects on the interpretation of subsurface joint orientations. The rose diagrams of the square array supported by the Schlumberger VES diagrams and field photographs in the current study indicated that rock layers with different weathering and water saturation may affect the interpretation of orientations of joints subsurface. Lane, Haeni, and Watson (1995) used azimuthal square-array direct-current resistivity soundings to detect fractures in a crystalline bedrock underlying glacial drift. Their study was similar to the current study in using azimuthal square array to detect fractures in bedrock beneath cover. They emphasized that with the square array, the “paradox of anisotropy” is avoided, and the direction of minimum apparent resistivity coincides with the fracture direction. This validates the choice of using the electrical resistivity method and the square array to detect fractures beneath cover for the current study. Hao et al. (2002) experimented on samples from a magnetite quartzite rock using a compressed uniaxial test cell to study the variation of saturation in connected rock pores and cracks and its effects on rock electrical conductivity. In the current study, the effects of water saturation on the readings of instrumental measurements were taken in consideration when interpreting results. Carlson (2010) concluded that azimuthal resistivity surveys are a useful and reliable method for determining the orientation of a pair of regional joint sets within the Silurian-Devonian dolomite in Milwaukee County in Wisconsin. Similarly, the current study used the electrical resistivity method to determine the orientation of joint sets, but at a local scale of circular area of 10-15 m radius. Al-Zubedi and Thabit (2016) used 2D azimuthal resistivity imaging in delineation of the fracture characteristics in the Dammam aquifer within and outside of the Abu-Jir fault zone, central Iraq. They employed a Wenner–Schlumberger array along four lines with 45° interval
between each line (N-S, E-W, NE-SW, and NW-SE), symmetric about a common center point. They concluded that the Wenner-Schlumberger array was the most suitable electrode array when both vertical and horizontal structures were present in the subsurface. They also concluded that their 2D azimuthal resistivity technique was very successful in marking out the subsurface fracture extension in all directions. The rotating square array used in the current study to measure the electrical resistivity has shown to be a less time and labor consuming in addition to covering an area of a circle rather than only four azimuths out of the 180 degrees possible used in Al-Zubedi and Thabit (2016).

The Circular Array Seismic Survey (CASS) was quick to deploy and easy to handle in the field. It only required several shots by a 5 lbs. sledge hammer in one spot (center). The survey was conducted in circular areas of 10-15 m radius. Preliminary data can be printed by the instrument in the field after each shot for quality control, and digital laboratory processing done later. Results produce clear elliptical images giving a perspective on the orientation of vertical discontinuities such as faults, shear zones, or joints beneath cover that retard the seismic wave propagation. Result resolution varies with survey scale. The purpose of the survey determines the size of the surveyed area (as does the amount of open space). To produce high resolution results, more data must be acquired and data processing with various computer programs is needed. The survey circle used for CASS can be utilized for other forms of the seismic surveys like the azimuthal SH, rotating square resistivity, and linear array along any azimuth chosen in the circle as the markers on the 15 degree interval stay with each survey saving time and labor. Surveys presented in the current study provide a low cost-effective approach to detection of vertical fractures and joints in bedrock beneath cover.
CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The current study has investigated the determination of vertical fractures such as joints beneath cover using geophysical methods including; seismic refraction, electrical resistivity, and electromagnetics. For verification of validity, the instrumental results were compared with nearby measurements of joints in outcrops obtained using a Brunton Compass. The measurements were conducted in three locations in the State of Michigan; Jackson Quarry, Rockport Quarry, and Grand Ledge. In each location, linear and azimuthal arrays of seismic refraction and electrical resistivity were conducted in different sites where and when feasible. The electromagnetic measuring was done in some sites to measure lateral resistivity changes, and to verify the absence of any metal objects that might affect the azimuthal resistivity readings.

After literature review and data acquisition for detection of vertical joint sets beneath cover, the current study has concluded that the detection of vertical joints on a local scale and near surface has not been thoroughly covered by previous studies. Fieldwork and computer laboratory work done in the current study has shown that integrating several geophysical methods to the detection of vertical joints gives better results. The current study has shown that seismic refraction method and electrical resistivity method in the circular array when combined provide an improved estimate of the orientation of vertical joint sets. On the other hand, the electromagnetic method works to screen sites for the presence of metal that would invalidate the use of electrical resistivity. The Jackson Quarry location (shallow water table) has shown that water or moisture content in fractures can affect interpretations of the results of both the seismic and electrical
methods. In particular, moisture impacts interpretation of the orientation of vertical fractures. Seismic wave plots at Site 3 in the Rockport Quarry location were indicative of two prominent fracture sets slightly varying in direction with depth (SV and SH). Such variation may be due to differences in joint aperture, or else filling material with depth, thus affecting the shear wave propagation differently than P-wave, which in turn affects final interpretations of the orientation of vertical fractures. Previous studies of vertical fractures did not use the Circular Array Seismic Survey. The current study has found that the Circular Array Seismic Survey is effective in detection of vertical joints when integrated with other geophysical methods. Another advantage is that the circle used in the CASS can be utilized for other azimuthal surveys including azimuthal SH, and square array electrical resistivity, thus saving time and labor in the field. We also found that the diameter of survey circle affects the resolution of the survey results. The bigger the diameter is, the better the depth penetration that will be reached. However, increased diameter also has the tradeoff of lower resolution. On the other hand, an increased number of survey sites and access to outcrops for measuring strike and dip provide more information about the chosen location. Manual pre-treatment of data is a subjective matter as it is based on human decision (time picking in seismic inversion software) and is influenced by human error. Outcrop distance from the survey sites affects the validation of the instrumental measurements, the closer the outcrop to the survey site, the better the correspondence between the geophysical and Brunton measurements. Labor associated with field measurements in the current study is relatively low compared with the labor associated with previous studies making the approach in the current study more economical than previous studies. Lithology did not seem to have a major impact on results. Some results showed more than one direction of vertical plane suggesting joint set pattern, which was confirmed by field observations.
6.2 Future Work

To better understand the joint set pattern in the Grand Ledge location, instrumental and strike and dip measurements need to be expanded to include areas in the northwest and north of Site 5 in the location. To further study the impact of moisture on instrumental readings, measurements need to be done at a chosen area in a dry season and repeated at the same location in a wet season. For this a dry desert environment is recommended. Measurements in more locations in various environments need to be done to further evaluate the methods used to detect vertical planes beneath cover in the current study. Locations are suggested to be in desert environments and plain environments, where the land is flat and moisture levels in fractures vary. To predict orientation of vertical fractures when applying seismic and electrical measurements, a computer model is recommended that can take into consideration factors affecting the detection of vertical planes beneath cover such as; vertical plane strike and dip, lithology, fracture aperture width and filling material, and moisture levels in the fractures.
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