

**THE USE OF INTEGRATED GEOPHYSICAL
METHODS TO CHARACTERIZE THE SHALLOW
INHOMOGENEITY ON DAMMAM DOME, SAUDI
ARABIA**

BY

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I Dedicate my work to my father may Allah have mercy upon him, mother, my wife, daughters,
brothers and sisters

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ABSTRACT

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A new outcrop was recently exposed near King Fahd University (KFUPM) on a new road cut. A large deformation zone, 30 meters wide, is observed at this outcrop. To the left and right of this deformation zone several strata of the Dammam Dome are exposed. This study aims to explore and identify the geological reasons for the deformation zone observed in the study area and to use multi-geophysical methods to generate a comprehensive geological interpretation that explains the nature of the deformation zone. In addition, the study investigates the relationship between the near-surface structure and the Dammam Dome, a prominent geological feature in Saudi Arabia associated with significant hydrocarbon reserves. The study utilizes a combination of geophysical methods, including a 2D seismic reflection survey with 120 receivers and 120 shots, and a 3D seismic survey with 108 receivers and 385 shots, as well as an Electric Resistivity Tomogram (ERT) with 96 electrodes using a dipole-dipole array. Geological observations and measurements are also conducted, including the collection and analysis of six rock samples, to provide additional information on the subsurface geology.

ملخص الرسالة

الاسم الكامل: أحمد عبد الله الشيباني

عنوان الرسالة: استخدام الأساليب الجيوفيزيائية المتكاملة لوصف عدم التجانس الضحل بقبة الدمام بالمملكة العربية السعودية.

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تم الكشف عن مقطع صخري بالقرب من جامعة الملك فهد على طريق الدمام-الجبيل بالقرب من مركز إثراء. بالنظر الي هذا المقطع يتضح وجود تشوه صخري بعرض 30 متر. يتميز هذا التشوه باختفاء التتابع الصخري المنتمي لتتابع قبة الدمام والموجود بوضوح على جانبي التشوه. نهدف من خلال هذه الدراسة الي تحديد الاسباب الجيولوجية لتواجد وتكوين هذا التشوه وكذلك دراسة امتداده التحتسطحي. تم استخدام عدد من الطرق الجيوفيزيائية والقياسات الجيولوجية لتكوين تصور عن الوضع الجيولوجي التحتسطحي في منطقة الدراسة وتوضيح امتدادات هذا التشوه الصخري. وكذلك تمت دراسة العلاقة بين الجيولوجيا الضحلة (اي الاعماق البسيطة) وتتابع قبة الدمام في منطقة الدراسة، علما بان تتابع قبة الدمام هو تكون جيولوجي هام في المملكة العربية السعودية لاحتوائه على احتياطي نفطي عالي. في هذه الدراسة تم قياس قطاعات سيزمية ثنائية وثلاثية وقطاع جيوكهربي وكذلك جمع عينات جيولوجية لدراستها في المعمل وتحديد نوعية الصخور والمعادن المكونة لها.

CHAPTER 1

INTRODUCTION

Seismic and resistivity methods are commonly used in geophysical surveys, especially for shallow applications. In cases of complex shallow geology, we may face ambiguities in the seismic and/or resistivity's final model. Hence, integrating both seismic and resistivity will decrease the uncertainty of the results. In this study, electrical resistivity and seismic methods are applied to explore the near-surface geology, and integrate them to produce a comprehensive interpretation of the study area (Cardarelli et al., 2010)

Seismic method is considered one of the main methods used to characterize the sub-surface features and help to define the thickness of the subsurface layers and locate local anomalies (Hanafy, 2013). Seismic energy is refracted and reflected at the boundaries between subsurface layers where impedance (density-velocity product) changes. The ray path passes through different layers and is then recorded by the receivers; hence, the velocity-depth information can be extracted from the recorded data.

Zhang et al. (2020) used 3D seismic data and advanced imaging and interpretation techniques to investigate the geometry, kinematics, and displacement characteristics of these faults. The study shows that the strike-slip faults in the northern slope of the Tazhong uplift are generally characterized by a steep dip angle and a moderate to high throw. The authors observe a complex pattern of fault interaction and segmentation, which suggests that the faults are controlled by a combination of structural and lithological factors. They also identify several areas of fault linkage and relay ramps, which can have important implications for reservoir characterization and hydrocarbon exploration.

Electrical Resistivity Tomography (ERT) is mainly used for investigating groundwater, but it can help in imaging sub-surface structure which has deformation where the variance of the resistance in the material can help to get more information about the structure, thicknesses, and fluid content. The 2D ERT is the recommended option for mapping subsurface structures (Cardarelli et al., 2010).

The power of combining two or more geophysical methods is demonstrated by Soupios et al. (2007), where the ERT and Horizontal to Vertical Spectral Ratio (HVSr) are used to image the subsurface. Here, the ERT can detect the variation of resistivity distributed in the subsurface due to different features such as fracture, leakage, cavities, and water table, while HVSr can estimate the resonant frequency of sedimentary layers on the top of the bedrock.

This study focuses on investigating a shallow outcrop located at Dhahran city ($26^{\circ}21'32.3''\text{N}$ $50^{\circ}06'09.9''\text{E}$), where a local anomaly is observed at this outcrop (Figure 1). In this study, ERT and seismic methods were applied to explore the anomaly and study its relationship with the Damman Dome.

The study area is part of a geological structure known as Damman Dome which is related to salt and tectonic processes since the Jurassic and Cretaceous times (Hariri & Abdullatif, 2005). The roadcut on the east side of the Dharan-Jubail high-way, Saudi Arabia allows a 3D view of a fresh section of the Damman Formation (Figure 1). The investigation was initiated with a single profile using Ground Penetration Radar (Hanafy et al., 2021), which will be discussed later in this chapter.

1.1 Research Objectives

The objectives of this study are listed as follows:

1. To explore and identify the geological processes caused the anomaly observed at the study area.

2. To use multi geophysical methods and generate one geological interpretation explain the nature of the anomaly.

1.2 Geology of The Study Area

The study area is located about 2.7 km north of Ithra (King Abdulaziz Center of World Culture) on the east side of the Dharan-Jubail main road in the Eastern Province Saudi Arabia (Figure 1a), where the main hydrocarbon trap known as the Dammam Dome is found. This Dome that covers an area of about 500 km², has an oval shaped structure that is constrained approximately by longitudes 50°00' and 50°14' N and latitudes 26°12' and 26°26' E (Alkhalifa & Kurison, 2022).

In the northern part, a larger elliptical shaped dome of sedimentary rocks is exposed. The geomorphologic features of Dammam Dome such as Jabal Um Er Rus are believed to be mainly resulting from salt tectonics (Weijermars, 1999).

Geological investigations divided the Dammam Dome strata in the study area into four formations: Rus Formation, Dammam Formation, Hadrukh Formation, and Dam Formation, from bottom to top (Figure 2). According to previous geophysical studies, the Rus formation is considered the bedrock, where it is mapped laterally in an extensive study done by Weijermars (1999). He grouped recent road maps and compiled them with the existing Dammam Peninsula.

The investigation area has a cut of approximately 500 m long across the sedimentary rock in a NE-SW direction of the Dammam Formation. The Dammam Formation, overlying the Rus Formation, comprises five members (Bramkamp 1941, unpublished Saudi Aramco report; Powers et al. 1966). These are (from bottom to top) (1) Midra Shale, (2) Saila Shale, (3) Alveolina Limestone, (4) Khobar limestone member, and (5) Alat dolomitic limestone/marl member (Figure 2). Alkhalifa & Kurison (2022) recently interpreted the NW slope in the outcrop (Figure 1c) as a collapse zone which is about 28m wide in the NNW-SSE direction.

Three geological formations are present in the Dammam Peninsula, Including Dam Formation (Td), Dammam Formation (Tdm), and Upper Rus Formation (Tr"u"). Dammam formation is the main formation exposed in the study area (Figure 3).

The outcrop under investigation provides a unique opportunity to study the deformation zone and fracture systems and relate this to their geological formation mechanisms. Natural fractures including normal faults and gypsum-filled veins are common features that were observed within the deformation zone and in the surrounding layers in the Dammam formation cropped in the study area along the freshly cut road (Figure 1c).

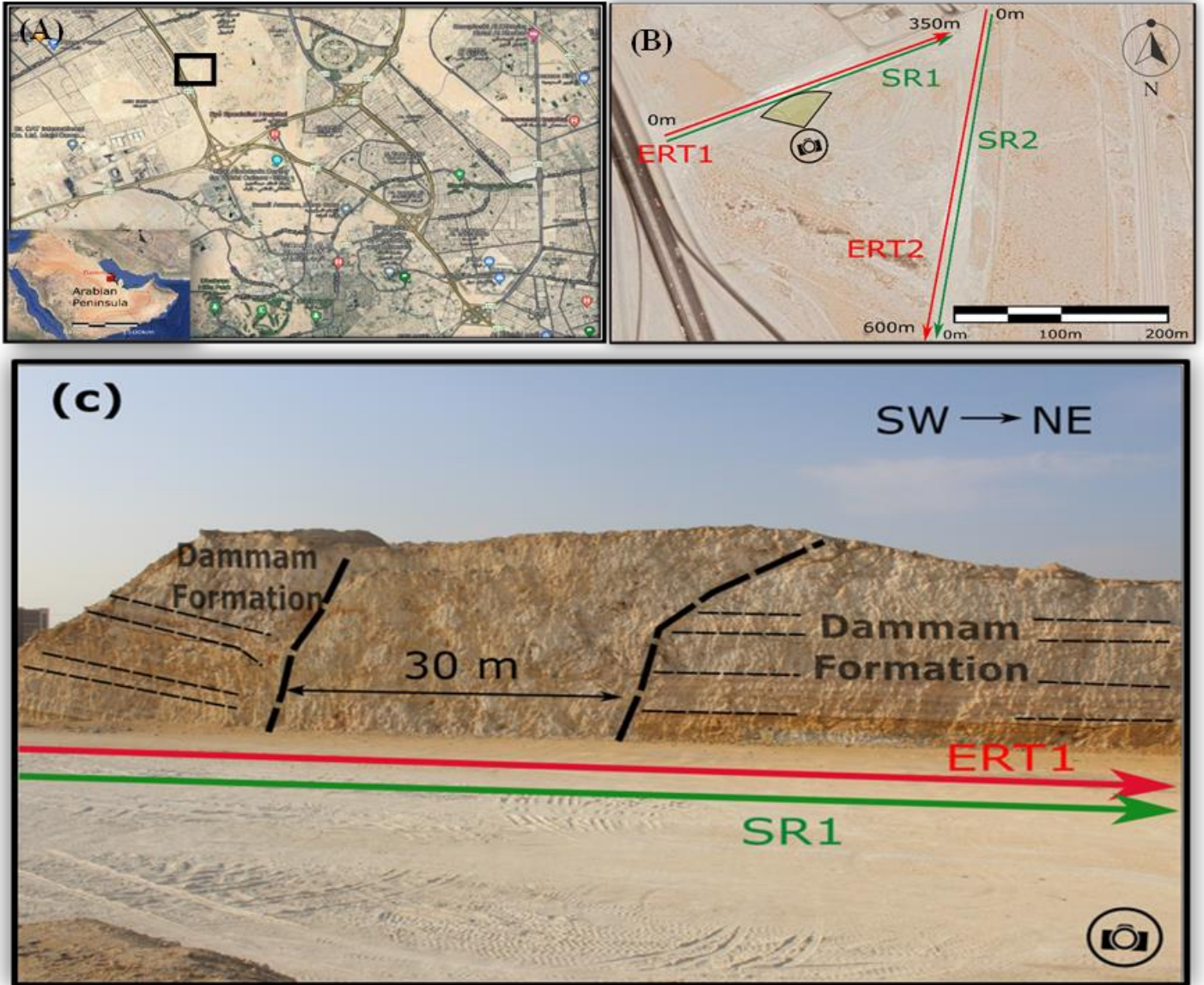


Figure 1: A) Satellite map of the study area which is located at the eastern side of Saudi Arabia. B) Location of the seismic and resistivity profiles recorded at the study area. C) the outcrop shown at the study area.

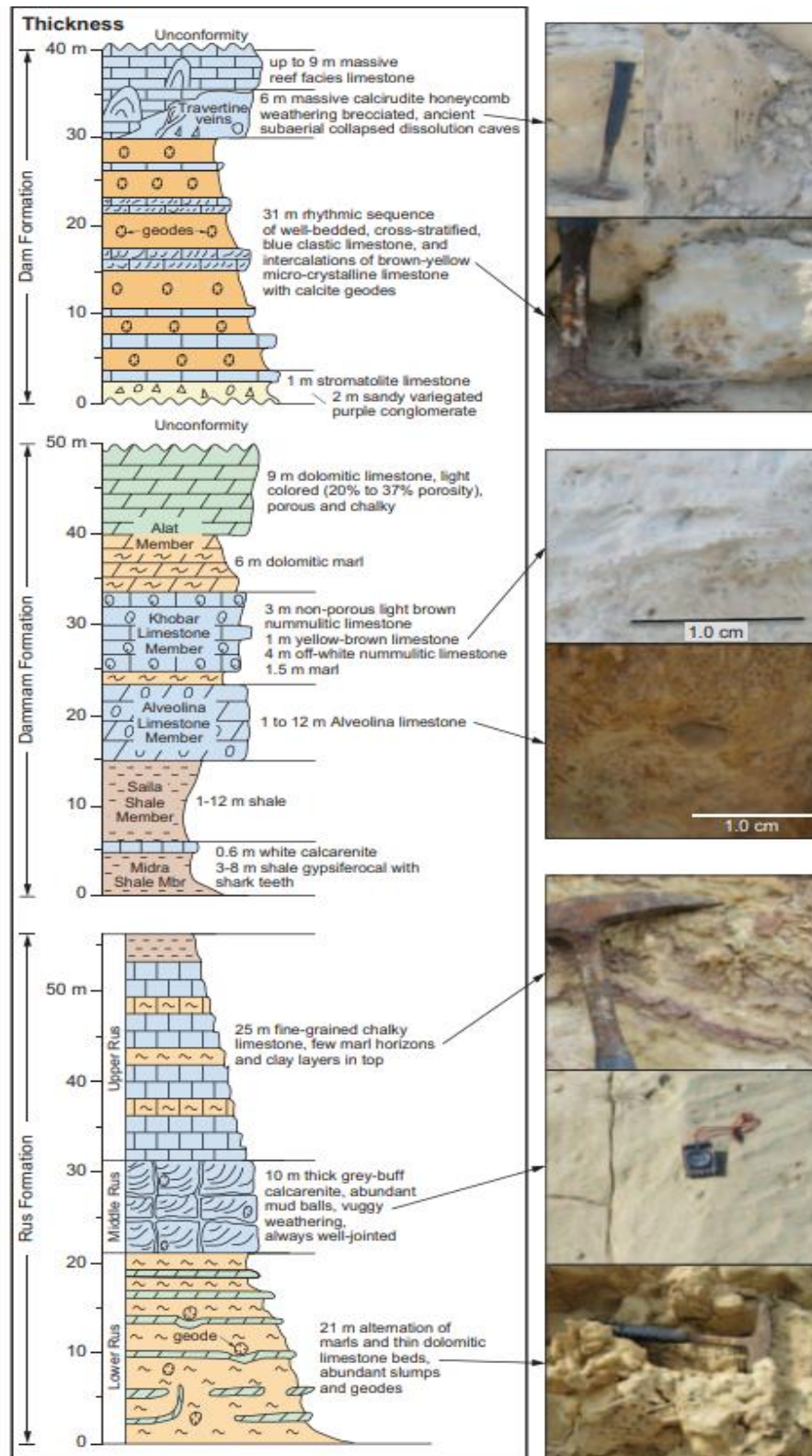


Figure 2: The stratigraphic column describing different formation in the area (after Weijermars, 1999; Powers, 1966; Tleel 1973).

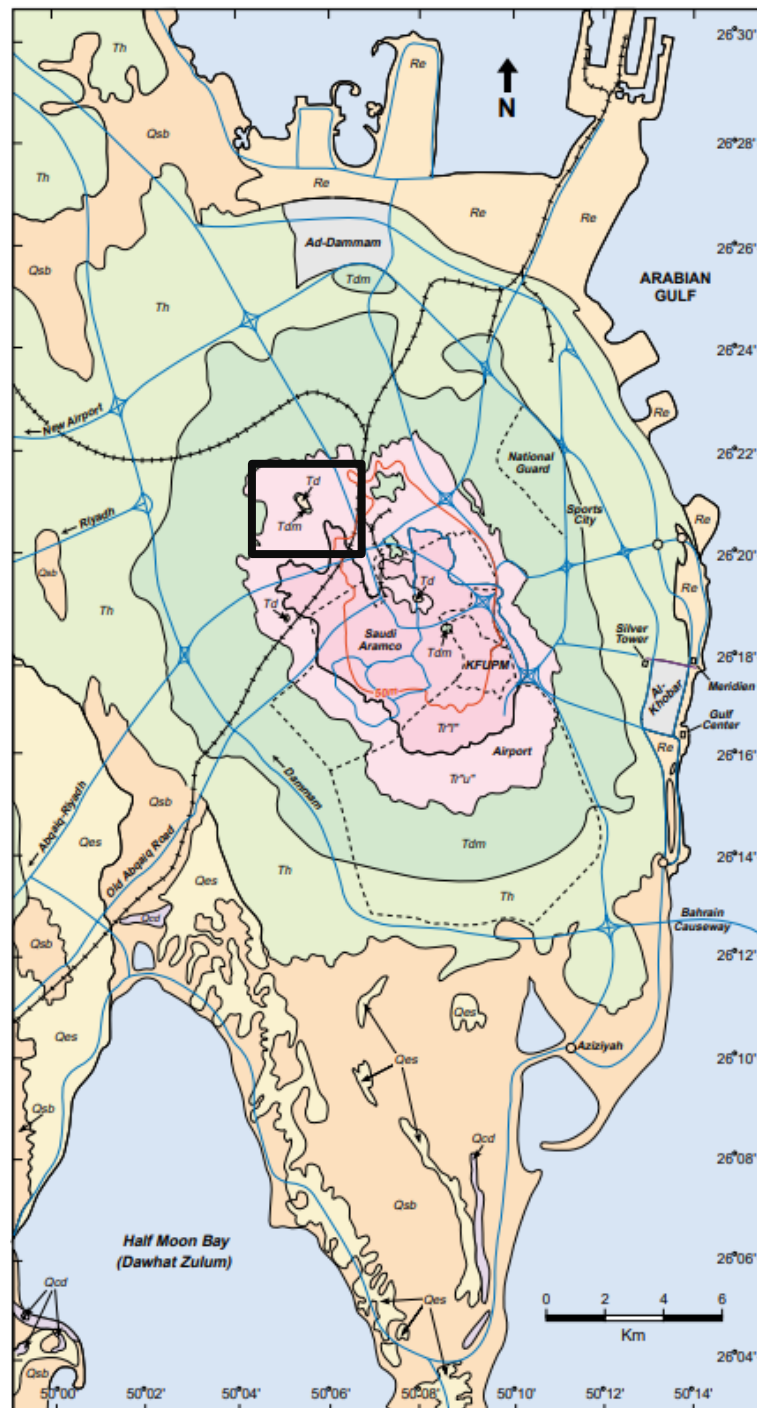


Figure 3: Geological map of the Dammam Peninsula showing the location of the study area (black box) and the different geological units (from Steineke et al., 1958; Tleel, 1973; Roger, 1985). Td: Dam Formation, Tdm: Dammam Formation, Tr'u": Upper Rus Formation(1c).

CHAPTER 2

LITERATURE REVIEW

Hanafy (2013) used seismic and electromagnetic (EM) methods to image the subsurface and characterize the near-surface geological section. They optimized the groundwater usage by finding the depth of the aquifer, its thickness, and the rate of aquifer recharge.

Awais and Hanafy (2022) presented a new method for enhancing the accuracy of DBSCAN's first arrival traveltimes picking using super-virtual refraction interferometry. The authors note that accurate traveltimes picking is crucial for seismic data processing and interpretation, and that traditional traveltimes picking methods can be limited by the presence of noise and other factors.

The proposed method involves using super-virtual refraction interferometry (SVI) to enhance the signal-to-noise ratio of the seismic data, which can improve the accuracy of DBSCAN's first arrival traveltimes picking. The authors compared the performance of their method to other commonly used traveltimes picking methods, such as the STA/LTA method, and show that their method is more effective at picking the correct arrival time, especially in noisy seismic data.

Zhou and Hanafy (2022) introduce a new method for traveltimes picking that is based on an iterative interferometric denoise filter for random noises. The authors emphasized that accurate traveltimes picking is crucial for seismic data processing and interpretation, especially in near-surface imaging applications.

To address the challenges of noisy seismic data, the proposed method uses an iterative approach to denoise the data and enhance the signal-to-noise ratio, leading to improved accuracy in traveltimes picking. The authors compare the performance of their method to other commonly used traveltimes

picking methods, such as the STA/LTA method, and demonstrate that their method is more effective at picking the correct arrival time.

Moreover, the authors discuss the potential applications of their method, including near-surface imaging and subsurface structure monitoring. They also highlight the ease of integration of their method into existing seismic data processing workflows, which can enhance the accuracy and quality of seismic data.

Furthermore, ERT can be used to characterize cavity (Herb et al., 2015) where the unconsolidated weak zones of deep structure can be detected and mapped to understand the subsurface, in their research he used a 2D profile using 112 electrodes with 1m spacing between each electrode and for the sequence protocol Dipole-Dipole was selected since it has the highest resolution and depth.

Additionally, in a study done by (Soupios et al., 2007) the geophysical investigation was conducted in a landfill area as part of a preliminary study. Electrical resistivity tomography (ERT) was used for geophysical modeling due to its effectiveness in resolving environmental issues. The survey took place in Akrotirion Peninsula, near Chania city in Crete. The geological setting consisted of limestone, marly limestone, and a weathered clay layer with identified cavities. The ERT survey involved seven tomographies, reaching a depth of 36 meters. The resulting images helped address geotechnical challenges by identifying the spatial distribution of karstic voids, planning waste disposal sites, and estimating waste thickness. The images were confirmed using available borehole logs.

The study conducted in Florida, USA, used 3D seismic imaging to detect sinkholes in a karst region characterized by complex geological structures (Gutierrez et al., 2017). The research team used a combination of 3D seismic imaging and borehole drilling to identify and map the locations of

sinkholes and other subsurface cavities. The study area was in the western part of the state, which is known for its karst topography and high incidence of sinkholes. The authors found that 3D seismic imaging was able to detect both active and dormant sinkholes with high accuracy and resolution. They also noted that the technique was able to identify other subsurface features, such as fractures and voids, that may contribute to sinkhole formation. Overall, the study highlights the potential of 3D seismic imaging for sinkhole detection in karst regions and provides important insights into the geological processes that contribute to sinkhole formation.

The combination of XRD and XRF techniques has been used in various research studies, such as the characterization of mineralogy and geochemistry in soils and sediments, the analysis of archaeological artifacts, and the study of geological processes. The combination of these techniques can provide a comprehensive understanding of the chemical and structural properties of materials, making them a valuable tool in materials science and geology research (Sharma & Singh, 2018).

Al-Fahmi (2014) used GIS and google maps to outline the outcrops within the Dammam Dome depending on the type of rock and stratigraphical positions. Then compare that with the presence of lithological features unmatched surfaces. In another study, other aspects were considered to characterize fractures and other structural elements within the mapped outcrop. They used aspects such as stress regimes of far and near surface fields, dome modeling, and potential influence (Powers et al., 1966).

Recently, Alkhalifa & Kurison (2022) researched the same area and they concluded that the anomaly observed in the study area can be attributed to weathering of layers due to the tectonic uplifting and collapse processes.

Çağatay (1990) provides a detailed analysis of the occurrence and characteristics of palygorskite in the Eocene rocks of the Dammam Dome in Saudi Arabia. The author describes the geology of the region, including the stratigraphy and depositional history of the Eocene rocks. The research then focuses on the mineralogy and morphology of the palygorskite found in the area, including its crystal structure, chemical composition, and physical properties. The author notes that the palygorskite occurs as thin layers and nodules within the Eocene rocks, and that it is characterized by a fibrous morphology with a high aspect ratio. Çağatay (1990) is a valuable resource for researchers and practitioners interested in the mineralogy and geology of the region, as well as those interested in the properties and uses of palygorskite.

Recently, Ali et al. (2021) investigates the dolomitization and paleoenvironment of deposition of the Lower and Middle Rus Formation in the Dammam Dome region of Eastern Saudi Arabia. The authors describe the lithology and stratigraphy of the formation, noting that it is composed primarily of limestone and dolomite with interbedded shale and sandstone layers. The authors then analyze the dolomite mineralogy, texture, and geochemistry of the formation, and note that it has undergone extensive dolomitization. They suggest that the dolomitization was likely caused by the influx of magnesium-rich fluids during diagenesis. The authors also analyze the paleoenvironment of deposition of the formation, using sedimentological and stratigraphic data. They suggest that the formation was deposited in a shallow marine environment with periodic influxes of terrigenous sediments. They also note that the formation contains abundant fossils, including foraminifera, mollusks, and echinoids, which provide insights into the paleoenvironment and paleoecology of the region during the Early Eocene.

Finally, Salih et al. (2023) investigated the factors that control sonic velocity in dolostones. The authors describe the geological setting of their study area in the Western Desert of Egypt, which is

characterized by extensive dolomitization of the Lower Cretaceous carbonates. The authors then analyze the sonic velocity of the dolostones in the region, using laboratory measurements and petrophysical analysis. The authors identify several factors that influence sonic velocity in dolostones, including dolomite crystal size, porosity, and saturation. They note that larger dolomite crystals tend to have higher sonic velocities, while higher porosity and lower dolomite saturation tend to result in lower sonic velocities. The authors also note that the presence of fractures and vugs can significantly impact sonic velocity, by reducing the effective velocity of the rock.

CHAPTER 3

METHODOLOGY

The geophysical techniques used in this work include the seismic and electric resistivity. In this chapter, the two methods used in this study will be discussed with focusing on the background theory, data quality control, data enhancement and inversion.

3.1. Traveltime Tomography

Traveltime tomography is commonly used for reconstructing subsurface velocity distribution from first-arrival traveltime (Nolet, 1987; Lutter et al., 1990; Aldridge and Oldenburg, 1993; Ammon and Vidale, 1993; Nemeth et al., 1997 and many others). The technique involves iterative updating of velocities using methods such as the Simultaneous Iterative Reconstruction Technique (SIRT). The process typically involves estimating an initial velocity model from the x-t slope of the first-arrival traveltimes of the recorded data, followed by computing synthetic traveltimes using the finite-difference solution to the Eikonal equation, hence, minimizing the error between the observed and calculated (synthetic) traveltimes. The resulting P-wave velocity model can indicate features such as unconsolidated zones and sharp horizontal changes in velocity that may correspond to faults. However, reflection sections can provide a more definitive indicator of faults (Morey and Schuster, 1998).

The data misfit function (ϵ) in traveltime tomography (equation 1) is used to measure the difference between predicted and observed travel times. In the case where the traveltimes are computed from the starting model by a finite-difference solution to the Eikonal equation, the data misfit function can be defined as:

$$\varepsilon = \frac{1}{2} \sum_i (t_i^{obs} - t_i^{cal})^2 \quad (1)$$

where t_i^{obs} , is the observed travel time at point i , t_i^{cal} , is the calculated travel time at point i , and Σ is the sum over all points i . The $1/2$ factor is included for convenience and does not affect the minimization of the function (Aldridge and Oldenburg, 1993). So, the j gradient of the misfit function can be expressed as:

$$\gamma_j = \frac{\delta \varepsilon}{\delta s_j} = \sum_i \delta \tau_i \frac{\delta \tau_i}{\delta s_j} = \sum \delta t_i \delta l_{ij} \quad (2)$$

Where δs_j is the slowness (inverse of the velocity), $\delta \tau_i$ is the travelttime residual and l_{ij} is the length of the ray inside cell i . A gradient optimization method (like steepest descent) is used to iteratively update the slowness model in travelttime tomography. The method adjusts the slowness model based on the gradient of the misfit function, aiming to minimize the difference between the observed and calculated travelttime data (Nemeth et al., 1997).

3.1.1 Quality Control and First break picking:

After recoding the field data, a first break picking is completed, using manual or automatic routines. In our case an in-house software, called DataPick, is used to complete the first arrival picking step. Picking the first breaks can be a time-consuming step depending on the signal to noise ratio (SNR) of the recorded data. Figure 4 shows an example of one shot gathered with the picked first arrivals highlighted.

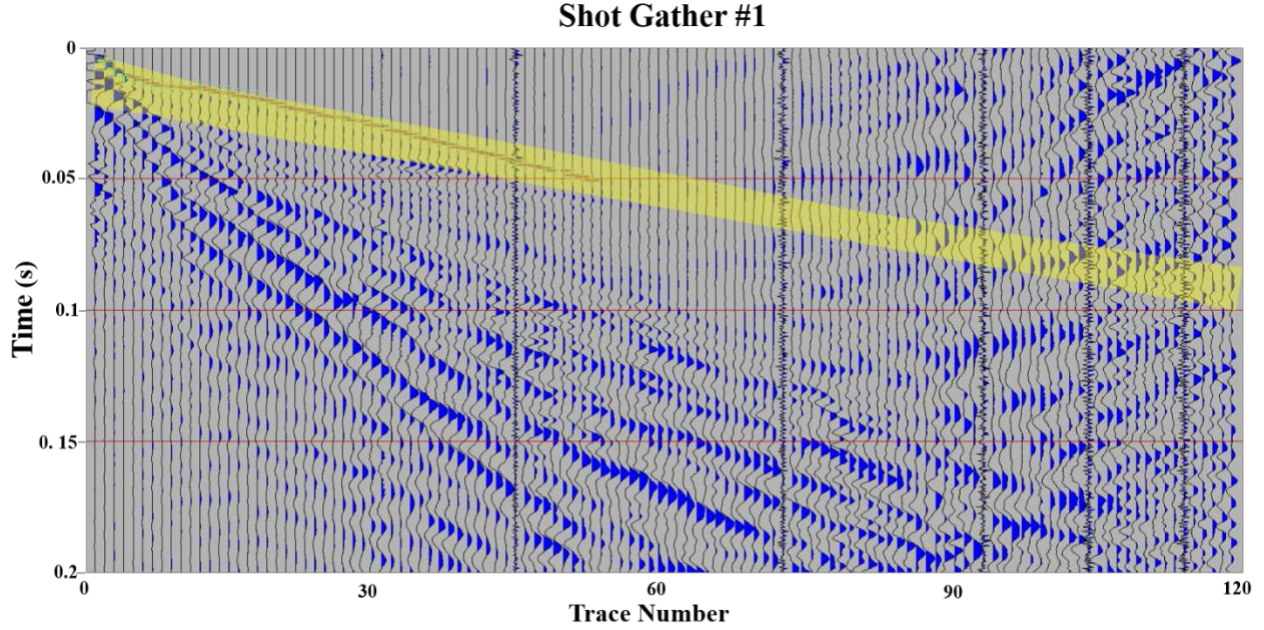


Figure 4: Shot gather no. 1. The highlighted area indicates the first arrival traveltimes. The data shows a low SNR, which makes the first arrival picking very hard especially at large source-receiver offsets.

To invert the first arrival traveltime data, we need to make sure that the picked data is reliable. A reciprocity test is an important step for quality control to test the picked data. Reciprocity tests can be performed by comparing the travel time measured from a source at location i to a receiver at location j (τ_{ij}) to the travel time recorded from a source at location j to a receiver at location i (τ_{ji}). This test assumes that ($\tau_{ij} = \tau_{ji}$), however, for practical reasons, we use a certain tolerance in our case, which equals to 3 milliseconds. In our field example, a total of 120 traveltime did not pass the reciprocity test, and, hence, were rejected out of 14400 recorded traveltime

3.1.2 Data enhancement using SVI

The SVI (Super-Virtual Interferometry) method is a technique used in seismic data processing to enhance the signal-to-noise ratio (SNR) of refraction arrivals. The method was originally described by Bharadwaj and Schuster (2010) and (2012), as well as by Bharadwaj et al. (2011) and Mallinson et al. (2011).

The SVI method employs the far-field reciprocity equation of both correlation (equation 3) and convolution (equation 4) types to create super-virtual refractions. This results in an enhanced SNR by a factor of $\sqrt{N}$, where N is the number of source positions associated with the generation of the head-wave arrival and coincident with the receiver.

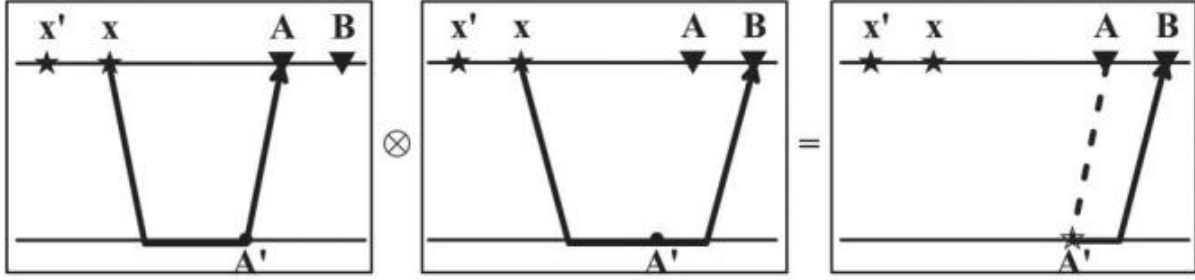
$$\text{Im}[G(A|B)^{virt.}] \approx \sim k \int G(A|X) * G(B|X) dx \quad (3)$$

$$G(B|X')^{super} \approx 2ik \int G(A|B)^{virt.} G(A|X') dA \quad (4)$$

In the SVI method, the source positions are denoted by x in Figure 5(a) and x' in Figure 5(b), while the receivers are located at A and B . The average wavenumber is represented by k . $G(A|B)$ denotes the head-wave contribution in Green's function for a virtual shot at A' , a receiver at B , and the virtual excitation time is equal to the negative traveltimes from A to A' .

On the other hand, $G(B|x')^{super}$ represents the super-virtual data obtained by convolving the recorded data $G(A|x')$ with the virtual data $G(A|B)^{virt.}$, as shown in Figure 5b). This convolution process enhances the SNR of the refraction arrivals by combining the recorded data with virtual data generated from the head-wave contribution in Green's function.

a) Crosscorrelate and stack over x to generate virtual refractions



b) Convolve and stack over A to generate super-virtual refractions

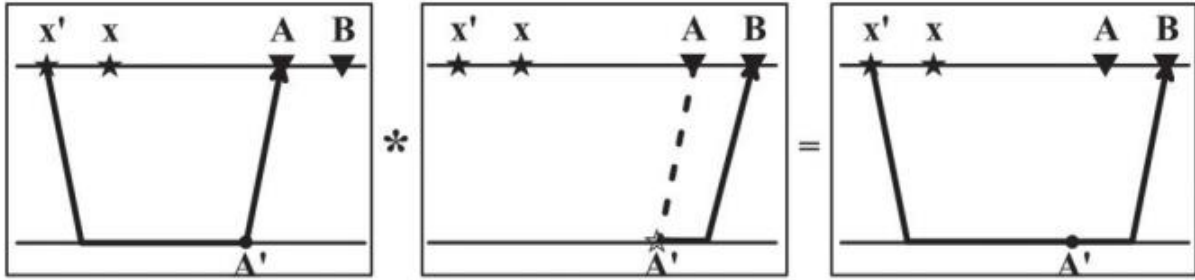


Figure 5: The steps for creating super-virtual refraction arrivals. a) Correlation of the recorded trace at A with that at B for a source at x to give the trace $G(A, B, t)$ with the virtual refraction having traveltime denoted by $\tau_{(A'B)} - \tau_{A'A}$. This arrival time will be the same for all post-critical source positions, so stacking $\Sigma G(A, B, t)$ will enhance the SNR of the virtual refraction by $\sqrt{N}$. b) Similar to that in a) except the virtual refraction traces are convolved with the actual refraction traces and stacked for different geophone positions to give the super-virtual trace with a SNR enhanced by $\sqrt{N}$. Here, N denotes the number of coincident source and receiver positions that are at post-critical offset for this particular refraction.

As mentioned earlier, the SVI method may produce artifacts in the super-virtual data set due to the limited recording aperture and discrete sampling. To avoid these artifacts, Dong et al. (2006) suggested a windowing technique.

The workflow of the SVI method with windowing is as follows:

1. Filter the raw data to remove high-frequency noise.
2. Window about the first arrivals. The suggested window length is 1 period before the expected first-arrival times and 2 to 3 periods after it. This windowing technique ensures that only head-wave arrivals, which are less affected by artifacts, are correlated with one another.
3. Use equation (1) to generate the virtual traces.

4. Use equation (2) to generate the super-virtual traces.

3.1.3 Smoothing Filter

In the seismic inversion process, a rectangular smoothing filter is often applied after each iteration to account for irregular ray path coverage in some parts of the velocity model (Nemeth et al., 1997). This filter helps to smooth the seismic image and reduce the effects of noise and artifacts in the data. The table below shows the smoothing filter used in the inversion process of the data. The smoothing grid started with a size of 20m x 10m, and after the fifth iteration, the size of the smoothing filter was halved until the last smoothing size was reached.

Table 1 Smoothing schedule of 2D data with 5 iterations each.

Grid size	0.5 m
Smoothing size 1	20 X 10 (pixels)
Smoothing size 2	12 X 6 (pixels)
Smoothing size 3	8 X 4 (pixels)
Smoothing size 4	4 X 2 (pixels)

3.2. Electrical Resistivity Tomography (ERT):

Electrical resistivity tomography (ERT) is a non-invasive geophysical imaging technique used to map subsurface resistivity distributions. ERT is based on the measurement of electrical resistivity, which is a measure of a material's ability to resist the flow of electrical current. In ERT, an electrical current is injected into the ground through two or more electrodes, and the voltage difference is measured between other electrodes. By measuring the voltage difference between different electrode pairs, we can calculate the apparent resistivity of the subsurface at each measurement location.

The inverse problem in ERT is to determine the true subsurface resistivity distribution vs. depth from the measured apparent resistivity data. This is typically done using inversion algorithms that minimize the difference between the observed and calculated apparent resistivity values. There are various inversion algorithms available, including smoothness-constrained least-squares inversion (Loke, M. H. 2011), Occam inversion, and Bayesian inversion.

ERT surveys can be conducted using a variety of electrode configurations, including Wenner, Schlumberger, and dipole-dipole arrays, depending on the specific application and the desired resolution of the subsurface imaging. The choice of electrode configuration depends on the depth of investigation, the subsurface geology, and the spatial resolution required for the imaging (Loke, M. H., & Barker, R. D. 1996).

Wenner Array: In the Wenner array, the potential electrodes (M and N) are positioned at equal distances from the current electrodes (A and B). The potential electrodes are located outside the current electrode spacing.

Schlumberger Array: The Schlumberger array involves placing the potential electrodes (M and N) at a fixed distance from each other, which creates a central measurement point. The current electrodes (A and B) are symmetrically positioned on either side of this central point.

Dipole-Dipole Array: In the Dipole-Dipole array, the potential electrodes (M and N) are positioned further apart compared to the Wenner and Schlumberger arrays. The current electrodes (A and B) are placed between M and N, resulting in a larger electrode spacing (Loke, M. H. 2011).

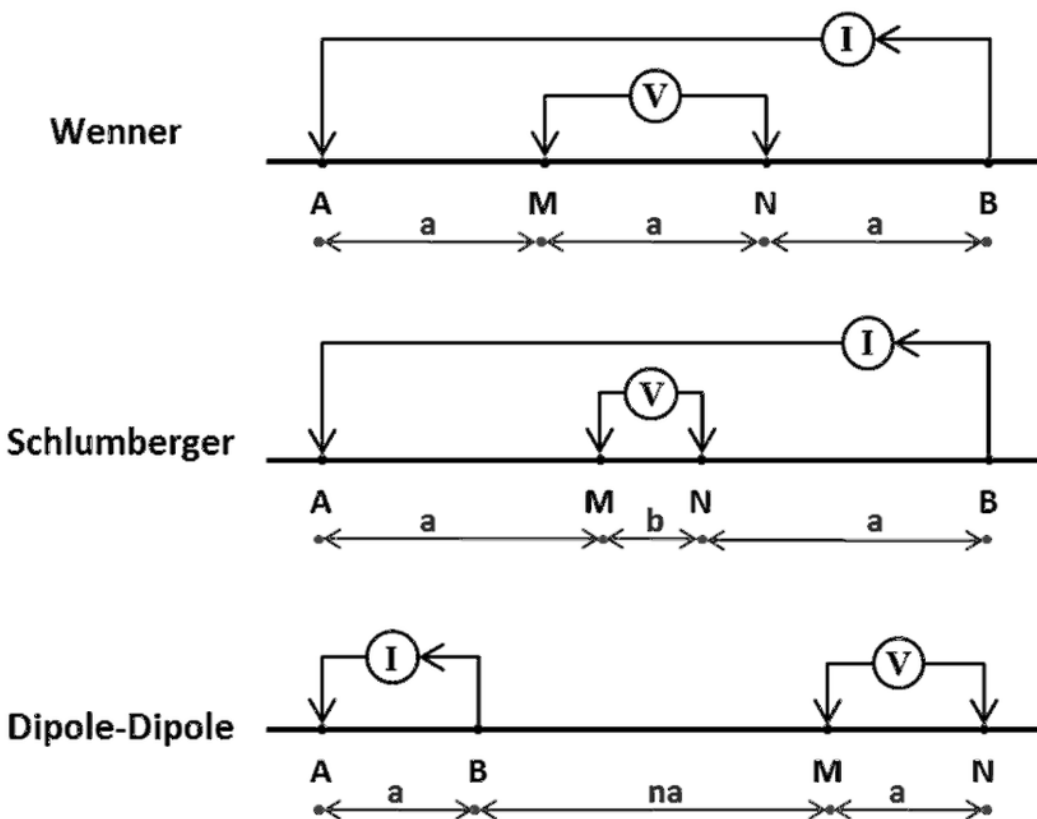


Figure 6: The electrodes are labeled as A and B for the current electrodes and M and N for the potential electrodes and a for the space between the electrodes.

To conduct an ERT survey, the first step is to design the electrode array, which involves selecting the type of array, the electrode spacing, and the number of electrodes. The electrodes are then placed in the ground, and an electrical current is injected into the ground through two or more electrodes. The voltage difference is measured between other electrodes, and the apparent resistivity is calculated. The measurement process is repeated at different locations to obtain a set of apparent resistivity data (Loke, M. H. 2011).

The next step is to invert the apparent resistivity data to obtain the subsurface resistivity distribution. This is done using inversion algorithms, which typically involve iteratively adjusting the resistivity distribution until the calculated apparent resistivity values match the observed values within a certain tolerance. The final result is a resistivity image of the subsurface, which can be used to identify subsurface features such as groundwater reservoirs, contaminant plumes, geological structures, and archaeological artifacts (Loke, M. H. 2011).

One of the key advantages of ERT is that it is non-invasive and can provide high-resolution imaging of the subsurface. However, ERT has limitations, including the assumption of a homogeneous subsurface and the sensitivity of the method to electrode placement and noise in the data (Loke, M. H. 2011).

CHAPTER 4

DATA ACQUISITION

4.1 Geology fieldwork

Six rock samples were collected and analyzed using XRD and XRF to find the mineral and chemical composition of the formation. More investigation was done to find the extension of the outcrop by tracing fractures on the other side of the outcrop after the cut rode (Figure 7).



Figure 7: Left, a normal fault observed within the deformation zone. Right, outside the deformation zone

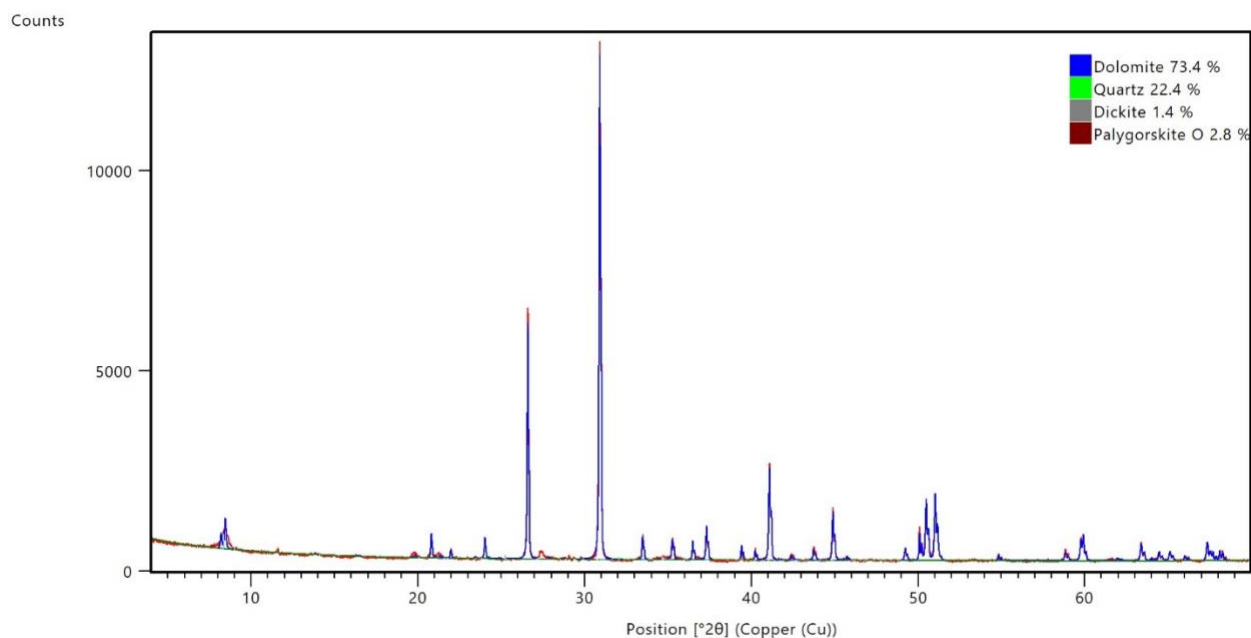


Figure 8: XRD data for Sample 1 contains a relatively high percentage of dolomite (73.4%) and a moderate amount of quartz (22.4%). It also contains a small amount of calcite (4.2%), this sample took from left side of the wall of the deformation zone.

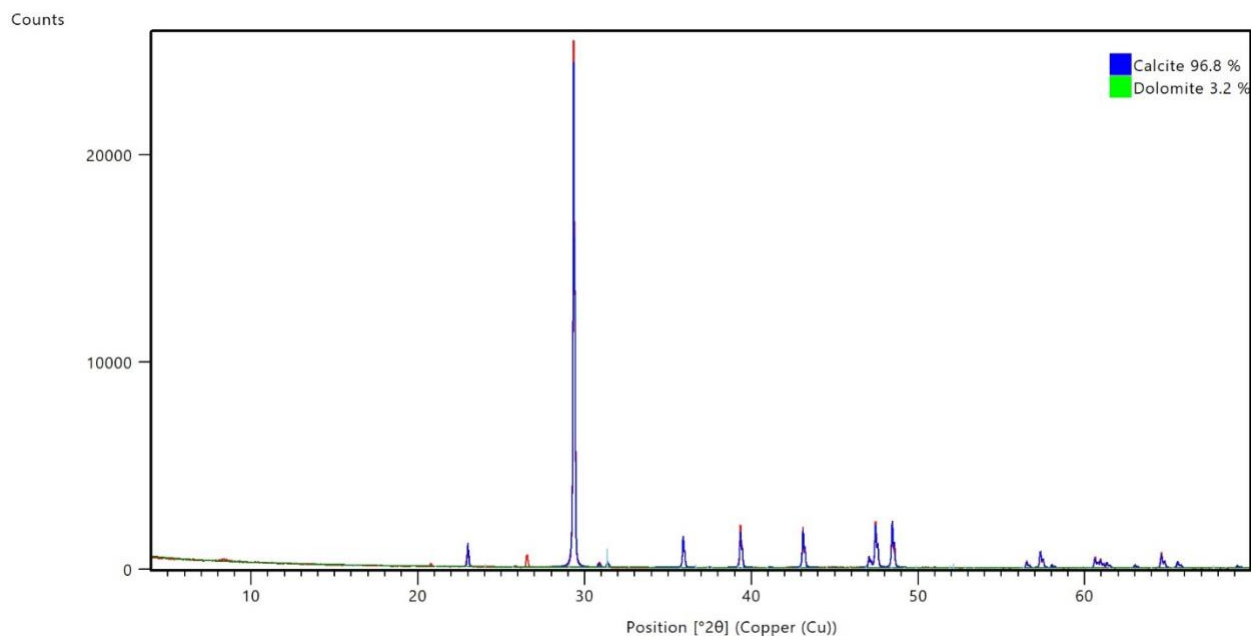


Figure 9: XRD data shows a very high percentage of calcite (96.8%) and a small amount of dolomite (3.2%) in sample 2 which was collected from the right side of the deformation zone.

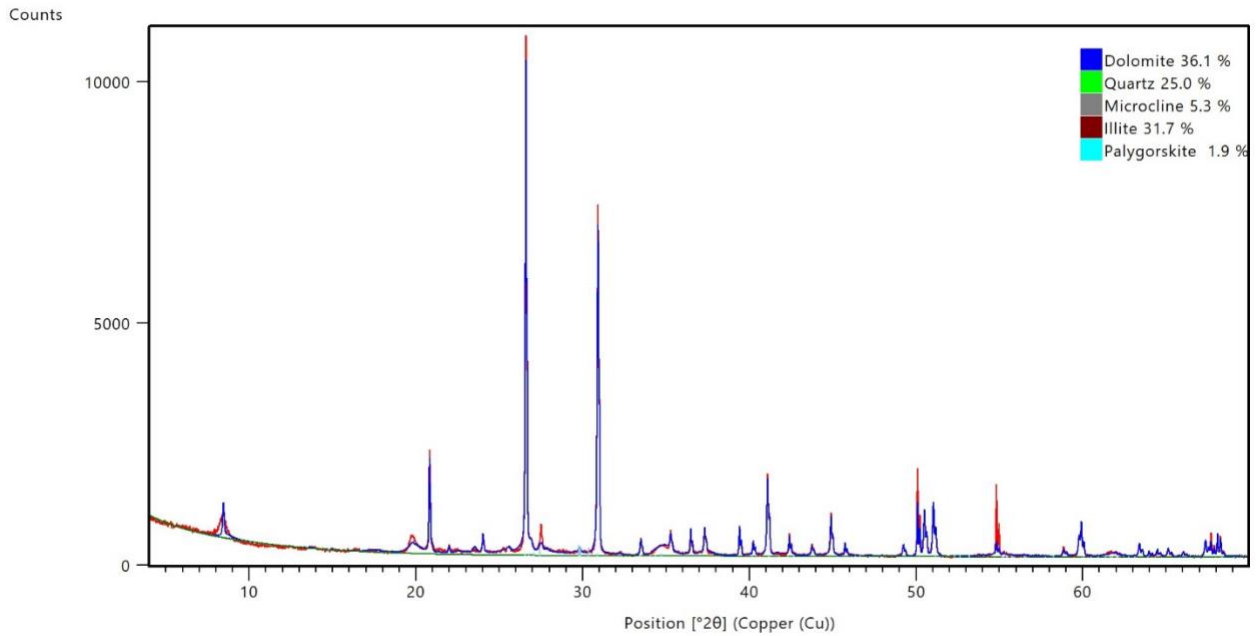


Figure 10: XRD composition of sample 3 which is characterized by a roughly equivalent percentage of quartz (25%), dolomite (36.1%), and calcite (33.6%). Additionally, a minor proportion of evaporites (5.3%) is present in the sample.

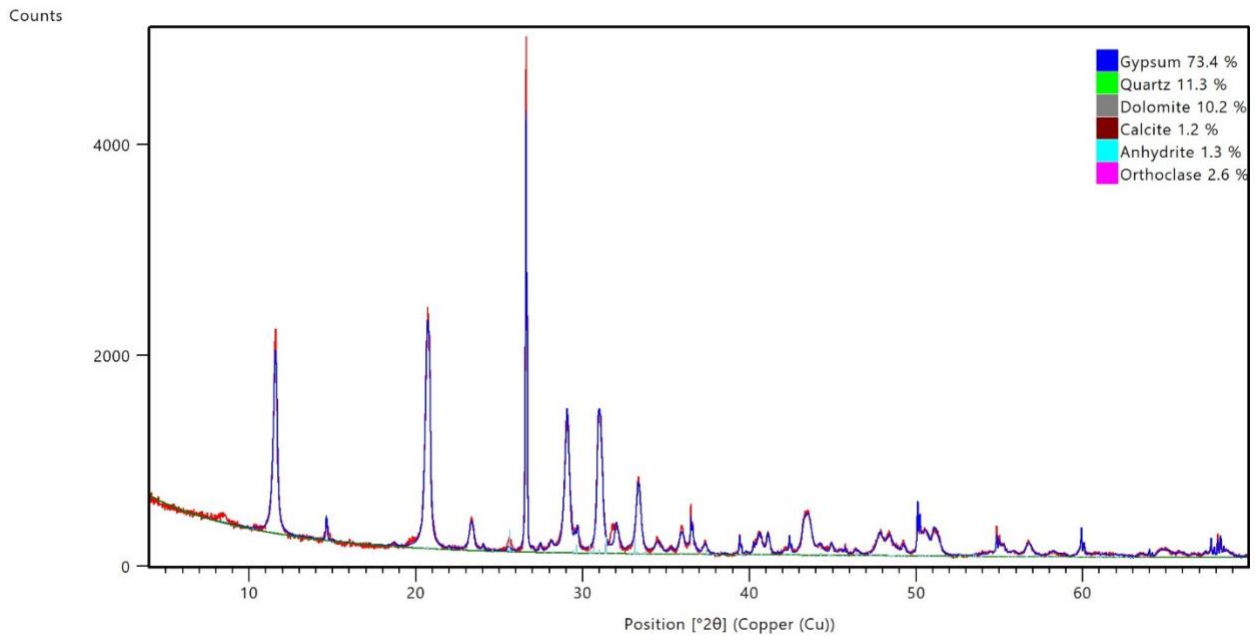


Figure 11: XRD mineral content of sample which 4 is relatively low, with the most abundant mineral being evaporites (74.7%). In addition, it contains small quantities of quartz (11.3%), dolomite (10.2%), and feldspar (2.6%).

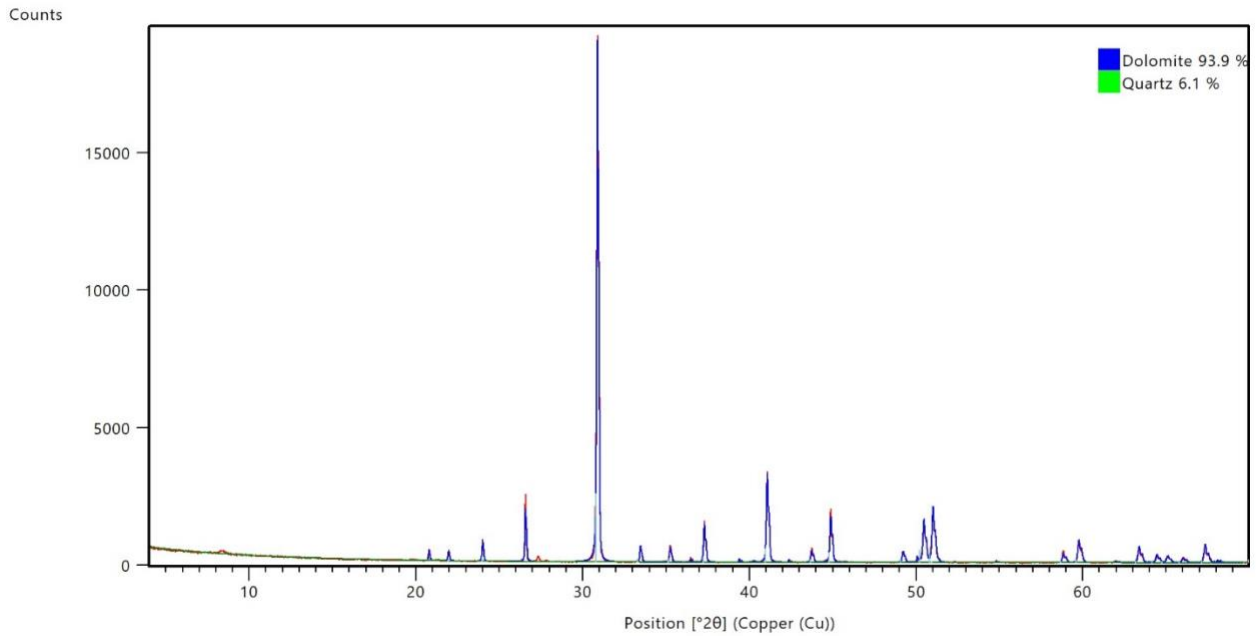


Figure 12 XRD of sample 5 is rich in dolomite (93.9%) and has a minor amount of quartz (i.e., 6.1%).

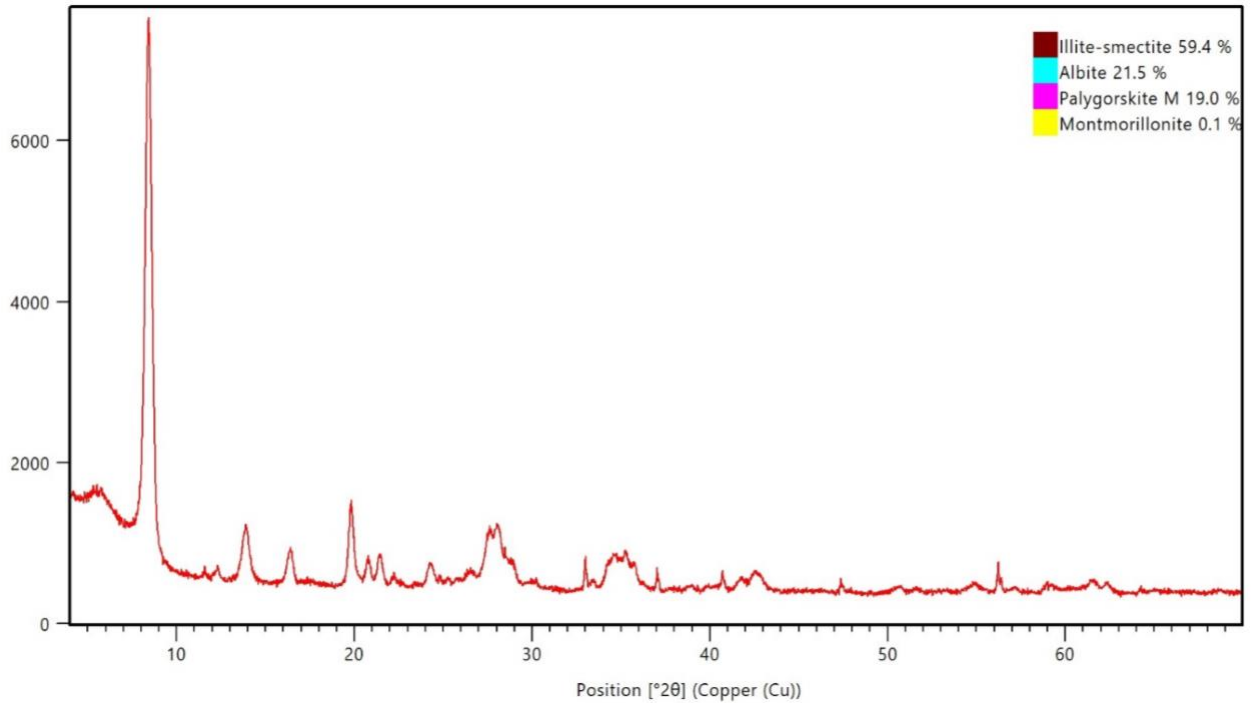


Figure 13: Shows the source which has been used in both 2D and 3D seismic acquisition which is acceleration weight-drop. The source is capable of generating P- wave as well as S-wave by only tilting the hammer in different angel, or keeping it perfectly vertical to

4.2 Geophysics Field Work

Figure 14, shows the sequence of the workflow of the geophysical field work. This chart for both seismic and resistivity

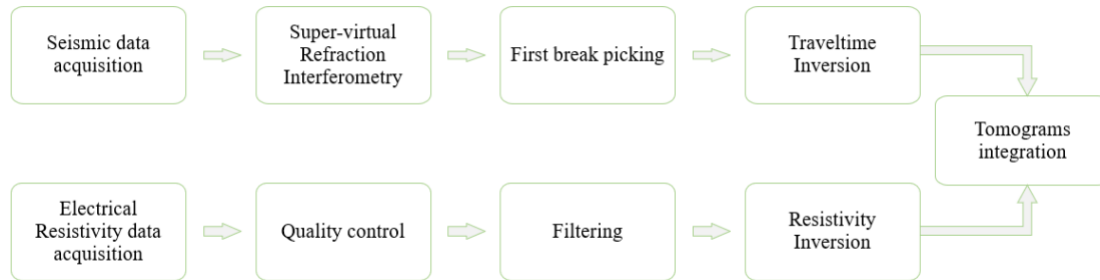


Figure 14: Chart explain the workflow for both seismic and resistivity.

4.2.1 2-D Seismic

The seismic profile (SR) has 120 single-component geophones with an interval of 3 m. 120 shot gathers were recorded with a shot interval of 3 m, where there is one shot at each receiver location. The profile has a SW-NE direction with a total profile length of 360 m. The seismic data was recorded using a Geode system. The seismic reflection profile (SR) was recorded using a 200-lb accelerated weight drop to generate the seismic energy (Table 2).

Table 2 Parameters for the 2-D and 3-D seismic surveys

Survey	2-D	3-D
Source	200-lb weight drop	200-lb weight drop
Recording instrument	Geode system	Smart Solo
No. of shots	120	385
No. of receivers	120	108
Shot spacing	5 m	4 m
Receivers spacing	5 m	8 m
Survey length	600 m	50 X 144
No. of traces	14,000	41,580
Sampling interval	0.2 ms	0.1 ms
Record length	1.0 sec	1.0 sec



Figure 15: Shows the source which has been used in both 2D and 3D seismic acquisition which is acceleration weight-drop. The source is capable of generate P- wave as well as S-wave with only tilting the hammer in different angel, or keeping it perfectly vertical to generate P-wave.

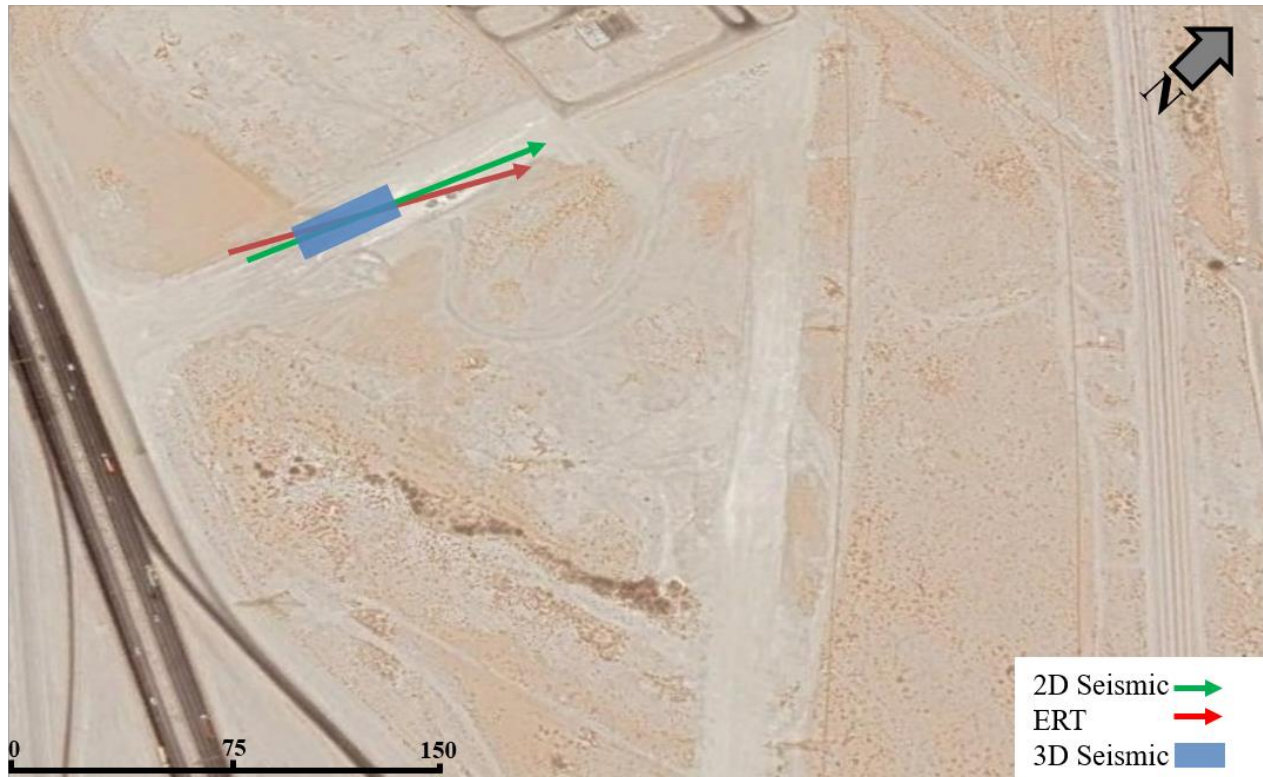


Figure 16: Shows with all geophysical methods used. The green arrow indicates the direction of the 2D seismic profile where the blue box indicates the 3D seismic location finally is the ERT profile which indicate here with the red color arrow.

Next, after recoding the data, quality control is crucial to enhance the SNR signal-to-noise ratio (Al-Mashhori et al., 2019; Zhou and Hanafy, 2022). The seismic profile (SR) was then processed and inverted, and the results are shown in Figures 17 to 21. Figure 17 shows an example of the recorded seismic data (shot gather # 1 from the SR data set). The red line in Figure 18 is the first break after applying SVI that was picked manually (Awais and Hanafy 2022). The first breaks of all shot gathers are picked in Figure 20 and then inverted to generate the travelttime tomogram shown in Figure 21.

The traveltime tomogram (Figure 21) has three layers, where the anomaly has low velocity within high velocity layers.

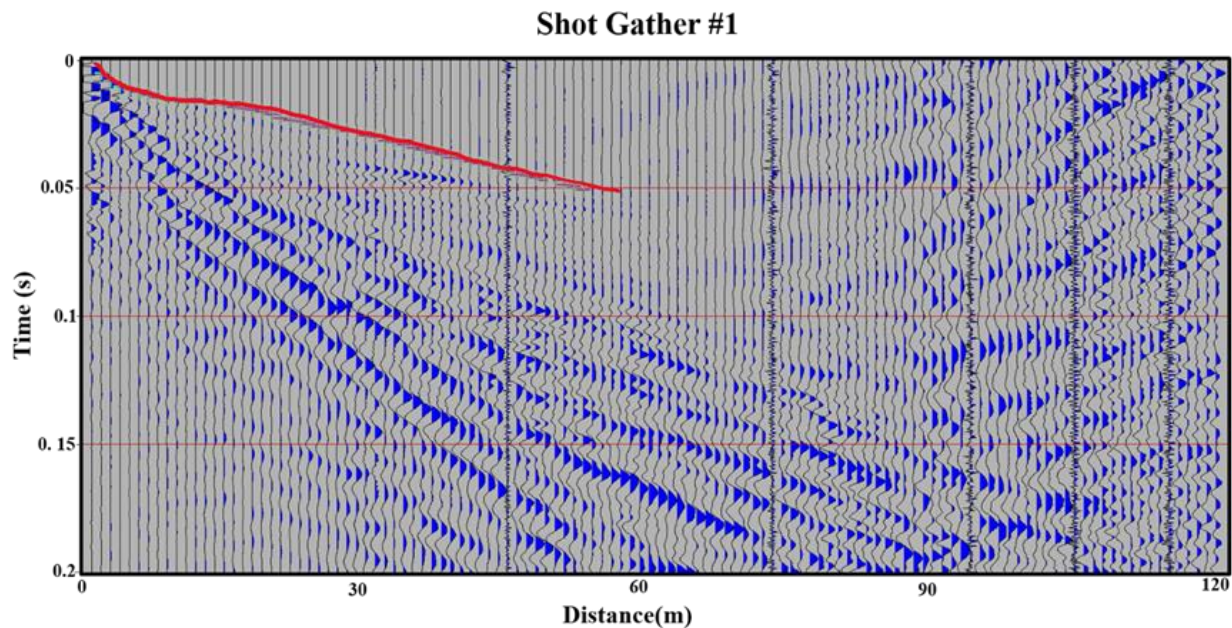


Figure 17: Shot gather #1 from SR first break picking after applying SVI, with an increase of signal to noise ratio I picked until the last trace.

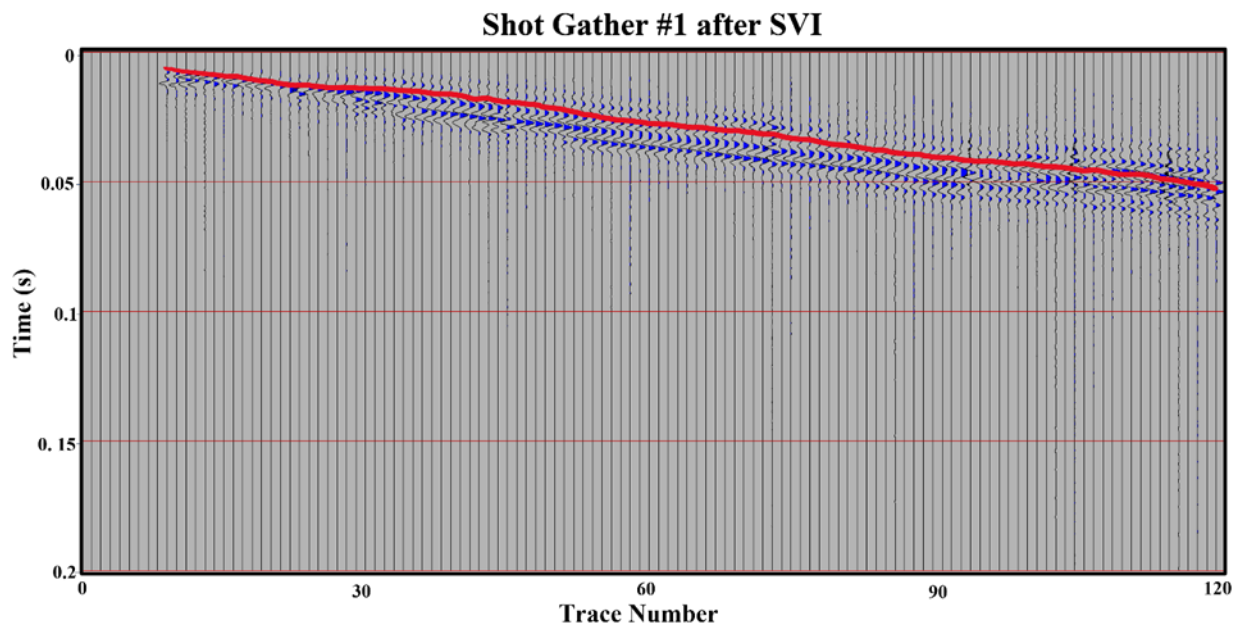


Figure 18: Shot gather #1 from SR first break picking after applying SVI, with an increase of signal to noise ratio I picked until the last trace

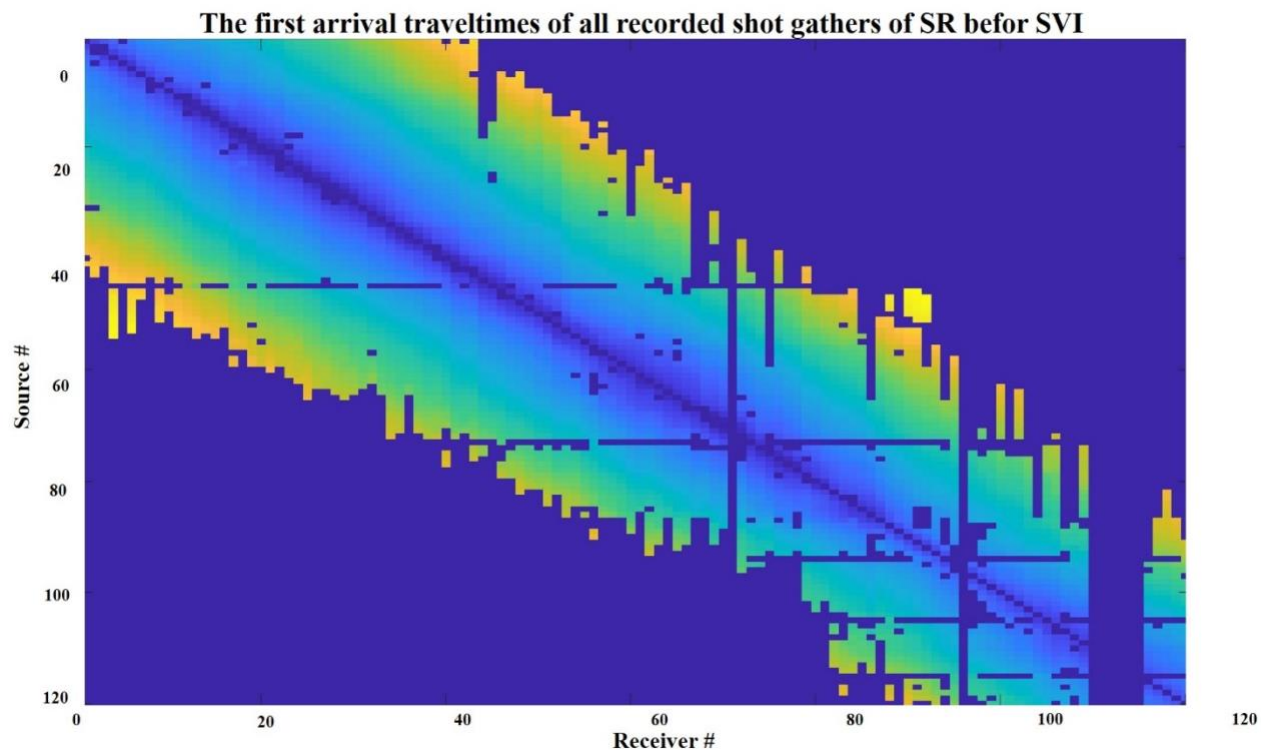


Figure 19: shows all shots gather it's clear that there many missing data where the dark blue color indicates unpicked traces either it's not picked or it does not pass the reciprocity test.

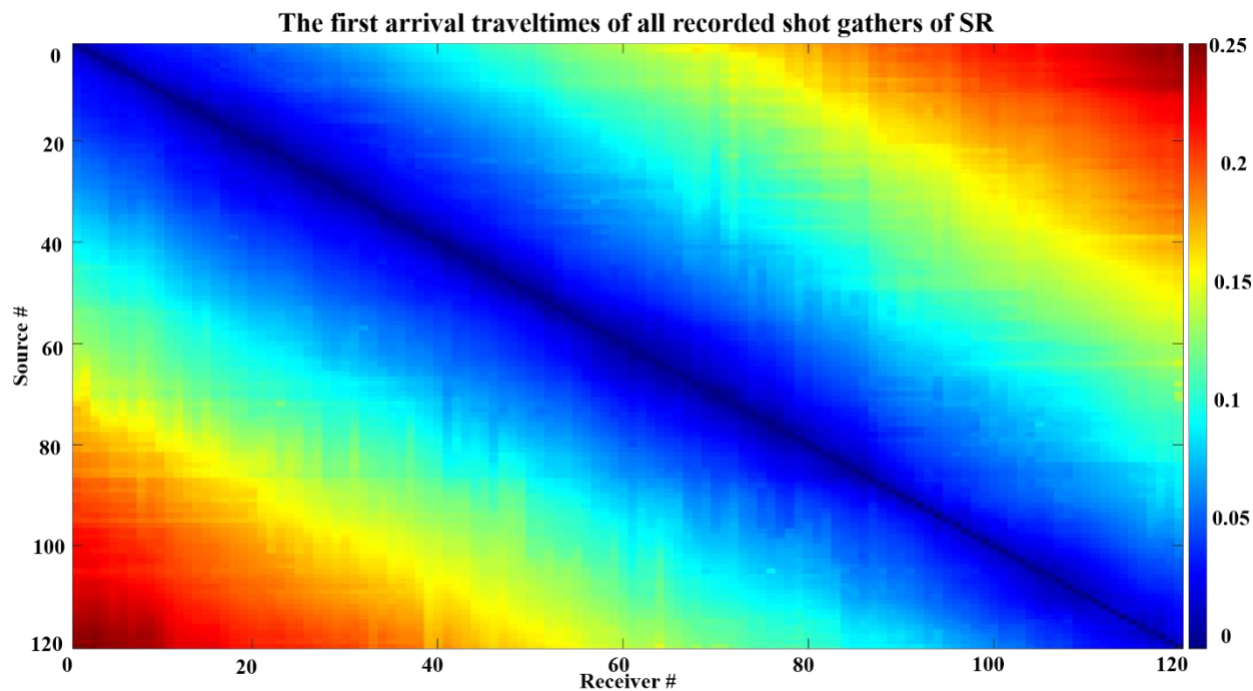


Figure 20: The first arrival traveltimes of all recorded shot gathers of SR 14400 traces were picked and pass the reciprocity test after the enhancement by using SVI.

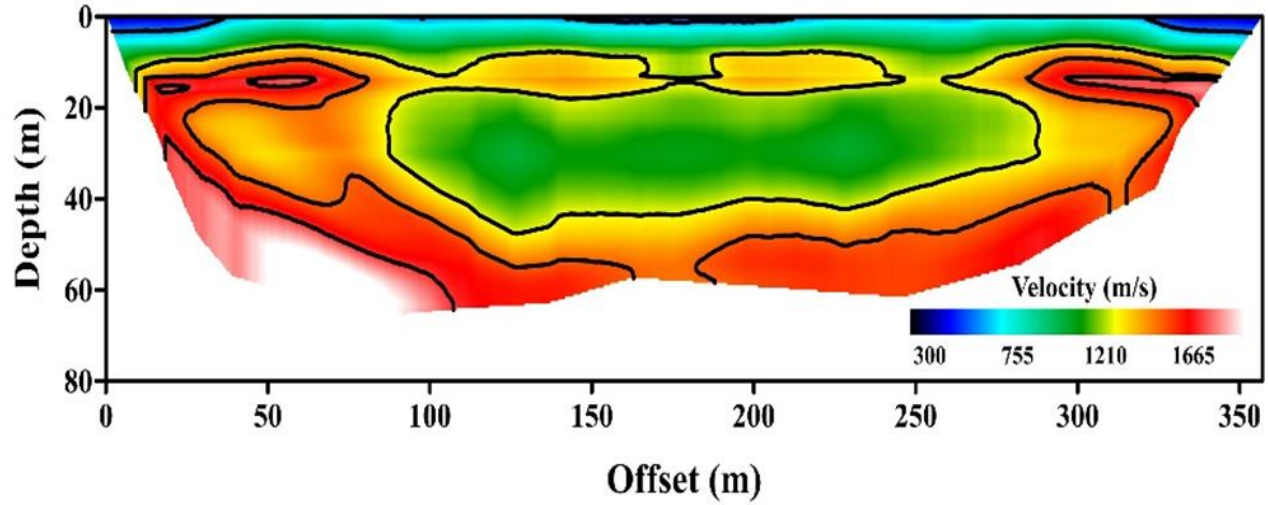


Figure 21: The final tomogram of the 2D seismic shows several layers with different velocities. Within the high velocity layer, a low velocity appears below the deformation zone which is shown on the surface.

4.2.2 3-D Seismic

108 wireless nodes were distributed in 6 profile lines, each profile has 18 nodes receivers with 8 m spacing. the shooting inline and cross line shot intervals are interval was 4 m on each receiver line and cross line (Figure 22). A weight-drop was used as the source of the signal, and the total number of shots was 385, where every receiver line and cross line had 35 shots.

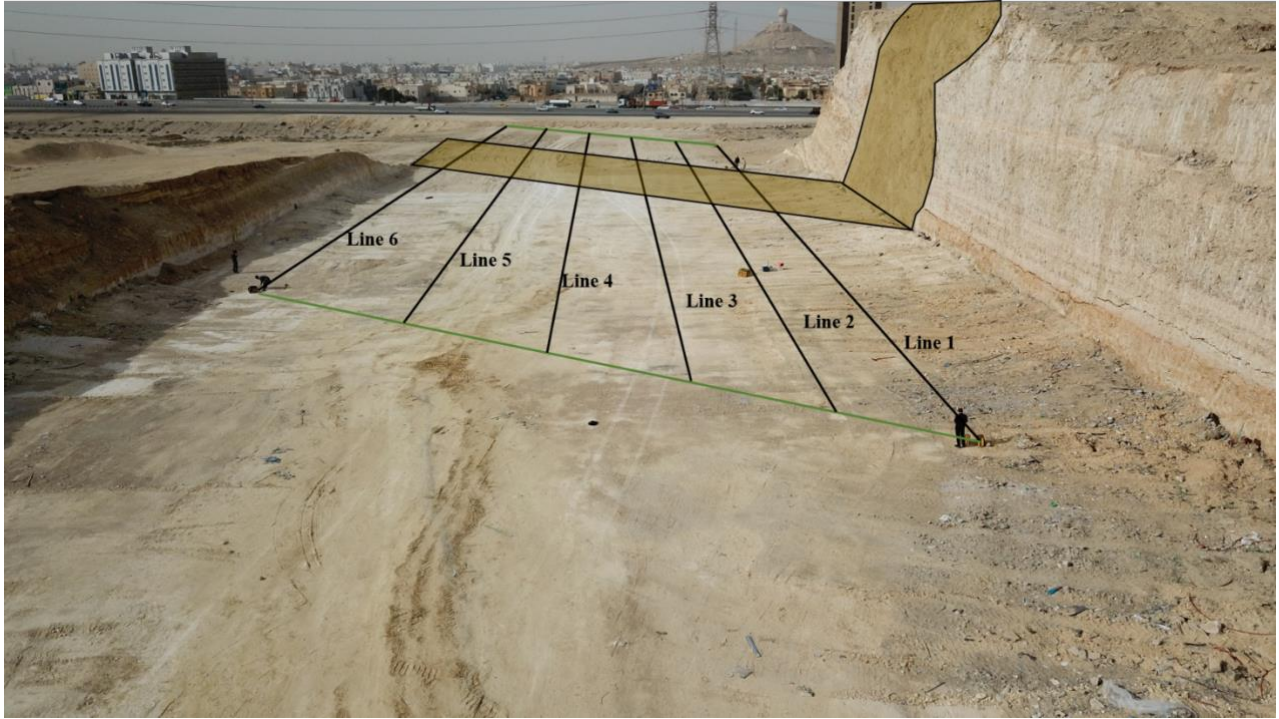


Figure 22: Shows the receiver distribution in the study area, where each black line represents a receiver line and the inline and cross-line distance is 8 m. The highlighted area on the outcrop indicates the location of the deformation zone, and the highlighted area on the surface indicates the expected extent of the deformation zone

Figure 23 is a sample of the shot gather. The first arrival was picked using in-house software. Before that, quality control should be done to help clean the data.

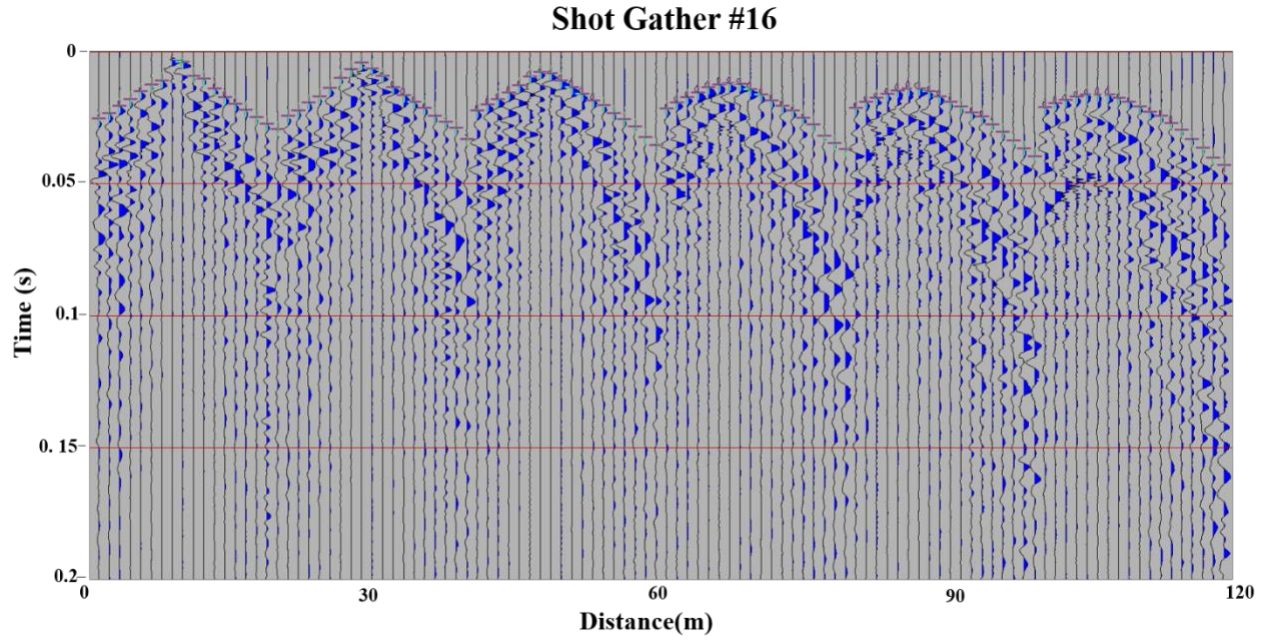


Figure 23: Shows the receiver distribution in the study area, where each black line represents a receiver line and the inline and cross-line distance is 8 m. The highlighted area on the outcrop indicates the location of the deformation zone, and the highlighted area on the surface indicates the expected extent of the deformation zone.

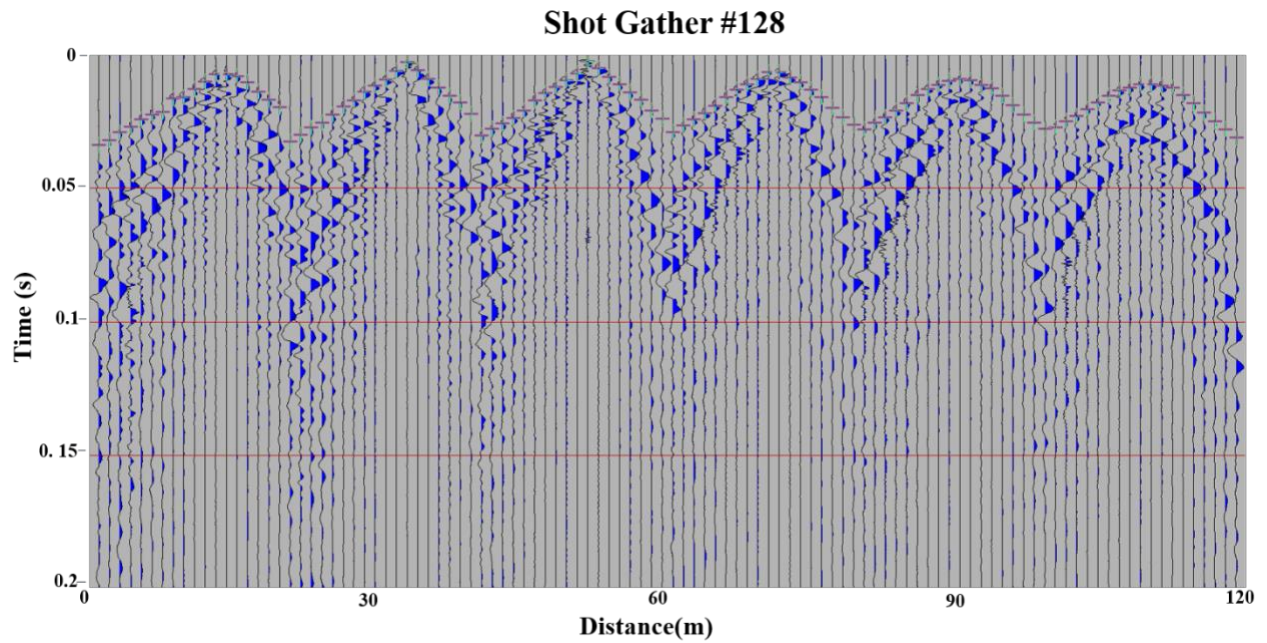


Figure 24: Shot gather #128 the traces can be picked easily since SNR is high

3D Seismic Trip: Layout Sketch (Receiver)

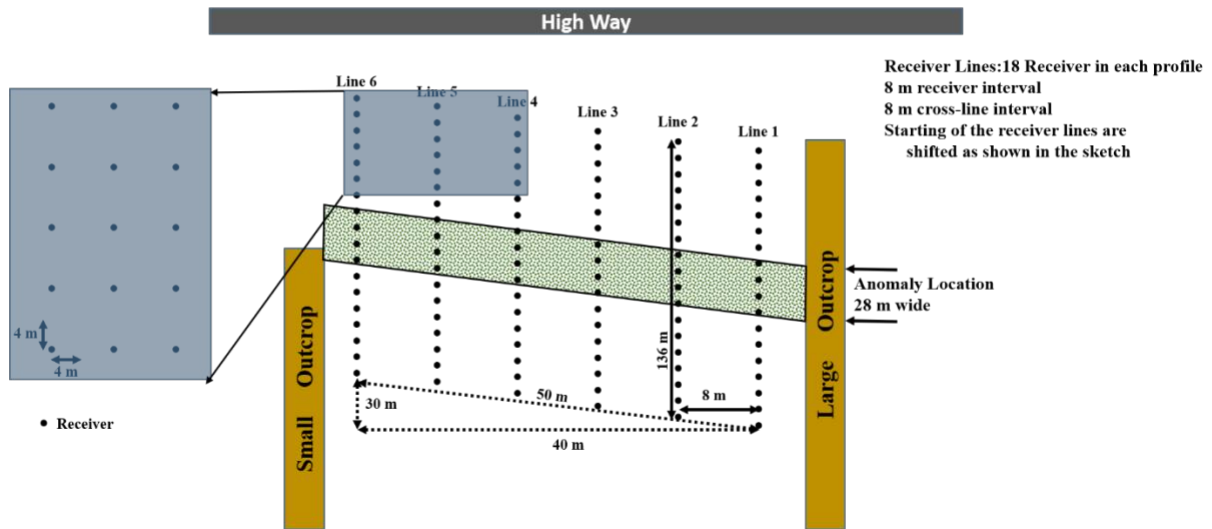


Figure 25: The layout of the receiver profiles is shown, with a total length of 144 m for each line. The receiver interval is 8 m, and each line has 18 receivers.

3D Seismic Trip: Layout Sketch (Shot line)

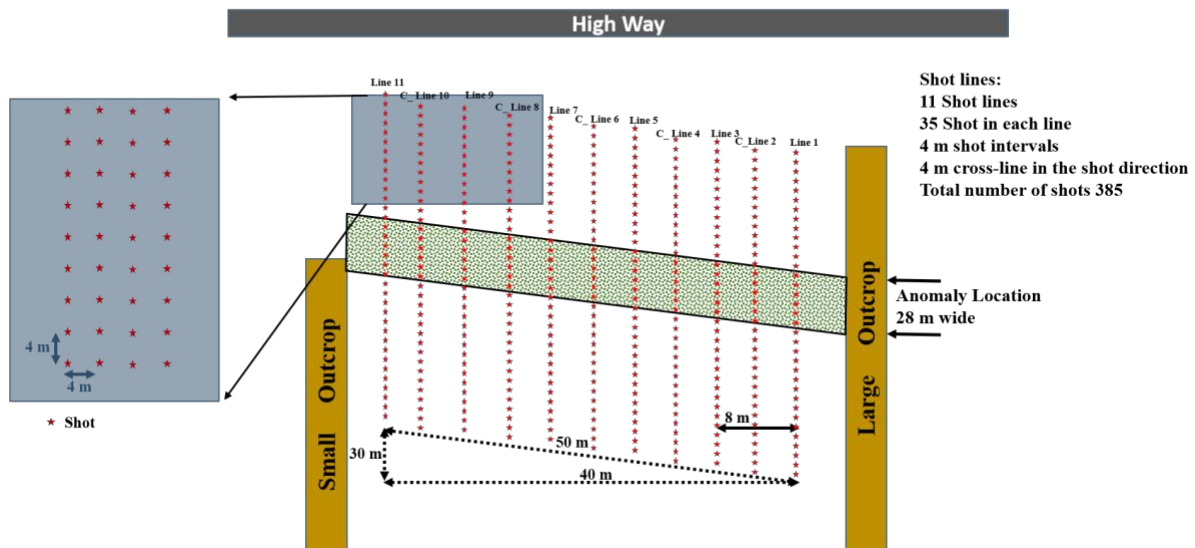


Figure 26: The shot location is shown, with shots taken very close to each receiver and between each receiver. We then moved between each receiver line and shot as if it had a receiver. The shot interval is 4 m inline and cross-line, and a total of 11 shot lines were recorded using a weight-drop method. The highlighted area in the figure provides an example of the shot layout."

4.2.3 Electrical Resistivity Tomography ERT

In Figure 27, the initial electric resistivity profile is recorded in a SW-NE direction and aligned with the seismic profile. The data in Figure 28 is recorded via a multi-electrode Syscal Pro Switch 96 resistivity instrument from IRS, using 96 electrodes with a 5 m interval to cover a total profile length of 480 m. The ERT acquisition sequence employed is dipole-dipole (DD) to effectively capture lateral variations, as anticipated by Reynolds (2011).



Figure 27: The ERT acquisition system, a Syscal Pro multichannel with 96 channels.

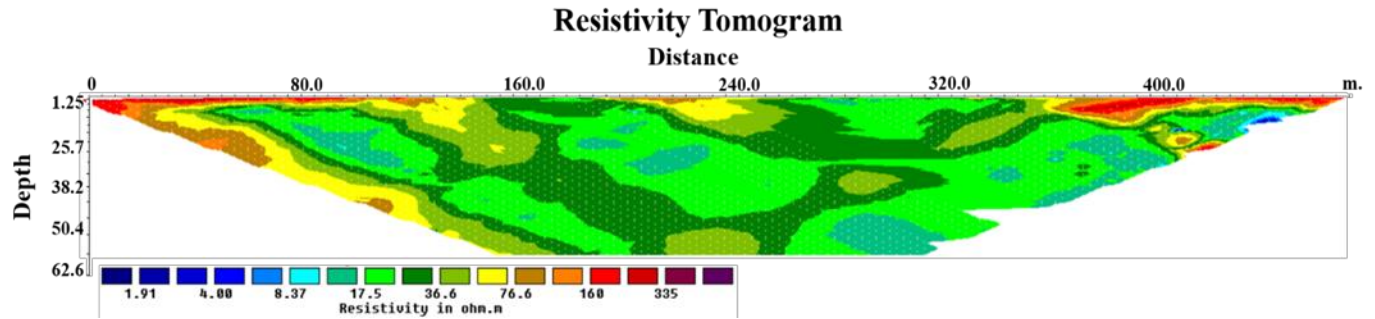


Figure 28: Row ERT data after removing bad electrodes.

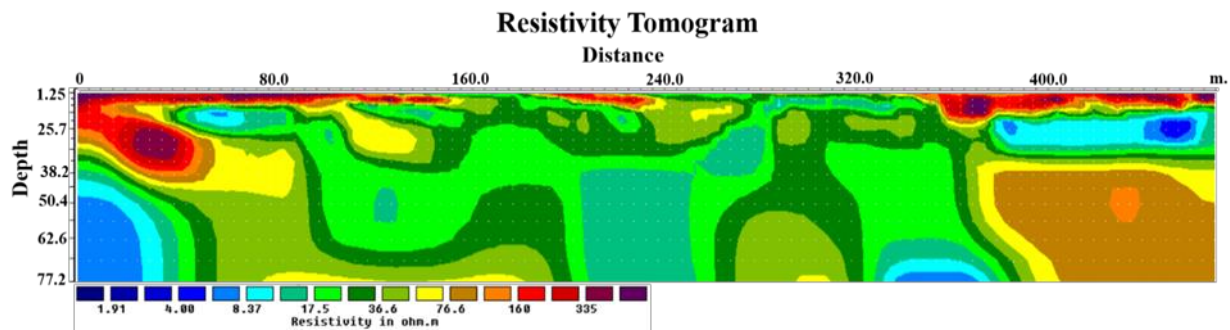


Figure 29: Electrical Resistivity Tomogram of ERT which shows the anomaly as a low resistance value.

As is shown in the tomogram the maximum depth of ERT reach is 77.2 m, and in the shallow part of the tomogram we see clearly that the first few meters have high resistance value resistivity anomalies of (~ 175 ohms.m) can be observed. However, at the deformation location, when reaching the anomaly location, we can see that the resistivity dropped to approximately 16 to Ohm.m - 17.5 ohms.m which matches the result of the SR.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Mineralogy Results

Mineralogical compositions of the host lithologies and fracture cement were measured for representative samples collected from the outcrop in the study area in order to characterize the fracture geochemistry within the deformation zone (Figure 30).

Samples 1 and 5 were extracted from the left boundary/wall of the deformation zone with host rocks, sample 6 was extracted from the right boundary of the deformation zone with host rocks and samples 2, 3, and 4 were extracted from the deformed interval and fracture/fault cement within the deformation zone.

The XRD and XRF result of the six samples (Figure 31) shows that the filling material of samples 1, 2 and 4 are gypsum, quartz, dolomite, and clay minerals. Moreover, the dominant mineral in the host rock within the deformation zone (samples 3 & 5) is dolomite. The results of sample 6 show dominance of clay minerals.

The XRD results of the samples collected from the fault cement observed within the deformation zone show that the filling material is from the same surrounding sedimentary unit, which indicates that the system is chemically closed.

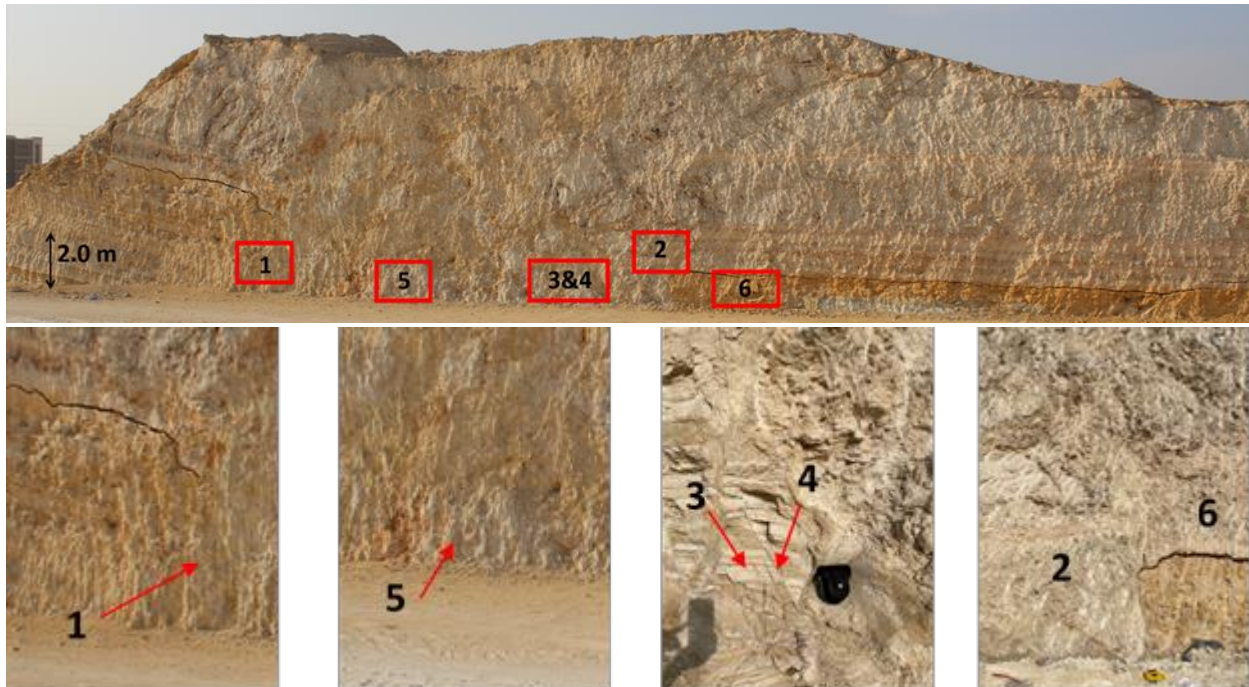


Figure 30: Samples 1&2 collected from fracture filling of the right and left wall of the deformed zone. Where sample 3 was collected from the host rock within the deformed zone close to the small fault. Sample 4 was taken from a small fracture within the deformation zone. Sample 5 was collected from the bottom of the deformation zone. The 6th sample was from the host rock on the bottom right outside of the deformation zone.

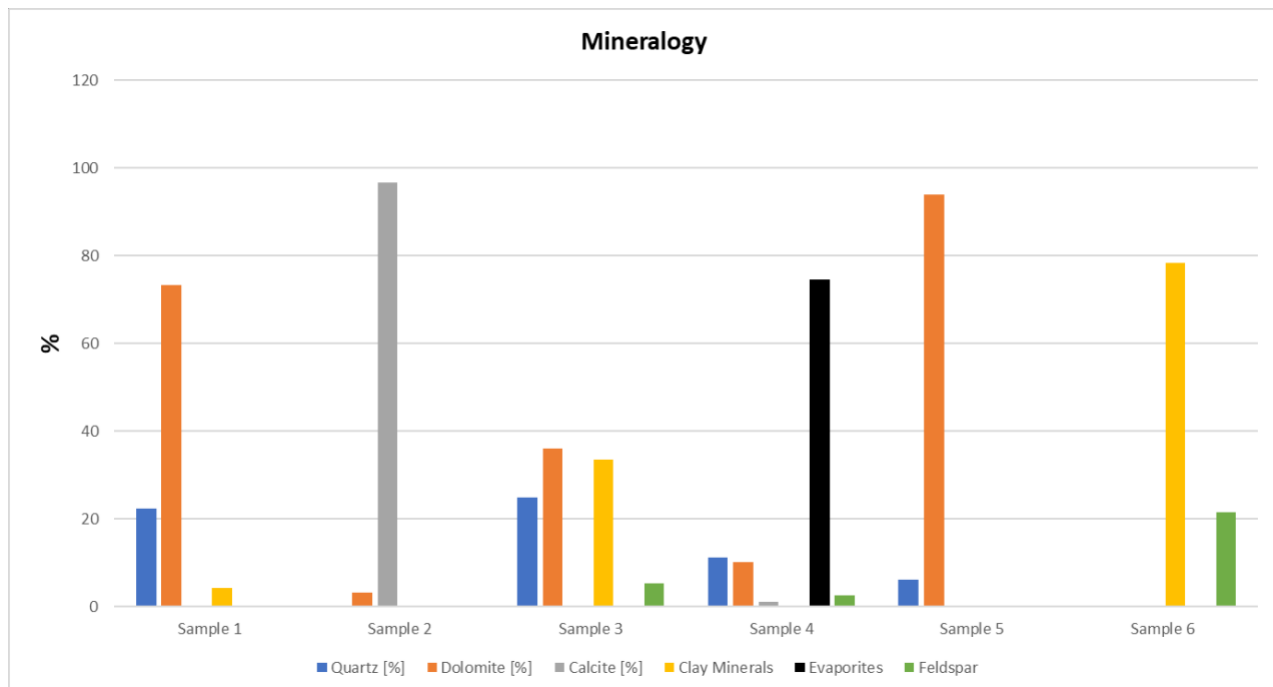


Figure 31: The analyzed samples 1, 2, and 4 exhibit filling materials composed of gypsum, quartz, dolomite, quartz, and clay minerals. Furthermore, samples 3 and 5, taken from the deformation zone, indicate that dolomite is the dominant mineral in the host rock. In contrast, sample 6 is characterized by the prevalence of clay minerals.

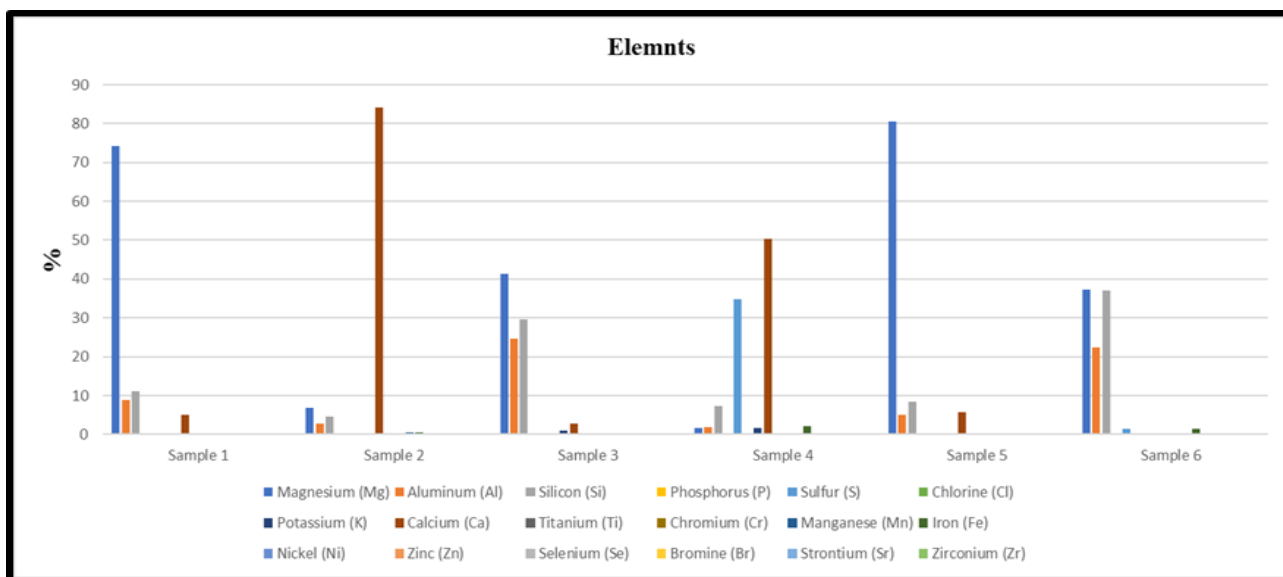


Figure 32: The XRF result agrees with the finding XRD where magnesium is the most common element in the most of samples along with calcium. Furthermore, sample # shows that the filling material has elements (Mg,Al,Si).

5.2. Geophysics Results

Integrating 2D and 3D seismic tomograms with the resistivity tomogram shows a good matching in both offset and depth, where the high-velocity and high-resistivity zones appear at depths less than 20 m (Figure 33). The high-velocity zone is, later, conformed using one line of geophone with 24 channels and placed on the wall of the deformation zone.

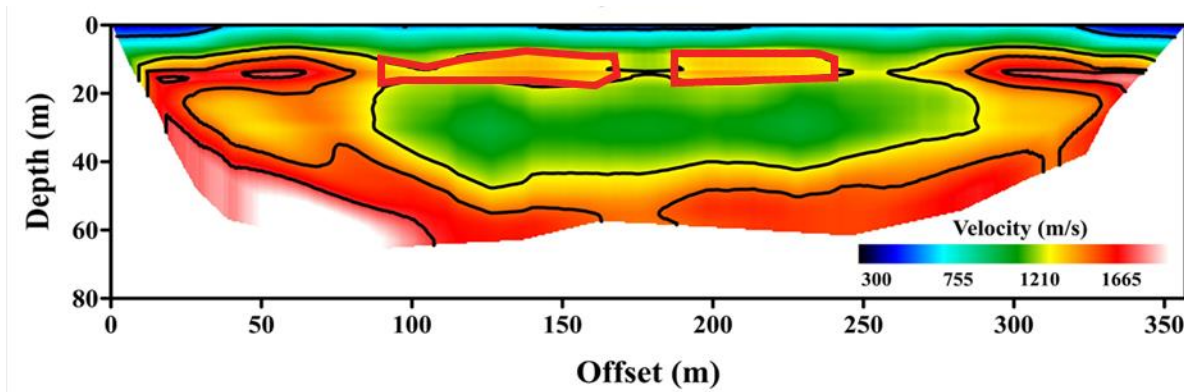


Figure 33: Shows a highlighted area in the first 20 meters of the subsurface, where high velocity values are present and coincide with the location of the deformation zone. The velocity range in this area is between 1210 to 1665 m/s.

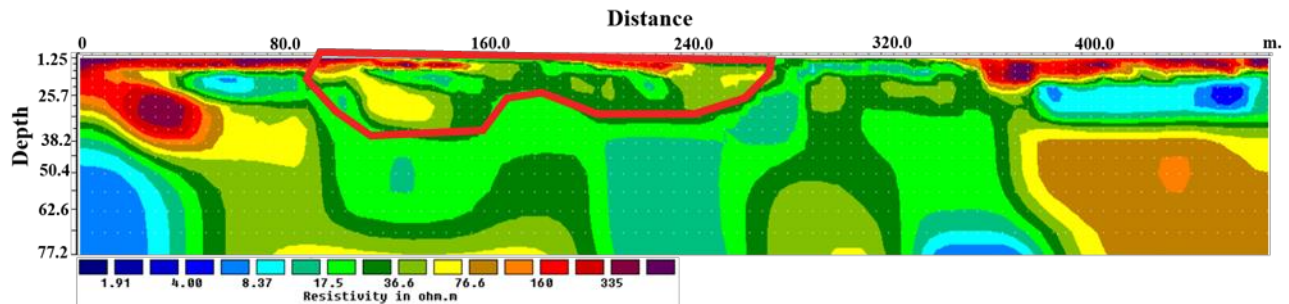


Figure 34: The highlighted area in the resistivity tomogram indicates the presence of a high resistive anomaly that corresponds with a similar anomaly observed in a 2D seismic image. The value of this resistive anomaly is measured at 76.5 ohm.m.

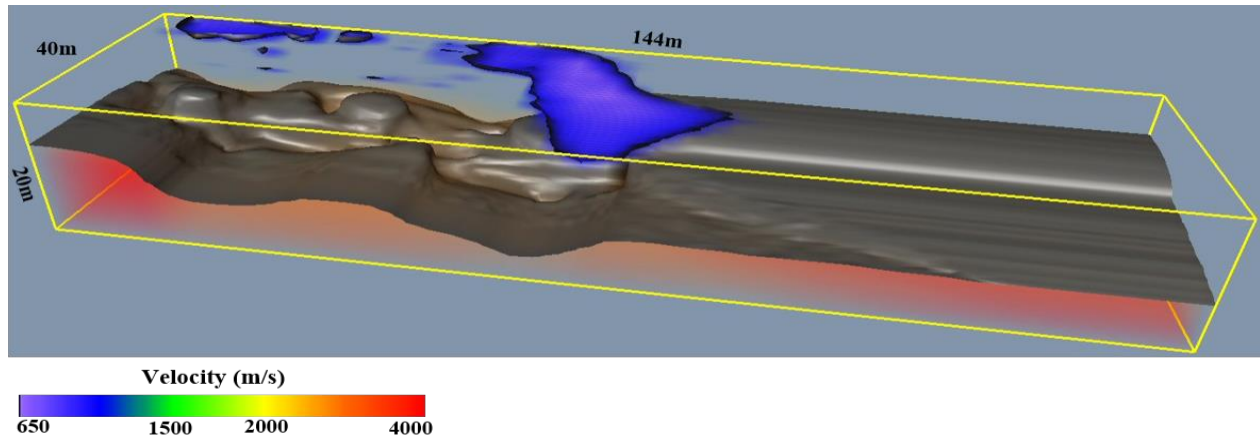


Figure 35: Illustrates a three-dimensional model of the subsurface, where the extension of the deformation zone is highlighted in dark blue color. The velocity range in this zone is measured between 650 to 800 m/s. This result is consistent with the findings from 2D seismic and resistivity data, which also suggest the presence of the deformation zone in the subsurface.

To get velocity on the wall of the outcrop, a line with 24 channels was placed on the wall of the outcrop to make sure that the receiver-line crosses the deformation zone (Figure 36). The geophone interval was 3m and the shot interval was 1.5m with 4 stacks per shot which enhanced the signal to noise ratio.



Figure 36: The geophone line that was used to measure seismic velocities along the deformation zone. The geophones are represented by black triangles, while the shot location is indicated by a red star. The numbers on top of the figure indicate the number of geophones selected to measure the velocity outside and inside of the deformation zone

As a result of this test we can see as is shown in (Figure 37) several shots gather and their corresponding velocity profiles. Shot gather #6 was located outside of the deformation zone, where the velocity was measured to range between 436 m/s to 555 m/s, which is relatively low. Shot gather #9 was located at the beginning of the deformation zone, where the velocity increased dramatically

from 555 m/s to 1280 m/s. Shot gather #14 also exhibited a high velocity within the deformation zone. However, as shown in shot gather #20, as we exit the deformation zone, the velocity decreases again, which is expected.

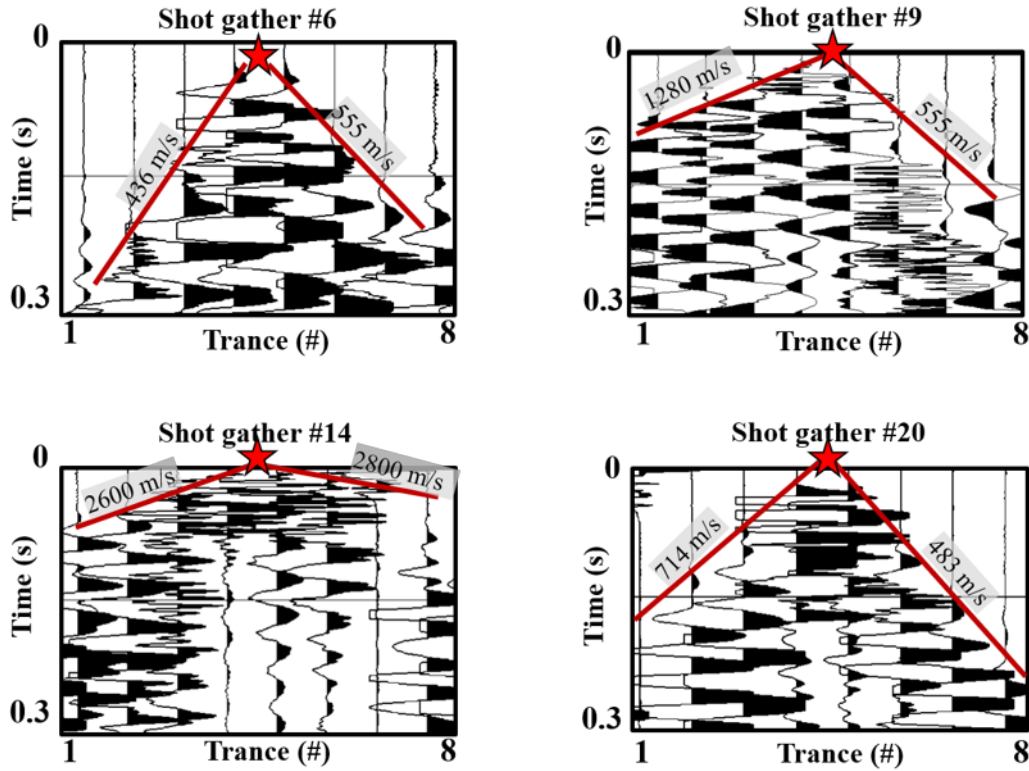


Figure 37: Shows four shot gathers were selected on the site to cover outside and in the side of the deformation zone. Where shot gather #6 and #20 were outside of the deformation zone and #9 where in the state of the deformation zone from the left side. Last shot gathers #14 where inside the deformation zone.

5.3. Deformation Zone Growth

The deformation zone evolved from one big fault and then this fault evolves to a fault zone due to the small faults that we saw during the geology investigation (Figure 7). Later this fault zone evolved to become a shear zone in the final stage (Figure 38).

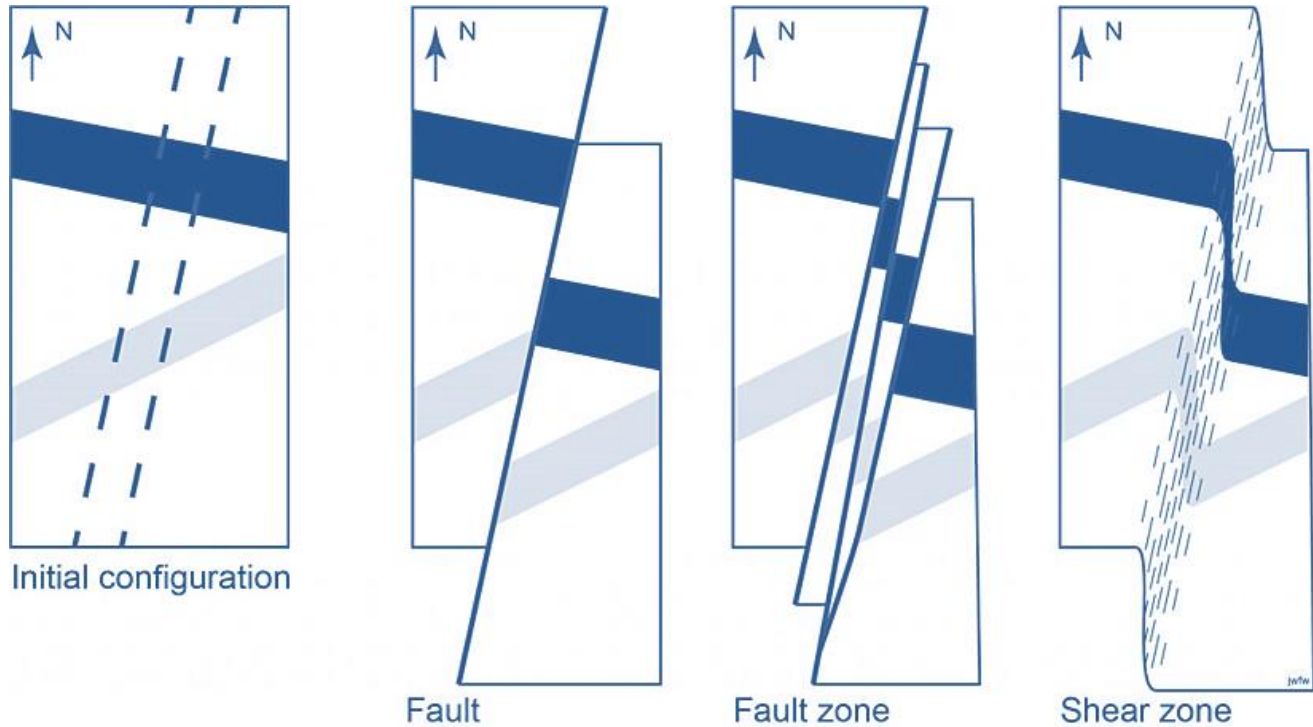


Figure 38: Schematic drawing illustrating the states that are believed to have occurred to result in the deformation zone in the study area, which is interpreted by four main sequential stages forming a shear zone.

Figure 38 shows the formation stages of a shear zone in which is the interpretation of the deformation zone formation stages by this study. This is evident by the mineralogical composition results of the fracture cement samples that indicate that the filling materials of the faults observed within the deformation zone (shear zone) is derived from the same sedimentary unit surrounding the deformation zone. This suggests that the system is a closed system, suggesting that the material within the system is not being exchanged with material from other units.

A shear zone is a type of geological structure formed when rocks slide past each other along a fault or fracture. The movement of the rocks causes deformation, and the resulting shearing can create a zone of crushed, broken, or pulverized rock. The filling material in a shear zone can provide important information about the history and evolution of the system.

The fact that the filling material in the shear zone is from the same sedimentary unit suggests that the system is a closed system, meaning that the movement and deformation of the rocks is likely due to internal forces within the system, rather than external forces from other geological units. This can provide important insights into the geological processes that have shaped the study area and can inform further research and exploration.

5.4. Conclusions

A new outcrop was recently exposed near King Fahd University (KFUPM) on a new road cut. A large deformation zone, 30 meters wide, is observed at this outcrop. To the left and right of this deformation zone, several strata of the Dammam Dome are exposed. This study aimed to explore and identify the geological reasons for the deformation zone observed in the study area and to use multi-geophysical methods to generate a comprehensive geological interpretation that explains the nature of the deformation zone. In addition, the study investigates the relationship between the near-surface structure and the Dammam Dome, a geological feature in Saudi Arabia associated with significant hydrocarbon reserves.

In this study, we recorded 2D, and 3D seismic surveys. In the 2D, we recorded a total of 120 common shot gathers (CSGs), each CSG has 120 receivers. The shot/receiver intervals are 3 m, the total recording time was 1 sec using a 0.5 ms sample interval. The first breaks of all recorded data are picked and the reciprocity test is used to test the picking quality, any picking that did not pass the reciprocity test is rejected and was not included in the inversion.

One of the problems in this data set is the Dammam-Jubail highway, which is very close to the study area, and hence, caused a lot of random and coherent noises, so, we used the super-virtual refraction interferometry to enhance the signal to noise ratio (SNR) of the recorded data.

The picked traveltimes are then inverted to generate the traveltime tomography, which shows the velocity-depth relation along the 2D profile. The analysis of the 2D seismic tomogram has provided valuable insights into the subsurface characteristics. Specifically, within the first 20 meters, we observed the presence of high velocity values that align precisely with the location of the deformation zone. This correlation highlights the significance of this subsurface region and its role in shaping the geological dynamics. The velocity range recorded in this area, ranging from 1210 m/s

to 1665 m/s, further emphasizes the intensity of the geological processes occurring within the deformation zone. These findings contribute to a deeper understanding of the subsurface structures and provide crucial information for various geological and geophysical studies.

The 3D seismic survey consisted of 108 receivers and 385 shots. They were aligned along 6 receiver lines and 11 shot lines. The receiver interval along the receiver lines and the receiver line intervals are (both) 8 m while the shot interval along the shot line and the shot line intervals (both) are 4 m. The first arrival times of the recorded data are also picked, and picking quality is tested using the reciprocity test. The construction of a comprehensive three-dimensional model of the subsurface has allowed for a detailed visualization of the deformation zone. The model highlights the extension of this zone, represented by a distinct dark blue coloration. Within this zone, the velocity range measures between 650 to 800 m/s, further confirming the presence and significance of the deformation processes occurring in the subsurface. These findings are consistent with the results obtained from the analysis of 2D seismic data and resistivity data, collectively supporting the existence and characterization of the deformation zone. The integration of these multidisciplinary findings enhances our understanding of the subsurface dynamics and provides valuable insights for geological and geophysical investigations.

The 2D electric resistivity tomography (ERT) has revealed a significant finding. The presence of a high resistive anomaly detected in the tomogram aligns with a similar anomaly observed in the corresponding 2D seismic image. This correspondence strengthens the validity and reliability of the results obtained from both techniques. The resistive anomaly is quantified at a value of 76.5 ohm.m, indicating a distinct variation in the subsurface electrical properties. This discovery contributes to a deeper understanding of the geological structures and processes in the surveyed area. The integration of resistivity and seismic data has proven instrumental in enhancing our knowledge and

interpretation of the subsurface, providing valuable insights for various applications in geology, hydrogeology, and environmental studies.

Finally, geological observations and mineralogical and geochemical measurements conducted, provided additional confirmation on the geology of study area and subsurface geometry of the deformation zone observed in the study area.

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