PROJECT REPORT

ON

GROUND PENETRATING RADAR (GPR) SURVEY FOR STRUCTURAL DESIGN OF IMJA LAKE LOWERING

FOR

COMMUNITY BASED FLOOD AND GLACIAL LAKE OUTBURST RISK REDUCTION PROJECT (CFGORRP)

SUBMITTED TO:

UNITED NATIONS DEVELOPMENT PROGRAMME
UN HOUSE, PULCHOWK, LALITPUR, KATHMANDU, NEPAL
(CONTRACT REF.: UNDP/PROF/15/2014)

SUBMITTED BY:

MEH CONSULTANTS PVT. LTD.
KATHMANDU, NEPAL

MARCH, 2015

GPR SURVEY REPORT: IMJA LAKE LOWERING

BY: R. P. SINGH

MARCH, 2015

ASSOCIATED ORGANIZATIONS:

DEPARTMENT OF GEOLOGY
UNIVERSITY OF DELHI, DELHI, INDIA

DEPARTMENT OF HYDROLOGY AND METEOROLOGY,
MINISTRY OF SCIENCE, TECHNOLOGY AND ENVIRONMENT
GOVERNMENT OF NEPAL, KATHMANDU, NEPAL

HIMALAYAN RESEARCH EXPEDITION
KATHMANDU, NEPAL

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PROJECT TEAM

S. No.	Name and Contact Details	Specialization and Role
1.	Dr. Ravindra Pratap Singh Department of Geology, University of Delhi e-mail: rpsinghsaran@gmail.com Mob.: +91-9911779963	Senior Geophysical Expert and GPR Team Leader
2.	Dr. Dericks Praise Shukla Department of Geology, University of Delhi	Senior Geophysical Expert
3.	Mr. Nawraj Sapkota	Geophysics Trainee and Field Assistant
4.	Ms. Yogita Garbyal	Geophysics Trainee and Field Assistant
6.	Dr. Dhananjay Regmi	Geomorphologist and External Expert
7.	Dr. Lalu Prasad Paudel	Geologist and External Expert

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We also express our gratitude to the **MEH Consultants Pvt. Limited, Kathmandu** for input to technical design of the Lake lowering.

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At last but not the least we want to express our thanks to ***people of Solukhumbu area*** for their kind cooperation.

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R. P. Singh and GPR Survey Team

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EXECUTIVE SUMMARY:

The Community Based Flood and Glacial Lake Outburst Risk Reduction Project (CFGORRP) intendeds to reduce human and material losses from probable GLOF at Imja Lake, Solukhumbu District (5010 m) and 27 settlements in downstream in the valley. Based on the previous studies it is proposed that 3m reduction of water level in Imja Lake will reduce GLOF risk through construction of an open channel. To design such a structure, a detailed survey is required and as a part of the project the task of *“Detailed Geophysical-GPR Investigation for Structural Design of Imja Lake Lowering”* was awarded to the MEH Consultants Pvt. Ltd. Kathmandu.

For the subsurface data collection two geophysical methods were used; i.e. Electric Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). The later is done in two phases, in October 2014, a field recognisance survey was completed while field data collection was completed in the month of November, 2014. There were four best suitable open channel alignments identified after consultation with other thematic teams during field recognisance survey. Two locations of water seepage were also detected south-eastward of the Imja Khola (on the way to Amalapcha Pass) for the GPR survey in order to get the flow direction.

The GPR data is collected using GSSI SIR-3000 with two antennas of different frequency (100MHz and 200 or 270MHz) for better resolution up to the depth of 13m. A total of 289 longitudinal and transverse GPR profiles were collected during field data collection at pre-recognised five locations. This report provides the geo-environmental interpretation of collected GPR profiles and also correlates the result with available ERT data.

Interpretation of the GPR profiles depicts presence of probable buried ice in various profiles at depth varying from about 4m to up to the depth of penetration. It is observed that the areas close to the periphery of Imja Lake tends to have buried ice. However at some other locations such as on the right bank of the Imja Khola (near the temporary bridge) buried ice is also present. Generally the upper surface in GPR profiles (~1 to 3m) has abundant loose material lying over comparatively compact and coarser material and/or boulder strata, which is observed at a varying depth of 2.5 to 5.5m from the surface. Steep north facing slopes are also present on the right margin of the lake which is favourable for the accumulation of snow. The left margin of the lake shows the seepage and steep slopes.

In case of R3 alignment, the steep slopes and seepage of water (which may be from the buried ice or infiltration from the lake) make this transect unsuitable for the construction of

structure. The GPR profiles along (current channel, along ERT-8) and across (along ERT-7) the Imja Khola suggests that this location is free from seepage and buried ice. Moreover, this site is the lowest available natural channel for the outflow of water from the lake, so least excavation would be required to lower down the level of lake by 3m and the narrow valley would help in reducing the cost of the structure. The most suitable channel alignment, for lowering of the lake by 3m, is the present channel. The currents channel is the safest and economic for excavation and/or construction as compared to other three suggested alignments.

1. BACKGROUND

In the recent decades, glacial lake outburst floods (GLOFs) become widespread and highly chronic incident in the Himalayas, in comparison with other glacier hazards (Iwata 1998; Komori 2011). Most of the glacial lakes have been expanding at the terminus of debris-covered glaciers (Chikita et al. 1997; Sakai 2012) which make it a serious natural disaster in the Himalayan region. Recent reports have indicated that glaciers continue to retreat worldwide as a result of contemporary warming trends. When the glacier retreats, it erodes the land surface creating depressions and these depressions are filled with water melting form ice/ snow, thus forming lakes in glacial regions. Over a period of time these lakes grow in size and volume and the areas downstream of these lakes can become vulnerable to GLOFs. Globally, the glaciers are shrinking, subsiding and retreating with the result of expansion and formation of glacial lakes to the stage of potential glacial lake outburst floods (Bajracharya et al. 2011).

1.1. Introduction

According to the studies in the Nepal Himalayas, the number of glaciers has increased (3252 to 3808) but the total area (3.6 to 2.9 % of the total area of Nepal) has reduced significantly (Mool et al.; 2001, 2005; (Bajracharya et al., 2010). In the Mt. Everest region of Nepal, due to melting and retreating of glaciers, 24 new glacial lakes have been formed and 34 have grown significantly during the past 50 years (Bajracharya et al., 2007; Valenzuela et al., 2014). Due to glacial retreat, the depth of the Imja lake has increase to a maximum of 90.5 to 116.3 ± 5.2 m in 10 years since 2002 (Valenzuela et al. 2014; Sakai et al. 2005). The appearance and danger posed by glacier lakes in this region has prompted calls for assessments of the increasing risk to communities downstream of the lakes, and in some cases implementation of risk reduction actions (e.g., at Tsho Rolpa, and proposed for Imja Lake).

1.2. Study Area

Several studies have been carried out on Imja Tsho and its downstream areas (Hammond 1988; Yamada 1992; Watanabe 1992; Watanabe et al. 1994, 2009, 2011; Kettelmann and Watanabe 1998; DHM 2001a, 2001b; Sakai et al. 2005, GEN 2006). The lake was first referred to in the literature by Vuichard and Zimmermann (1987) who used the name ‘Pareshaya Tsho’, although the derivation of this is not known. Hammond (1988) referred to it as ‘the Imja Glacier lake’. The same name is retained by Watanabe et al.1994 in his studies. It was mentioned as ‘Imja Cho’ in the topographic map prepared by the Survey Department of Government of Nepal. There was some reluctance to use the term Imja Tsho, or Imja Lake,

because neither variation had been formally approved by the relevant Nepalese authority, but both have since come into common usage by default (ICIMOD, 2011).

Imja Lake (or Imja Tsho) is located at 5010 m in the Solokhumbu region of the Nepalese Himalaya (27.898 N, 86.928 E), about 9 km south of Mt. Everest (Figure 1). The area is located in premises of Sagarmatha National Park Zone in south of Mount Everest. The study area is remote and inaccessible by road and the nearest airport is at Lukla. The trekking routes are through Namche, Tengboche, Pangboche, Dingboche, Chhukung and finally to lmja Lake. The hotel facilities are available from Lukla to Chhukung. Imja Lake lies within one of the top 10 tourist destinations in Nepal, with more than 30,000 tourists visiting the region annually. The area of the Imja basin is about 141 sq. km with altitude ranging from 4355 to 8501 m and it is about 38% covered by glaciers (Konz et al., 2005). It is bounded on the east by Imja glacier, on the north and south by lateral moraines, and to the west by a terminal moraine. The elevation of the lake in 2006 was 5006 m (Lamsal et al., 2011). It is located south east of Chokarma Tsho and northeast of Ambulapcha Tsho and is an intra-glacier lake and is fed by two major tributary glaciers are Lhotse Shar glacier flowing from northeast and Ambulapcha glacier from south. The valley opens in the southwest.The outlet of the lake is through the terminal moraine incised in the western end of the lake and forms the Imja Khola (river), which passes through the Mt. Everest massif and join Dudhkosi, a tributary of Sun Kosi River.

The terminal moraine associated with the lake is about 700m wide and 50m high with a dead-ice core (Watanabe et al., 2009). The moraine has sparse vegetation and numerous kettle holes and ponds. The lake level inside the moraine is about 40 m below the lowest point on the crest. Drainage from the lake, and hence the entire glacier, is focused on a single channel that winds its way between the hummocks (Hambrey et al., 2008). The minimum relative height between the lake level and the lateral moraine crest is 47m and increasing (Watanabe et al., 2009). The lateral moraine troughs also act as gutters, trapping debris derived from rockfall, snow avalanches and fluvial transport (Hambrey et al., 2008). There is only one outlet flowing through the southern part of the moraine dam, which is the main concern of the study. This moraine dam is seems to be composed of unconsolidated material like sand, gravel and boulder, with very steep slope.

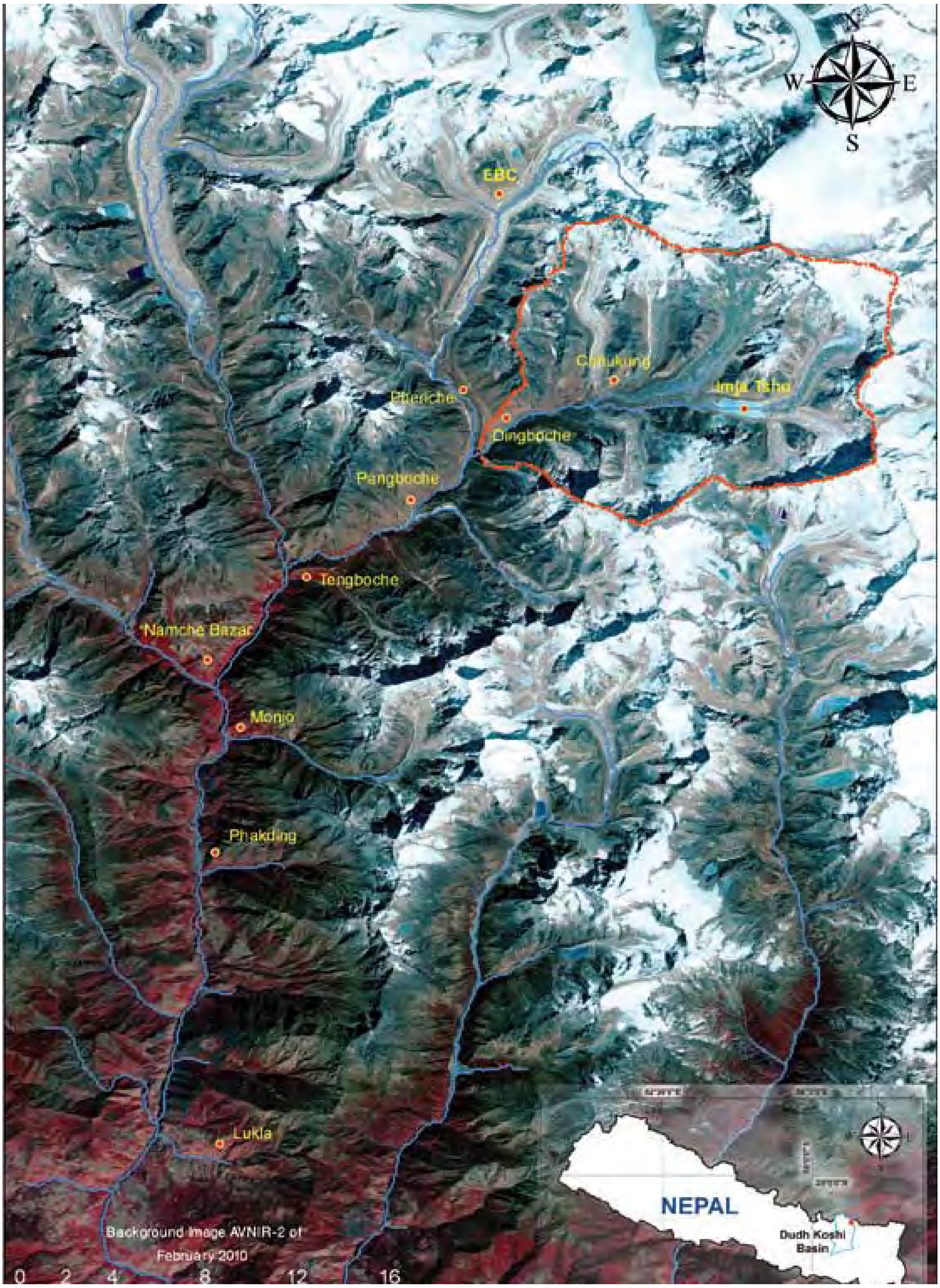

Figure 1: AVNIR-2 satellite image of Februaury 2010 showing regional map of Khumbu region displaying various locations on the way to Imja Lake in Dudh Kosi basin (Source: ICIMOD weblink)**.**

Ground photographs taken in the 1950s demonstrate that, except for several small melt ponds on the glacier surface, no lake existed at that time. The photographs were originally credited to Professor Fritz Müller who served as the 'scientific wing' of the 1956 Swiss Expedition to Everest and Lhotse and who was responsible for the first glaciological research in the Khumbu; however, they may have been taken by Erwin Schneider who was responsible for the first 1:50,000 map of the Mount Everest region (ICIMOD, 2011). By 1984, the lake area has grown to approximately 0.4 sq.km (Hammond 1988).

The Imja glacier has been extensively studied (e.g., Watanabe et al. 1994; Sakai et al. 2007; Bolch et al. 2008; Hambrey et al. 2008; Lamsal et al., 2011). The development of Imja Lake has been discussed by several authors (Quincey et al. 2007; Bajracharya et al. 2007a; Byers 2007; Yamada 1998; Watanabe et al. 2009; Ives et al. 2010; and Lamsal et al. 2011). Lamsal et al. (2011) provide a general description of the evolution of the Imja glacier and lake since the early 1960s. Imja lake appeared during the 1960s after several small meltwater ponds on the glacier coalesced into an emerging glacier lake (figure 2). Measurements in 2002 showed the average depth of the lake had grown to 41.6 m with a maximum depth of 90.5 m and a volume of 35.8 $x10^6$ m^3 (Sakai et al. 2003). By 2007 the lake was about 2000 m long, 650 m wide, and an area of about 1.03 km^2 (Watanabe et al. 2009). Recent estimates indicate that the volume of the lake is about $45x10^6$ m^3 (Budhathoki et al., 2010). Figure 2 shows an estimated progression of the area from 1956 to 2007 and the most rapid expansion took place during 1975 to 1978 (Watanabe et al., 2009). Although the lake has expanded rapidly in the last 50 years, most of the expansion has occurred through carving of the eastern end of the glacier and not through movement of the terminal moraine (Hambrey et al., 2008). The down-valley expansion has stabilized in recent years while the up-glacier expansion continues unabated (Watanabe et al., 2009). Figure 3 shows the variation in the size of lake in 10 years from 2004 to 2014. The ASTER satellite image for October, 2004 (figure 3A) clearly shows that the extent of lake is very small which increases to approximately 15% by 2014. The Ali hyperion satellite image for September 2014 (Figure 3B) shows an incredible increase in the lake size. The Imja glacier still covers the area beneath Imja Lake and melting of this ice has caused the lake level to fall in recent decades (Watanabe et al. 1995; Fujita et al. 2009). Lamsal et al. (2011) reported the average lowering of the glacier surface for the period 1964 to 2006 in the area west of the lakeshore is 16.9 m. The average lowering in the up-glacier area east of the lakeshore is 47.4 m.

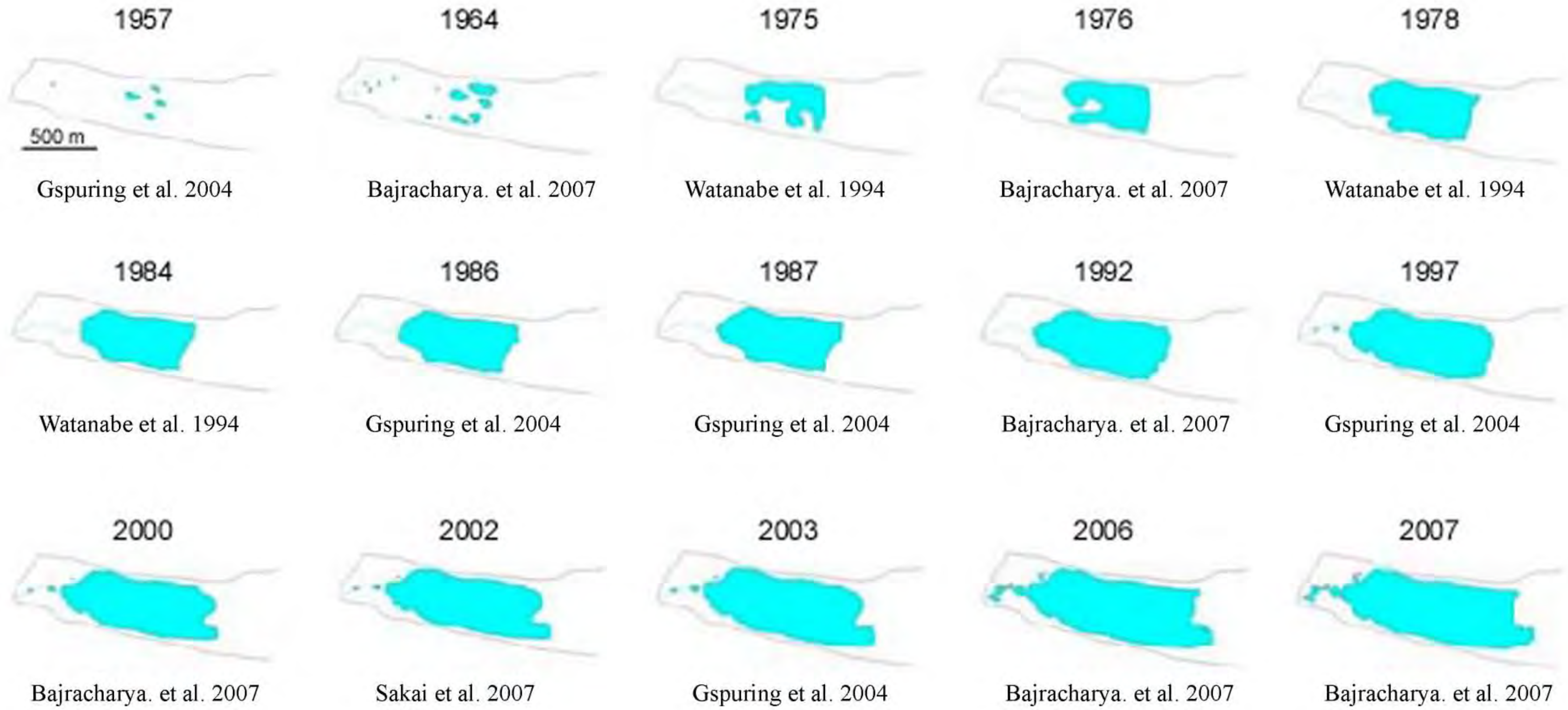

Figure 2: Changes in the Imja Glacier lake area in different years from 1957 to 2007 (Watanabe et al. 2009).

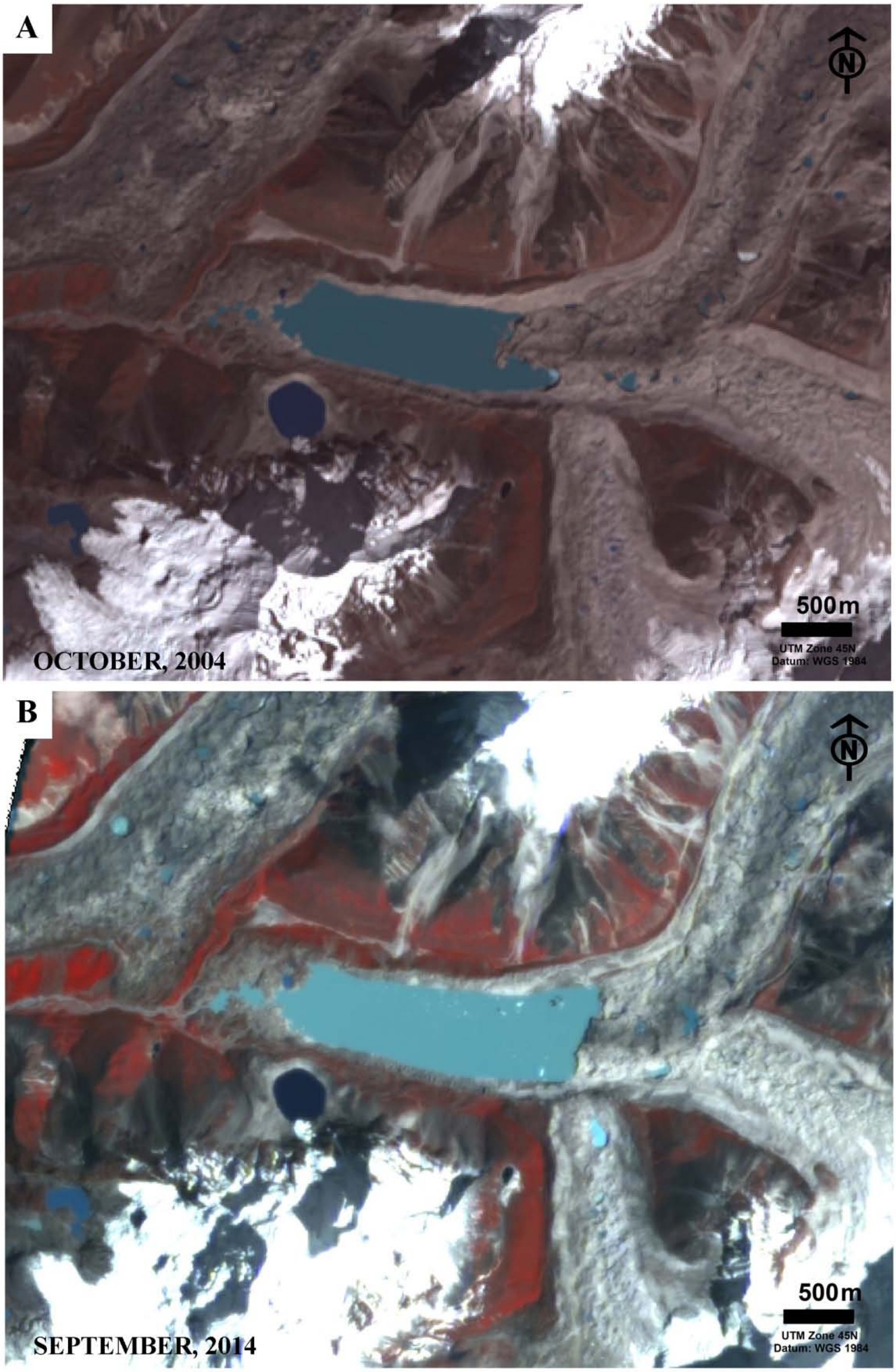

Figure 3: Satellite image of Imja Lake showing increase in the size from October, 2004 (A) to September, 2014 (B). Top image (A) was acquired from ASTER while bottom image (B) is from ALI Hyperion satellite data.

A team of ICIMOD (2011) carried out GPR survey to detect buried ice both within the moraine and within the Lake. A RAMAC GPR instrument with a 100 MHz antenna was used for the GPR surveys. The geophysical investigations showed the existence of dead-ice blocks within the end moraine, together with multiple thermokarst features. In places the ice was visible at the surface. Limited radarogram analysis based on a ground penetrating radar survey along the shoreline of Imja Lake showed that the moraine contains patches of unconsolidated materials made up of big boulders that create large voids. They recommended that further detailed GPR investigations are required around the end and lateral moraines as there are many exposed thermokarst features along the channel which will play a role in determining the stability of the moraine.

Somos-Valenzuela and his team from HMGW Program conducted an observation of the structure of the terminal moraine at Imja Lake in 2012 using a custom built, low-frequency, short-pulse, ground-based radar system. Their GPR survey showed extensive presence of ice in the core of the terminal moraine complex. The thickest areas of ice are observed by them in the moraine near the western end of the lake on the northern side of the lake outlet. The thickness of ice is variable and it ranges between tens of meters thick and up to fifty meters thick in some places. They observed that along the northern and southern sides of the lake outlet, the thickness of ice is between ten and twenty-five meters and in some portions of the moraine on the southern side of the outlet the ice thickness is up to 40 m. Extensive seepage of water from the terminal moraine was observed in two locations during visits to the lake in September 2011, May 2012, and September 2012. GPR transects above and below the site of seepage show the presence of ice above the seep and much less ice below the seep. Seepage of water through the terminal moraine is an indication of potential weakness in the moraine and a possible site of future moraine failure. They pointed out the presence of ice in the moraine in the vicinity of excavations site which must be considered while planning the construction of a diversion channel on the southern side of the outlet.

Terrestrial glaciers and lakes contain thick layers of morainal or bottom debris mostly covered by stratified dry snow and basal ice (Arcone et al. 1995; Lawson 1998). So, these serve as the best propagation medium of all geologic materials for GPR pulses as the stratification serves as reflecting horizons even with changes in ice fabric (Fujita et al. 1999). These stratifications are detectable with GPR within the right frequency bandwidth. The temperate glaciers also exhibit good penetration characteristics for GPR signals. At 0°C, or slightly below, depending on the pressure, water can exist along grain boundaries, or in pockets and conduits.

The density contrasts is the cause for the radar reflectivity, and mainly results from the formation of depth hoar (large grained, sublimating buried snow of low density), refreezing of hoar vapor into ice ‘‘crusts,’’ and wind packing (which causes low density but very small grain size). These density contrasts can persist even for hundreds of metres in polar-regions (Arcone et al. 2004) and even in terrestrial glacial region. In the case of pockets and conduits, such as in temperate en-glacial ice, scattering losses limit penetration. Whether the change is caused by a contrast in permittivity or conductivity, or both the concentration and the thickness of the anomalous layer help to determine its reflectivity. In the area dominated by dry snow and firn, the GPR pulses commonly used ranges from 2 to 1500 MHz

2. SCOPE OF WORK

The Khumbu region of Nepal has experienced two GLOF events in recent years; Nare in 1977 and Dig Tsho in 1985. Both the events caused several deaths and the loss of substantial downstream. Twelve new and/or growing lakes within the Dudh Kosi watershed of the Khumbu region have been designated as “potentially dangerous glacial lakes” based on the use of time-lapse satellite imagery. Imja Lake, located in the Khumbu region of Nepal (27.9°N, 86.9°E), has been investigated for more than 20 years.

The lake has experienced particularly rapid growth in area and volume since the early 1960’s, leading to concern over the risk of a catastrophic GLOF event. Imja Lake is thought by some to be among the most dangerous glacial lakes in the Khumbu region. A GLOF event would result in significant downstream damage, e.g., upon the village of Dingboche and Phakding, 8km and 33.6km downstream of the lake’s outlet, respectively. ICIMOD (2011) reported that the vulnerable population in village areas downstream of Imja Lake is about 96,767 people and that as many as 7,762 people likely would be affected directly by a GLOF event.

A number of attempts have been made in order to calculate the risk of glacial lake outburst in the Himalayas using remote sensing, bathymetry, geological, geo-morphological and geophysical survey techniques. The project is an attempt to get information of Imja lake water volume and thickness of terminus moraine as well as ice of the surrounding area using two different geo-scientific approaches, i.e. bathymetry and geophysics (GPR and resistivity survey), in order to select an appropriate site for the proposed diversion structure to reduce the human and material losses from GLOF from Imja Lake (5010 m) in Solukhumbu District. The GLOF hazard risk in 27 settlements in the downstream valley can be reduced by lowering of Lake Level by more than 3 m through construction of an open channel.

3. METHODOLOGY

The GPR (ground-penetrating radar, also known as ground probing radar), a geophysical technique developed for the non-invasive investigation of subsurface features (Davis & Annan 1989), is first developed in the 1950's to determine ice sheet thickness in Greenland and Antarctica. Applications grew rapidly through the 1970's to portable GPR systems for glaciological research in the 1980's (Woodward and Burke 2007).

Ground penetrating radar (GPR) is one of the near surface geophysical methods that is gaining acceptance as a viable means of field study in utility detection. It involves the transmission of high frequency radar pulses from a surface antenna into the ground. The electromagnetic radiation (EMR) wavelengths antennas (of microwave range; 5-900MHz), located within a "box," are moved along the ground in transects. In antenna one segment ***(transmitter)*** generates the propagating radar waves (very short, high-voltage pulses) and a second segment ***(collector or receiver)*** records the reflection traces generated from below (Annan 2001). These electromagnetic pulses are directed into the ground, and they are collected at the receiver after reflection or refraction of the same. Usually, antennas are placed directly on the ground surface or close to the ground within a fiberglass box of some sort. In case, the antennas are located too far above the ground, energy will not effectively penetrate the ground as most it will be reflected back to the receiving antenna from the ground surface. The time elapsed, when this energy is transmitted, reflected from buried materials or sediment and soil changes in the ground, and then received back at the surface, is then measured. The travel time of the reflected signal indicates the depth assuming subsurface material of uniform velocity conditions (e.g. 33×10^6 m/s for fresh water, 60×10^6 m/s for saturated sand, 110×10^6 m/s for loose debris and frozen sediments, 160×10^6 m/s for ice, and 300×10^6 m/s for air; Neal 2004). Data may be plotted as profiles, or as plan view maps isolating specific depths.

The electromagnetic field as a function of space and time is sampled and recorded to obtain subsurface information indirectly using GPR. The survey design must obey the criteria of fundamental sampling principles; e.g. suggested by Jol (2009). The GPR measurement used in this survey is most common reflection survey method (as suggested by Annan and Cosway 1992, 1994; Annan 2005), which uses a single transmitter and a single receiver. The specific terminology used for such array is single-fold common offset survey. The common-offset surveys deploy a single transmitter and receiver with a fixed offset (or spacing) between the units at each measurement location. In this survey both the measurement units (transmitter and

receiver) are fixed in a box called antenna (Figure Antenna; designed by GSSI) to maintain the offset. The transmitting and receiving antennas have specific polarization character for the field generated and detected. The antennas are deployed in a fixed geometry (i.e., separation and orientation) and measurements made at regular station intervals (as depicted in Annexure I) for advanced data processing and visualization.

The objective of reflection surveys is to map subsurface reflectivity versus spatial position. Variations in reflection amplitude and time delay indicate variations in wave velocity (v), attenuation (α) and electromagnetic impedance (Z). Ground penetrating radar reflection surveys are traditionally conducted on "straight" survey lines and systems are designed to operate in this fashion. Area coverage most often entails data acquisition on a rectilinear grid of lines, which cover the area, such as that depicted in Figures of Annexure I. The parameters defining a common-offset survey are:

- GPR center frequency
- Recording time window
- Time sampling interval
- Station spacing
- Antenna spacing
- Line separation spacing and
- Antenna orientation

The GPR frequency selection is synonymous with defining both GPR pulse width and bandwidth. Application exploration depths and resolution requirements determine bandwidth and also dictate temporal and spatial sampling intervals. Most often, attenuation is an issue; so frequencies are kept as low as possible to maximize penetration even if resolution is compromised.

3.1. GPR calibration

The moraines of Imja Lake site include boulder deposits and mixed material of glacial and fluvial environments. The reliability of the instrument and the applicability of the interpretation method is checked by comparing the acquired data (GPR profiles) with the available stratified boulder outcrops (near N27.90082º, E86.90792º at elevation of 5011 m). The good correlation between the two verified the reliability of both the instrumentation and the interpretation method. The experience gained from conducting a number of calibrations greatly enhanced our ability to understand GPR response and aided in the interpretation where other subsurface information was limited.

3.2. Instrumentation

The GPR surveys was be carried out using low-frequency, short-pulse, ground-based radar system of GSSI (Geophysical Survey Systems, Inc.) generally car mounted but can be refitted to a cart or box deployment with one person carrying the radar system while two other persons will drag antenna over the ground. A SIR-3000 (Subsurface Interface Radar) system was used with a 270 MHz, 200 MHz, and 100MHz antenna and survey wheel (Figure 5). The data is acquired with the survey wheel in order to minimize the spatial error. The specifications of the antennas are given in table 1.

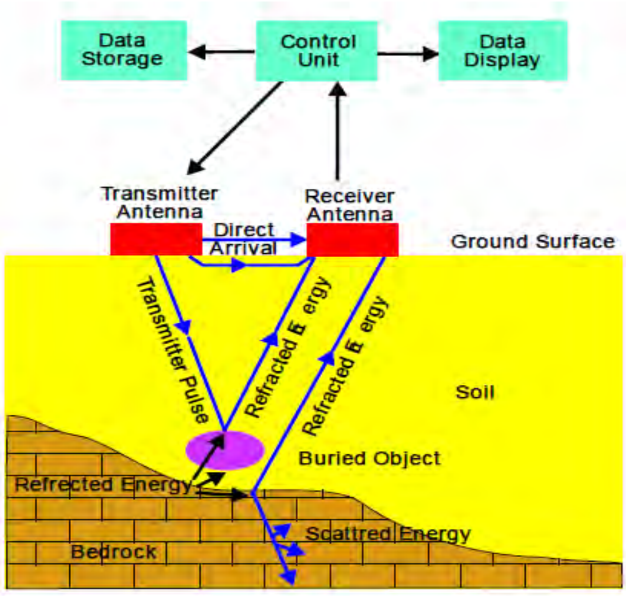

Figure 4: Block diagram for GPR survey instrument.

Table 1: Specification of the antennas used in the survey.

Center Frequency	Depth of Penetration*	Dimensions	Model	Weight	Typical Applications
270 MHz	6 m	55×55×25cm	5104	16 kg	Geological, Archeology,
200 MHz	8 m	60×60×30cm	5106	20.5 kg	Geotechnical, Engineering,
100 MHz	12m	25×96×56cm	3227AP	13kg	Environmental

***Penetration depths may vary depending on soil/surface conditions.**

Figure 5: Images of the instrument used for the GPR survey at the site.

SIR-3000

The GSSI SIR-3000 is a powerful, multi-channel GPR data acquisition unit coupled with a onscreen display system for ease of use and portability. This machine has revolutionized the GPR industry by combining a robust data collection unit with GSSI's leading GPR software.

270 MHz Antenna: The 270 MHz is a ground coupled antenna covering a depth of approximately 6m assuming a dielectric constant of 5. It is suitable for geotechnical and environmental applications, as well as archaeological investigations. Some specifications of the 270 MHz antenna are as follows:

Center Frequency: 270 MHz
Range: 75 ns
Samples per Scan: 512
Resolution: 16 bits
Number of gain points: 3
Vertical High Pass Filter: 75 MHz
Vertical Low Pass Filter: 700 MHz
Scans per second: 120
Transmit Rate: 100 KHz
(Model 5104)

200 MHz Antenna: The 200 MHz can penetrate to a depth of 9 meters (30 feet), making it ideally suited for geotechnical and environmental applications, as well as archaeological investigations. Some specifications of the 200 MHz antenna are as follows:

Center Frequency: 200 MHz
Depth Range: 9 m (30 ft)
Weight: 20.5 kg (45 lbs)
Dimensions: 60×60×30cm (24×24×12in)
Range: 100ns
Samples per Scan: 512
Resolution: 16 bits
Number of gain points: 5
Vertical High Pass Filter: 50 MHz
Vertical Low Pass Filter: 600 MHz
Scans per second: 64
Transmit Rate: 100 KHz
Model 5106

100 MHz Antenna: The 100 MHz can penetrate to a depth of 12 meters, making it ideally suited for geological, geotechnical and environmental applications. Some specifications of the 100 MHz antenna are as follows:

Center Frequency: 100 MHz
Depth Range: 2-15 m (5-50 ft)
Weight: 13 kg (45 lbs)
Dimensions: 25×96×56cm (10×38×22in)
Range: 500ns
Samples per Scan: 512
Resolution: 16 bits
Number of gain points: 5

Vertical High Pass Filter: 25 MHz	Transmit Rate: 50 KHz
Vertical Low Pass Filter: 300 MHz	Model 3207A
Scans per second: 16	

The higher frequency antennas have high resolution in the uppermost part, while 200MHz antenna has lower resolution in the shallow depth but it can penetrate up to 9 meters below the surface and 100 MHz pair antenna can penetrate up to the depth of 22 m. So, in our work, to get all the accurate details of subsurface features from 22 m below the surface, we used these three different kinds of antennas for the survey.

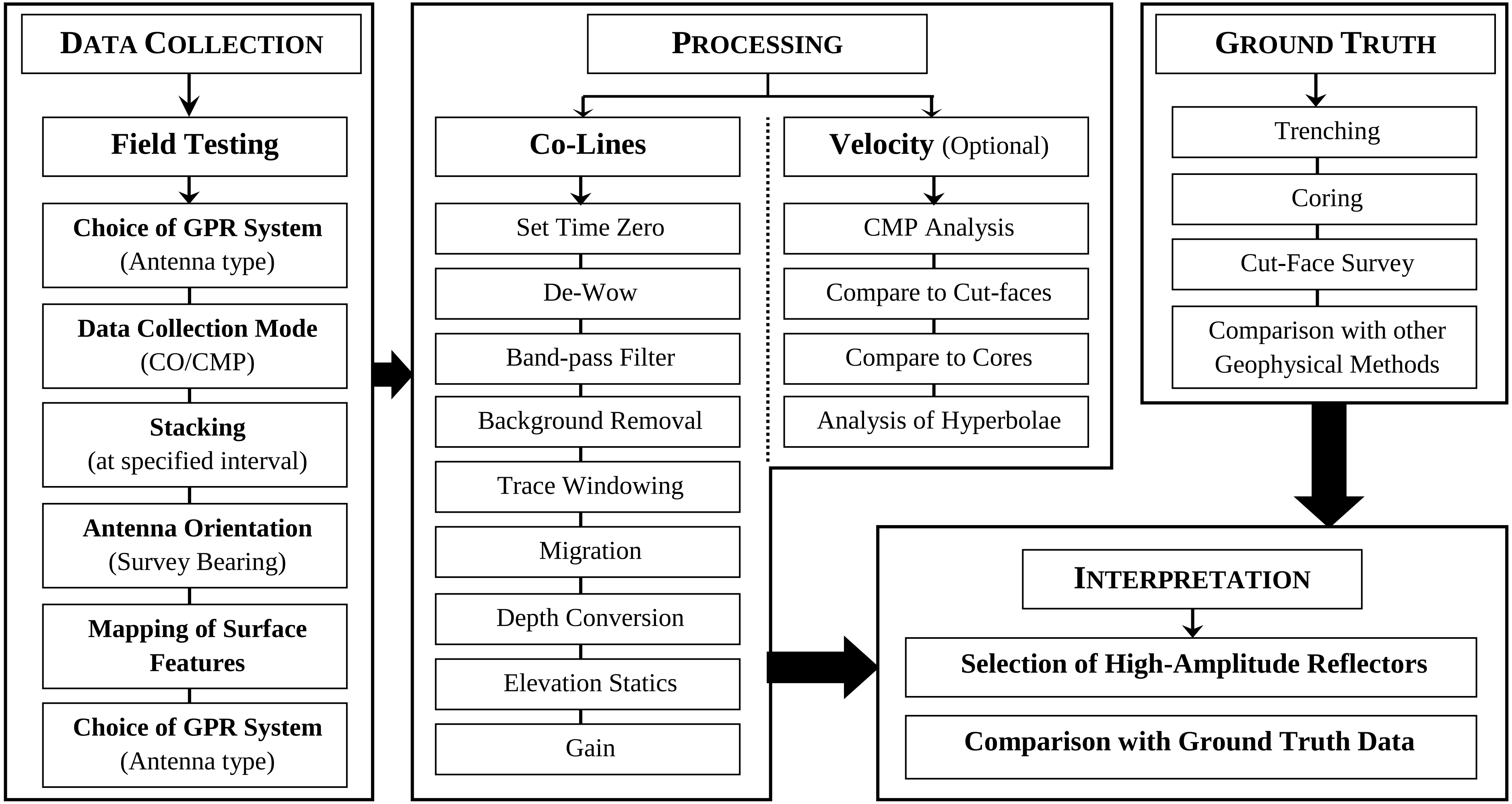

Figure 6: GPR Methodology Flow Chart

3.3. Survey Procedure

The main purpose of the survey is to trace out the subsurface lithological and/or buried-ice boundary in the study area. The required areas were scanned with 100MHz, 200 and 270MHz antennas to reach the required depth of penetration with a good resolution. The antennas have specific depth of penetration depending upon frequency, i.e. 100MHz antenna scan up to 12.0m below the surface and it is mainly used for subsurface geology and stratigraphic boundary detection while 200 and 270MHz antenna scan up to 8.0 and 6.0m below the surface respectively. The field parameters have been used according to the GSSI manual and ground conditions, like dielectric constant (Table 2).

Table 2: Electrical Properties of Media (after Davis and Annan 1989)

Material	Dielectric constant	Conductivity (mS/m)	Velocity (m/ns)	Attenuation (dB/m)
Air	1	0.3	0	0
Fresh Water	80	0.03	0.5	0.1
Seawater	80	0.01	30,000	1000
Unsaturated sand	2.55-7.5	0.1-0.2	0.01	0.01-0.14
Saturated sand	20-31.6	0.05-0.08	0.1-1	0.03-0.5
Unsaturated sand and gravel	3.5-6.5	0.09-0.13	0.007-0.06	0.01-0.1
Saturated sand and gravel	15.5-17.5	0.06	0.7-9	0.03-0.5
Unsaturated silt	2.5-5	0.09-0.12	1-100	1-300
Saturated silt	22-30	0.05-0.07	100	1-300
Unsaturated clay	2.5-5	0.09-0.12	2-20	0.28-300
Saturated clay	15-40	0.05-0.07	20-1000	0.28-300
Bedrock	4-6	0.12-0.13	10^{-5} - 40	7×10^{-6} - 24

3.4. GPR Profile Layout

The excavation in the moraine area is easy as compared to the tunnelling through the moraines. Moreover, the tunnelling in such sediments is not safe and needs extra support which would increase the cost of the project. The area along the selected profiles (i.e. R1, R2, R3 and C) has comparatively thin moraine deposits which suits for the surveys and probable location for the placement of the proposed structure. The five locations (Figure 7 and 8) were marked during field reconnaissance survey (in the Month of October 2014) and discussed with other thematic teams (i.e. bathymetry, electric resistivity tomography and design teams) based on geological, geo-morphological, topographical conditions and prerequisites for the hydropower generation, to fulfil the objectives set in the TORs of the project. The survey area was divided into 5 locations as mentioned below:

I. **R1 (Right Bank of the Lake)**
II. **R2 (North of R1)**
III. **C (Current Channel)**
IV. **R3 (Left Bank of the Lake)**
V. **S1 and S2 (Water Seepage Areas)**

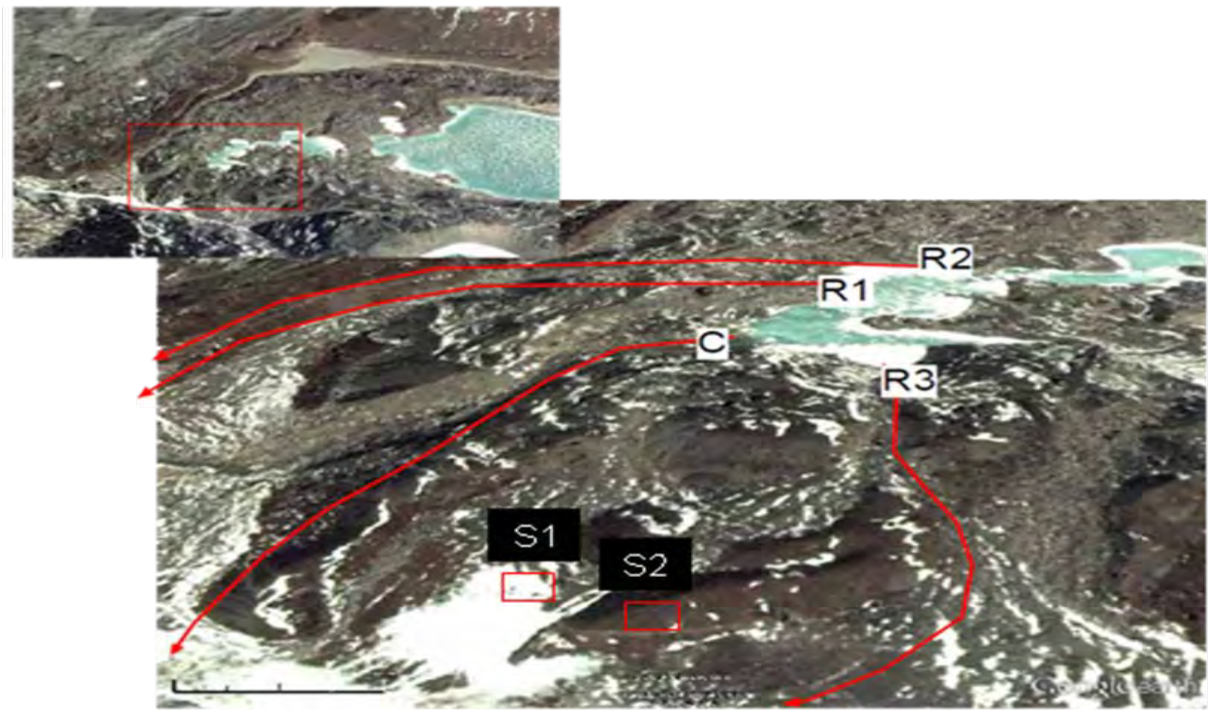

Figure 7: Geophysical survey locations around Imja Lake moraine deposits.

Figure 8: ERT Survey profile lines around Imja Lake moraine deposits.

These five areas have been subdivided into 10 profile lines by the ERT team, each being 200m to 300m in length. Along these profile lines, GPR survey was carried out in the first week of November 2014. Along with these profile lines, nearly 3m offset lines on both sides of the ERT profile lines were also considered for GPR survey for cross checking and gathering the data which was left unrecorded during survey along the ERT alignment due to the factors dicussed in the following paragraphs. This method helped in cross checking the results and in better interpretation. Since the terrain was very undulating and difficult to carry the antenna in one stretch, hence along each profile line, GPR surveys were carried out for smaller streches as per the terrain condition. This led to generation of huge number of profiles lines (289). Though the total number of GPR profiles taken is 289, and these are aligned in the same bearing of ERT lines but for its comparison and interpretation only 171 profile lines were finalized. Each profile line is scanned with two antennas (100MHz and 200 or 270MHz antenna) to get better subsurface resolution up to the depth specific to the antennas. The bearing with GPS locations were collected for all the survey lines with rough sketches in the field data collection sheet (as shown in Annexure II).

Two seepage areas S1 (west side) and S2 (east side) on the left side (south east) of lake have been observed and scanned with 270MHz antenna and a total of 12 profiles (Annexure IX) have been collected. Out of profiles (289), 11 profiles have been discarded because of the erroneous data; however it is provided in the raw form but not used in the interpretation. A total of 171 profiles have been collected along the ERT lines and 96 profiles have been

collected across the ERT-1 paths. In case of longitudinal profiles, 82 profiles have been gathered using 100 MHz antenna while for the rest 89 profiles were carried out using either 200 or 270 MHz antenna. Out of 96 cross profiles that were taken only across the ERT 1, 36 profiles were carried out using 100 MHz antenna while 60 profiles were carried out using 200 MHz antenna (Annexure V and VI). Among the profiles interpreted using Prism-2.59 software, only 52 profiles have been shown in blue and red colour plate and the rest are displayed in grey scale (provided in Annexure III, IV, V and VI). The same number profiles (longitudinal as well as cross) are also interpreted with the software Reflex2DQuick and presented in Annexure VII and VIII.

In the present investigation, only 171 profiles are used for interpretation as they represented the sub-surface most satisfactorily. Among the total interpreted profiles (171 Nos.), 52 profiles are selected and compared with the ERT profiles as these covered the longest stretch along the ERT profile alignments and contain minimal errors. The selected profiles (52 Nos.) are used to minimise the repetitions as proposed in the presentation. The ***reverse profiles*** (e.g. 136R, 137R, 145R, etc.) represent the data in the same direction as that of ERT profile alignment. The term ***reveres*** is used because the GPR instrument was moved in opposite direction to that of ERT profiles during the field surveys.

The errors associated with the conductance of GPR surveys results in non-continuous profiles. The errors might have occurred due to any of the following reasons:

- Uneven surface, which does not allow walking smoothly.
- Inaccessible areas (e.g. steep slopes, huge boulders, water logged areas, etc.).
- Lifting of the antenna or wheel of the instrument which results in anomalous air-gap or distance.
- Non-coordination among the survey team members (like uneven step or speed).
- Failure of power supply (discharge of batteries).
- Other problems associated with instrument (e.g. no response of operating system, connection problems, etc.).

Table 3: Detailed count of GPR profiles scanned along ERT survey lines.

Profile No.	Total number of GPR profiles collected from field (File Nos.)		
	100MHz	**200MHz**	**270MHz**
ERT 1	Two (File No. 55, 74)	Two (File No. 97R, 100R)	N.A.
ERT 2	Four (File No. 208, 209, 210, 202)	N.A.	Four (File No. 197, 198, 199, 200)

ERT 3	Three (File No. 124, 126, 135R)	Three (File No. 122, 130R, 132)	N.A.
ERT 4	Three (File No. 173R, 172R, 171R)	N.A.	Three (File No. 182, 183, 184)
ERT 5	Two (File No. 137R, 136R)	N.A.	Two (File No. 145R, 144R)
ERT 6	One (File No. 170)	N.A.	One (File No. 158)
ERT 7	Two (File No. 218, 219)	N.A.	Two (File No. 232, 223R)
ERT 8	Five (File No. 242R, 241R, 240R, 243, 244)	N.A.	Five (File No. 237, 238, 239, 236, 235R)
ERT 9	Two (File No. 249, 252R)	N.A.	Two (File No. 263, 257)
ERT 10	Two (File No. 280R, 272R)	N.A.	Two (File No. 281R2, 266)

3.5. Data Analysis and Interpretation

GPR data processing is usually an iterative activity, where data will flow through the processing loop several times. Data processing focuses on the highlighted areas: data editing, basic processing, advanced processing and visualization (or interpretation) processing. Batch processing with limited interactive control may be applied on large datasets after initial iterative testing on selected data samples has been performed. Advanced data processing methods require varying degrees of interpreter bias to be applied and result in data that are significantly different from the raw input information. The processes include such as spatial and temporal filtering, selective muting, dip filtering, deconvolution, and velocity semblance analysis as well as more GPR-specific operations such as background removal, multiple-frequency antenna mixing and polarization mixing (Jol 2009).

In the present study, the GPR data is transformed into application-specific information (GPR response) and is presented in a section, plan, or volume form to indicate anomalous target location. Typical processing flow for GPR data is depicted in Figure 6. The following data processing tools were applied to get proper visualisation:

3.5.1. Dewow

The close proximity of the of the receiver to the transmitter in the present survey generated low-frequency energy near the transmitter which caused the base level of the received signal to bow up or bow down. This effect is known as baseline “wow” in the GPR

lexicon. These “wow” signals are suppressed (dewow) by applying a high-loss temporal filter to the detected signal using REFLEX2dQuick software.

3.5.2. Band-pass Filtering

Filtering allows the removal of noise at the high and low end of the amplitude spectrum. For the 200 MHz antennae, the peak central frequency response, around which the filters are centred, is approximately 125 MHz.

3.5.3. Background Removal

Background noise is a repetitive signal created by slight ringing in the antennae and this causes a coherent banding effect, parallel to the surface wave which degrades the quality of the acquired data. In this study, background removal, using Prism-2.59 software, effectively eliminated this banding without degrading useful information. An operator window is specified, e.g. 100, which defines the number of traces used for one calculation.

3.5.4. FK Migration (Stolt)

Migration algorithms assume that all echoes arise from within the vertically orientated two-dimensional plane of the GPR profile. So, the migration is spatial deconvolution processing technique to remove source and receiver directionality from the acquired reflection data. It helps in the reconstruction and optimization of the geometrically correct radar reflectivity distribution of the subsurface. Thus this tool helped us to locate the observed subsurface sediments back in their exact shape and position. The subsurface is much clear and interpretable from these processed images as compared to the unprocessed images.

3.5.5. Depth conversion

Surveyed elevation data are used to apply topography to the GPR survey line. Firstly, trace windowing is applied to the data to remove all artefacts in the survey that arrived before the time-zero arrivals. The actual elevations recorded for survey points along the profile are then entered into the data processing package and the time-zero arrivals are 'hung' from the topographic profile by applying a time shift to each individual trace. Depth conversion is a simple display correction that allows the GPR profile to be displayed as a cross-profile of distance along the profile line plotted against depth. This requires calculation of a velocity of propagation for the EM energy in the subsurface for the survey area.

3.5.6. Automatic Gain Control (AGC)

Standard processing which includes dewowing and a three-point time filtering, as well as scaling is done using automatic gain control (AGC). An AGC time window of one or four pulse-widths was used. AGC with a time window of four pulse-widths enhanced relatively strong reflections, whereas an AGC with a time window of one pulse-width amplified all reflections equally. The result is that the strong signal are highlighted in the profile as compared to low amplitude reflections.

4. RESULTS AND INTERPRETATION

GPR survey was carried out using GSSI GPR- SIR-3000 with 100 MHz, 200 MHz and 270 MHz antennae in and around the outlet of Imja Lake. Both sides of the lake outlet complex were surveyed, including longitudinal surveys on each side of the lake outlet, and surveys near the lateral moraines as shown in Annexure IV. The data collected in this survey are compared to the ERT survey lines provided by the client.

Post-processing steps (Figure 6) performed on the data were gain correction; pre-trigger points removed; smoothing of mean trace; detrend; bandpass filter; convert two-way travel time to depth using a radar velocity in ice of 167×106 ms^{-1}.

Since the GPR survey was carried out by holding the antennae above the ground, hence in all the GPR profiles the top 1 to 1.5m is the Air Gap followed by other stratified geological materials like layer of boulders or loose materials of the moraines. While interpreting and discussion of the results in the succeeding text, the following points should be kept in mind. Here in all the GPR profiles, the depth measurements are referred from the surface (marked as zero on vertical axis). The distance travelled while taking the traverse, are recorded and referred from the start of the ERT profiles and hence the starting points are taken as zero. The “profile No.”/ “profile” in the text is equivalent to the “File no.”/ “File” of the GPR profile images. Beneath this layer the variation of loose materials, buried ice, hard rock, water saturated areas etc. are present. GPR survey was carried out along the alignment used by ERT survey as shown in figure (Annexure IV).

Two buffer profile lines at approximately ~3m distance were also carried out on either side of each ERT profile lines for better correlation and resolution of the data. Along each line, due to difficulty in walking on undulating terrain, various short and long GPR profiles were taken. Hence in all nearly 289 GPR profile lines were taken. The result of these profiles is discussed along the ERT profile lines and discussed here below:

Along ERT Line 1:

The GPR survey carried out along ERT line 1 was spread for nearly 220 m on the right side of the lake moraine deposit area in approximately NE-SW direction. Because of the variation in topography of ERT profile line 1, the GPR surveys was carried out in sections and in total 7 profiles were taken using 100 MHz antennae and 5 profiles were taken using 200 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 55 and 74 were used from 100 MHz antennae while profile numbers 97 and 100 were used from 200 MHz antennae. The direction of profile number 97 and 100 were in the opposite direction with the 100 MHz antennae as well as that of ERT profiles. Hence profile 97 and 100 of 200 MHz were reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 55 using 100 MHz antennae was obtained from the beginning of the whole profile sections (NE - SW) of ERT line 1 and follows it upto 105 m (0-105 m). Most of the upper subsurface layers show the mixture of loose sediments with boulders upto the depth of 13m. In this section, there seems to be a demarcation between damp material, present at the bottom, and boulder/ loose materials present in the upper layer. This demarcation can be clearly presented in Figure 9. Using 200 MHz antennae, profile 97 (reverse) was procured which shows presence of loose materials in top layer up to a depth of 2-3m. In the middle section up to a depth of 4-6m, coarse materials mostly composed of boulders is clearly seen. Beneath this layer of boulders damp loose materials can easily be demarcated. This damp material extends from beginning of the profile to 75m with continuous decreasing depths. This relates well with the ERT findings. At a distance of approximately 100m, loose material is present at a depth from 6-9m. After this, there is a band of data which cannot be associated with any structure, hence it is demarcated as system error. Though this section is in continuation with profile number 55, hence there is no loss of data due to this system error.

The GPR profile section 74 collected using 100 MHz antennae represent the end portion of ERT profile 1. It begins at 114m and ends at 196 m of ERT line 1. In this GPR profile, top layer seems to be composed of boulders at a depth of 5.5 - 6.5m from the surface. Beneath this layer loose sediments are present which can be demarcated from the above strata of boulders as shown in Figure 10. At the beginning of this profile at a depth of 10-13m buried ice can be traced for a stretch of about 7m at a distance of 9m. Similar observations are also seen in the profile 100 (reverse) of 200 MHz antennae. The resolution of this profile is better that 100

MHz, so demarcations within boulders and buried ice can be clearly seen. The upper portion of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, coarse materials, probable damp boulder strata are present at a depth of around 4 to 6.5 m. Beneath this layer of coarse materials, probable buried ice is present in the beginning of the profile at a depth of around 7-8m. The extent of buried ice is upto around 42m. After that from a distance of 50m, mixed to loose material is present. These observations relates well with the finding of ERT along line 1.

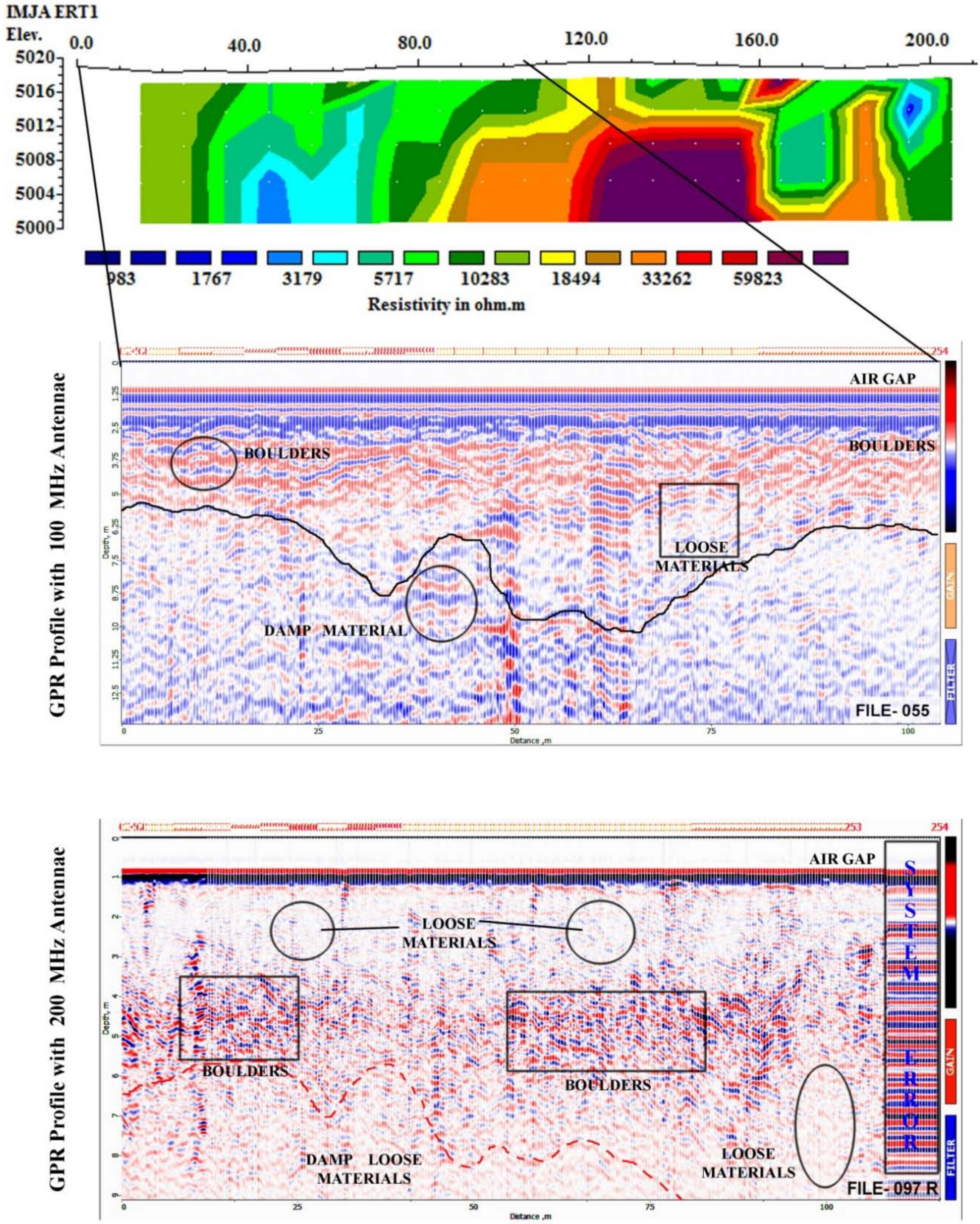

Figure 9: GPR profiles of 100MHz (middle; File-055) and 200MHz (below; File-097R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-1 profile (top) carried out around right bank of Imja Lake moraine deposits.

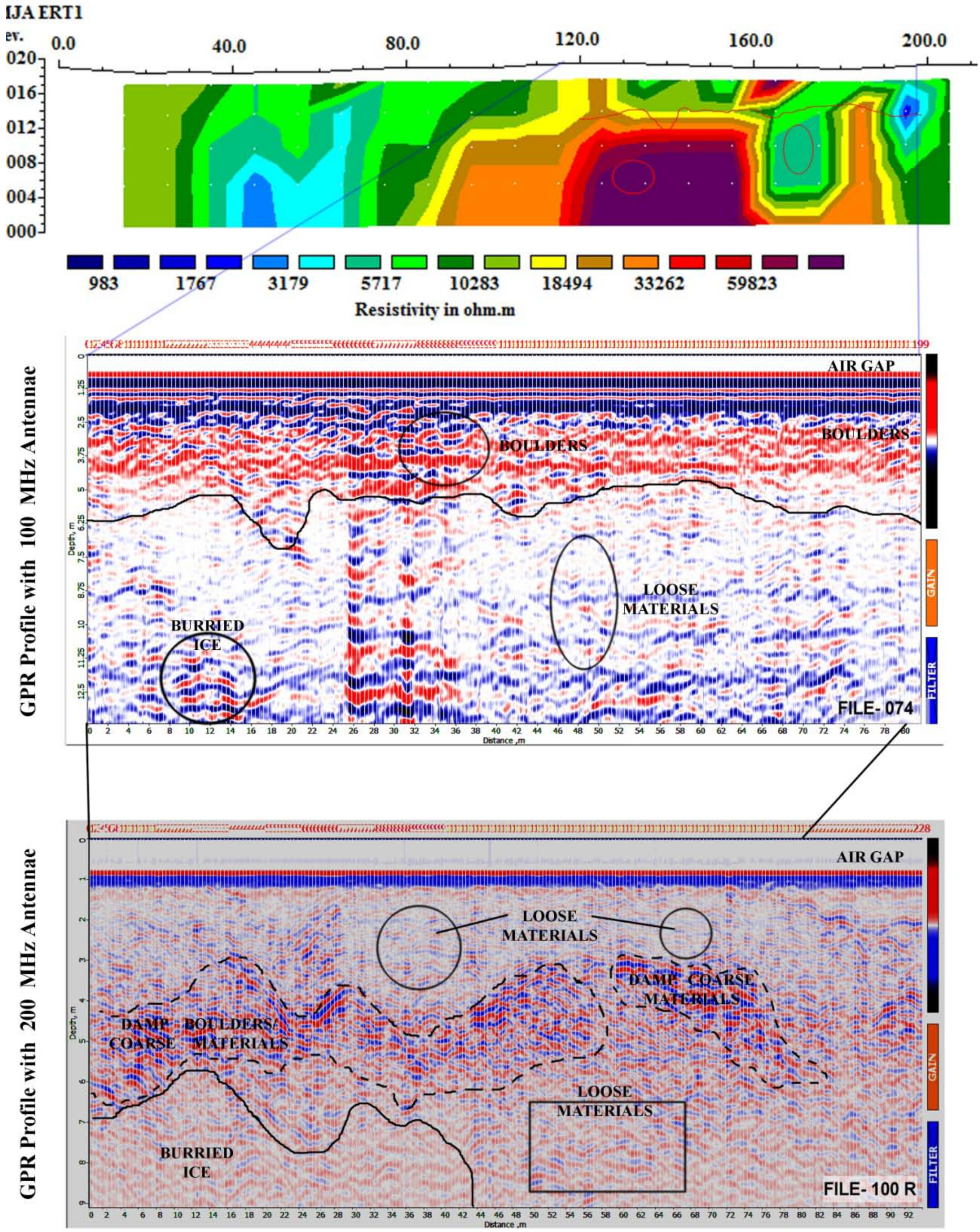

Figure 10: GPR profiles of 100MHz (middle; File-074) and 200MHz (below; File-100R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-1 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 2:

This GPR survey was carried out along ERT line 2 which was spread for nearly 300m on the right side of the lake moraine deposit area in approximately NE-SW direction. Because of the change in the direction/ bearing of ERT profile line 2, the GPR surveys was carried out in sections and in total 13 profiles were taken using 100 MHz antennae and 11 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section, GPR profile no 202, 208, 209 and 210 were used from 100 MHz antennae while profile numbers 200, 197, 198 and 199 were used from 270 MHz antennae. These profiles are in good correlation with ERT results.

The GPR profile 208 using 100 MHz antennae was obtained from the beginning of the whole profile sections, which starts from the same location as that of the starting points of ERT line and follow along the section upto 48.5 m (0-48.5 m). Most of the upper subsurface layers show the mixture of damp loose sediments with boulders upto the depth of 13m. In this section, the probable hard rock body seemed to be buried at the depth of 5 m below the surface with average stretch of nearly 14 m, starting from 12 m to 25.5 m. The demarcation of the probable buried hard rock body can be clearly witnessed in Figure 11. Using 270 MHz antennae, profile 197 was procured which shows presence of probable hard rock at a depth of 5 m. This relates well with the ERT findings.

The GPR profile section 209 collected using 100 MHz antennae represent the middle portion between 208 and 202 profiles section, which begins at 48.5m and ends at 84 m. In this GPR profile, presence of 2 probable pods of buried ice were located between 22 – 28m from the beginning of this section below the depth of 5 – 12 m. Boulders are present on top surface upto 5-6m as clearly demarcated on Figure 11. The upper portion of this profile section shows the presence of loose materials with boulders. Similar observations are also seen in the profile 198 of 270 MHz antennae. The resolution of this profile is better that 100 MHz, so demarcations within boulders and buried ice can be clearly realized.

The 100 MHz GPR profile section 210 covers a distance of 55m along the ERT 2 section from 88 – 144 m. In this section probable buried ice is located at the beginning portion of the profile section at a depth of 8 m. Two probable isolated patches of damp loose materials are located below the depth of 6.5m at an average distance of 21–24 m and 42-46 m. In between these damp loose materials, some loose materials are present at a depth of 5.5 m. The upper portion of the subsurface soil shows the presence of the mixture of boulders and loose sediments as

clearly indicated in Figure 12. Similar observations are interpreted using profile 199 of 270 MHz antennae. Top layer is of loose materials present at varying depths from 2 to 4 m. Below this loose material, boulders are present which can be seen at various locations. Buried ice, seen from the beginning of the profile to 10-12m, is present at a depth of 6m.

The GPR profile 202 carried out using 100 MHz which represents the last section of the ERT line, starts from 148m and goes till the end of the section. In this GPR profile, big boulders are present in the beginning and in the end on the scan line at a depth of 3-6 m and 8 m respectively. Damp loose material is present on the upper section of the profile line. This demarcation can be seen at a depth of approximately 5–6 m. Similar observations are furnished at profile 200 of 270 MHz where top layer defines loose materials which are underlain by boulders at various depths and locations. These interpretations can be easily visualized in Figure 13.

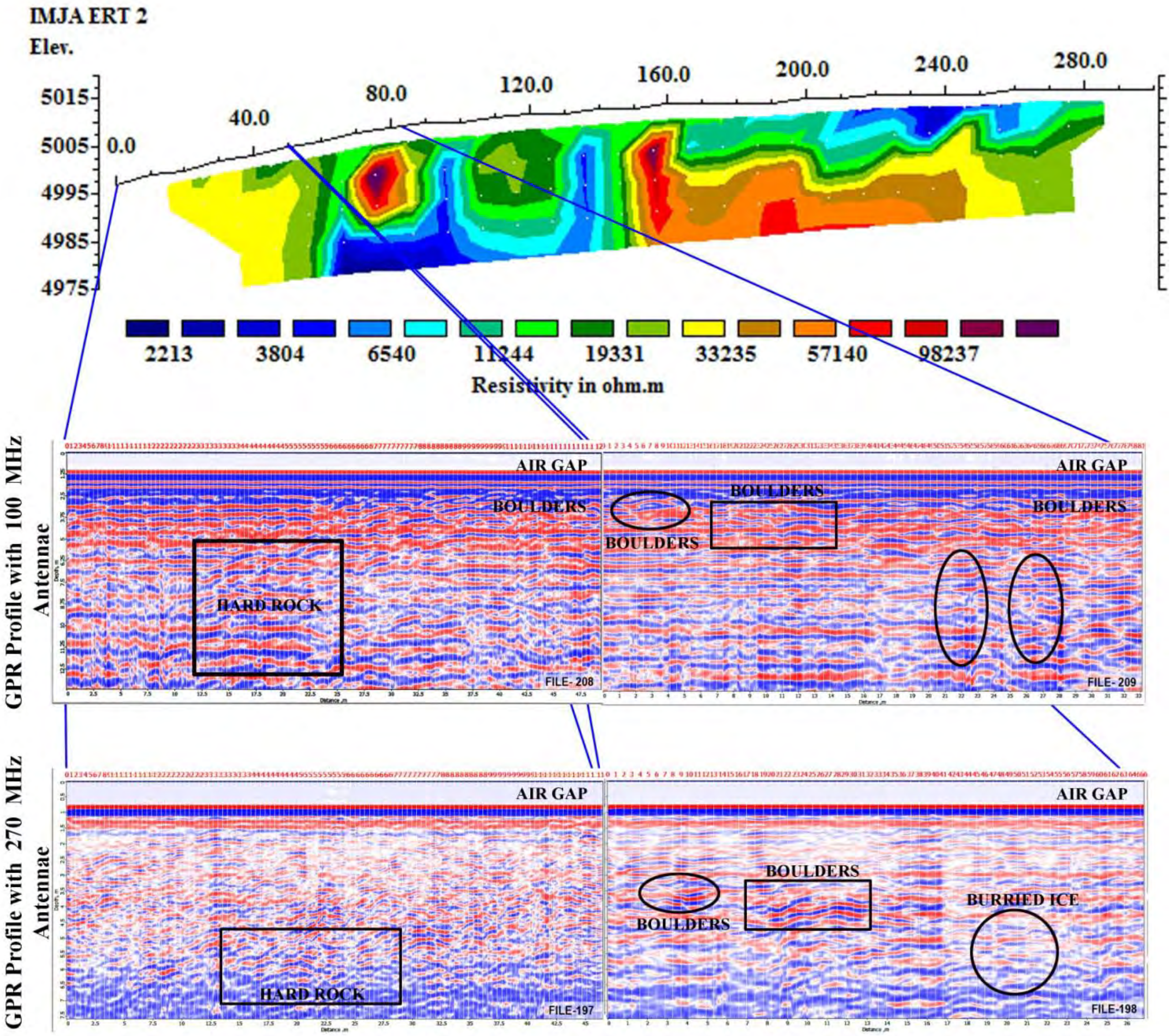

Figure 11: GPR profiles of 100MHz (middle; File-208, 209) and 270MHz (below; File-197, 198) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-2 profile (top) carried out around right bank of Imja Lake moraine deposits.

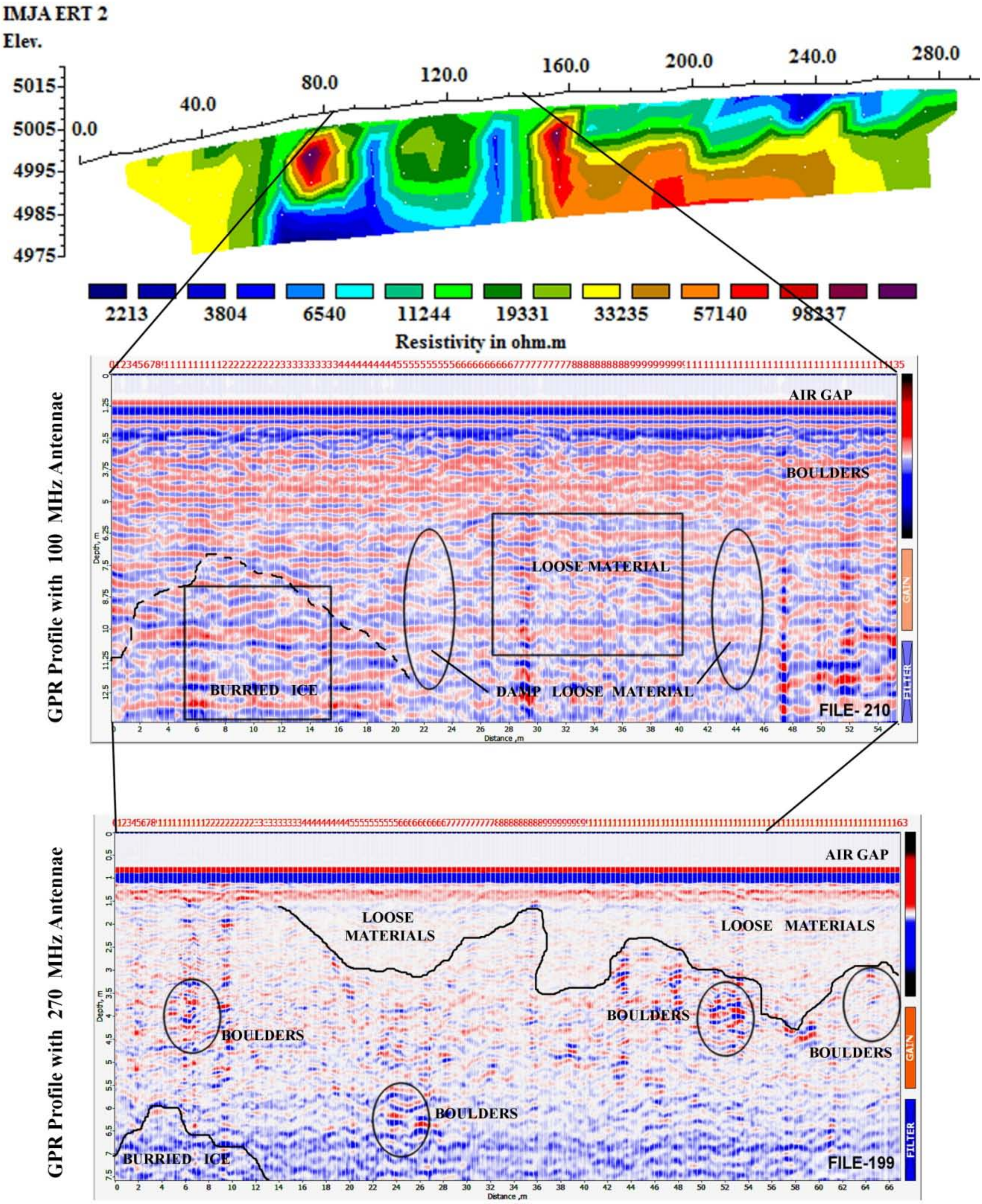

Figure 12: GPR profiles of 100MHz (middle; File-210) and 270MHz (below; File-199) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-2 profile (top) carried out around right bank of Imja Lake moraine deposits.

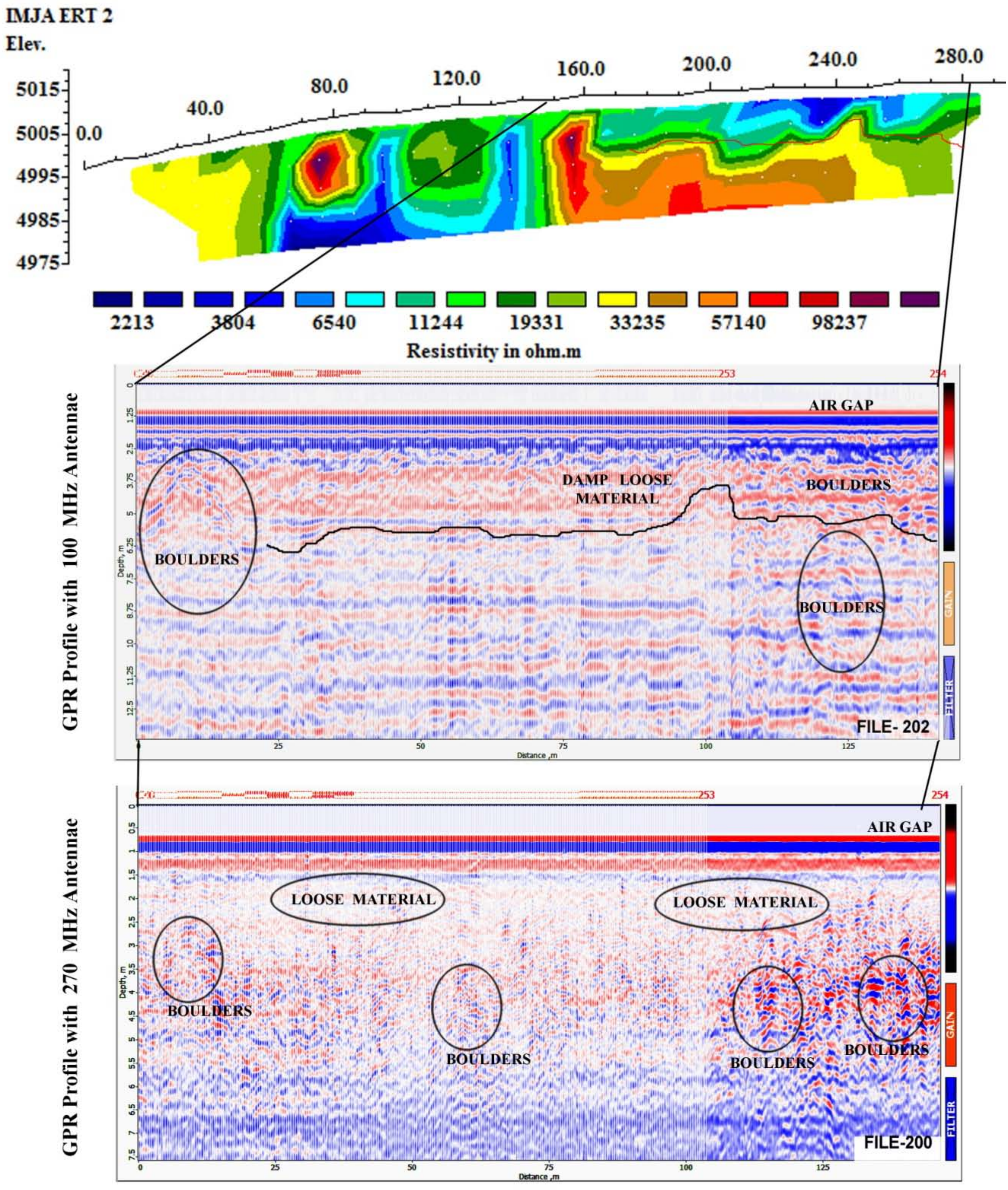

Figure 13: GPR profiles of 100MHz (middle; File-202) and 270MHz (below; File-200) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-2 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 3:

This GPR survey was carried out along ERT line 3 which was spread for nearly 200m on the right side of the lake moraine deposit area. This line starts near the lake and crosses over the moraine to the other side in western direction. Because of the variation in topography of ERT profile line 3, the GPR surveys was carried out in sections and in total 8 profiles were taken using 100 MHz antennae and 8 profiles were taken using 200 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 124, 126 and 135 were used from 100 MHz antennae while profile numbers 122, 130 and 132 were used from 200 MHz antennae. The direction of profile number 135 of 100 MHz and 130 of 200 MHz were in the opposite direction with respect to that of ERT profiles. Hence profile 135 and 130 of 100MHz and 200MHz respectively were reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 124 using 100 MHz antennae was obtained from the beginning of the whole profile sections, which starts from the same location as that of the starting points of ERT line and follows the section upto 96m (0-96m). Most of the upper subsurface layers show the mixture of loose sediments with boulders upto the depth of 13m. In this section, at a distance of approximately 30 – 50m, water saturated zone is present at a depth of 11-13m. Similar observations are also made in the profile 122 of 200 MHz antennae as indicated in Figure 14. The upper portion of this profile section shows the presence of loose materials upto a depth of 4-5m which are underlain by boulders. The resolution of this profile is better that 100 MHz, so demarcations within boulders and loose materials can be clearly seen.

The GPR profile section 126 and 135R collected using 100 MHz antennae represent the middle and end portion of ERT line 3 respectively. Profile 126 begins at 96m and ends at 134 m. Boulders are present on top surface upto 5-6m as clearly demarcated on Figure 15. The upper portion of this profile section shows the presence of loose materials with boulders. Similar observations are also seen in the profile 135R which starts at 136m and ends at 186m. This profile also shows the presence of mixture of loose sediments with boulders in most of the upper subsurface layers upto the depth of 13m. However, at the end of the profile at a distance of about 32 – 50m, probable buried ice is present at a depth of around 10m.

The profiles 130R and 132 captured using 200 MHz antennae showed better resolution for demarcations among loose materials, damp materials and boulder. Top layer is of loose materials present at varying depths from 2 to 4 m. Below this loose material, boulders are

present which can be seen at various locations. In the beginning (3 – 12 m) of profile 130R damp materials are present which can be differentiated from coarse (top) and loose (bottom) materials. There is a demarcating line present at a depth of 5-8m which can be clearly seen in Figure 15.

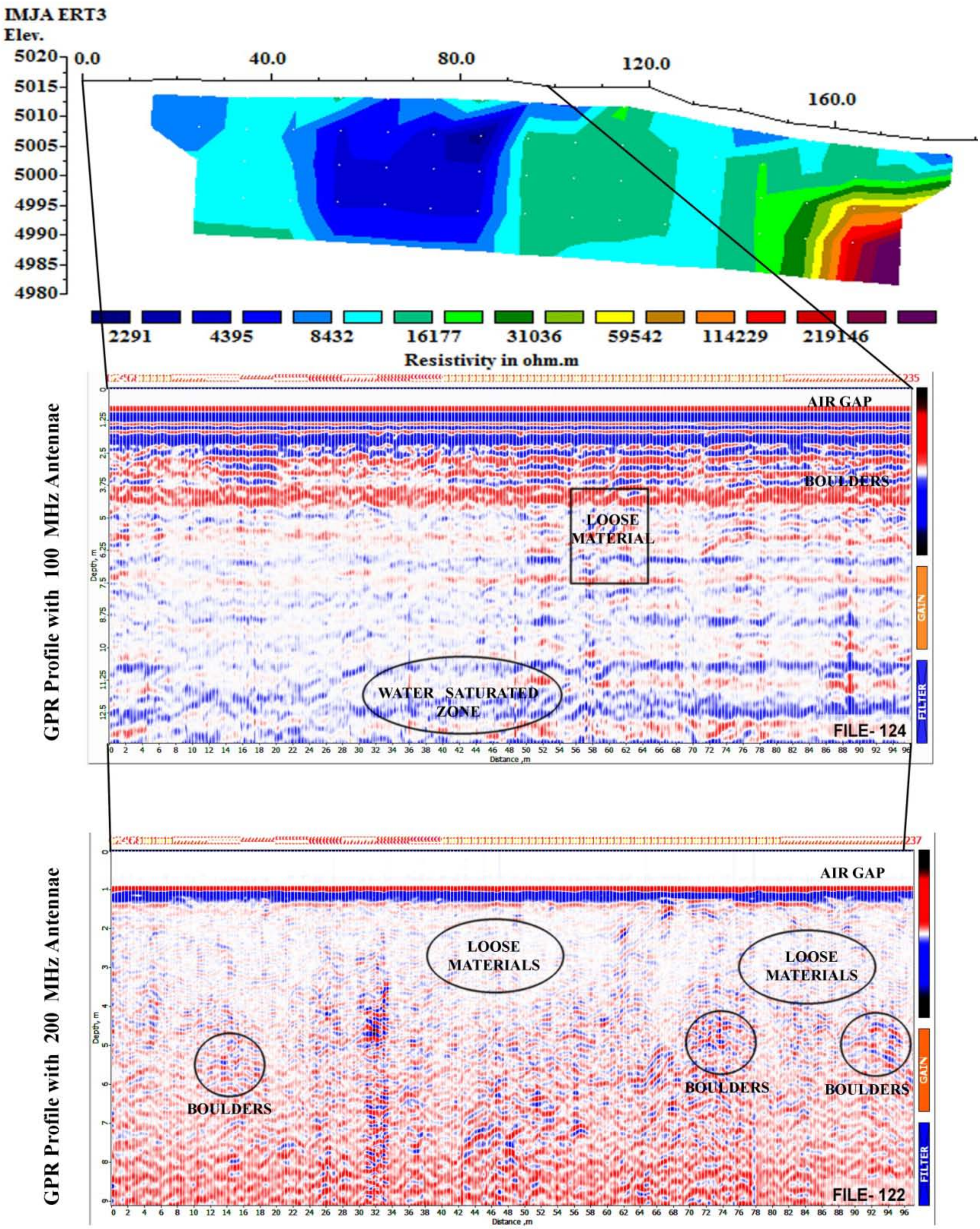

Figure 14: GPR profiles of 100MHz (middle; File-124) and 200MHz (below; File-122) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-3 profile (top) carried out around right bank of Imja Lake moraine deposits.

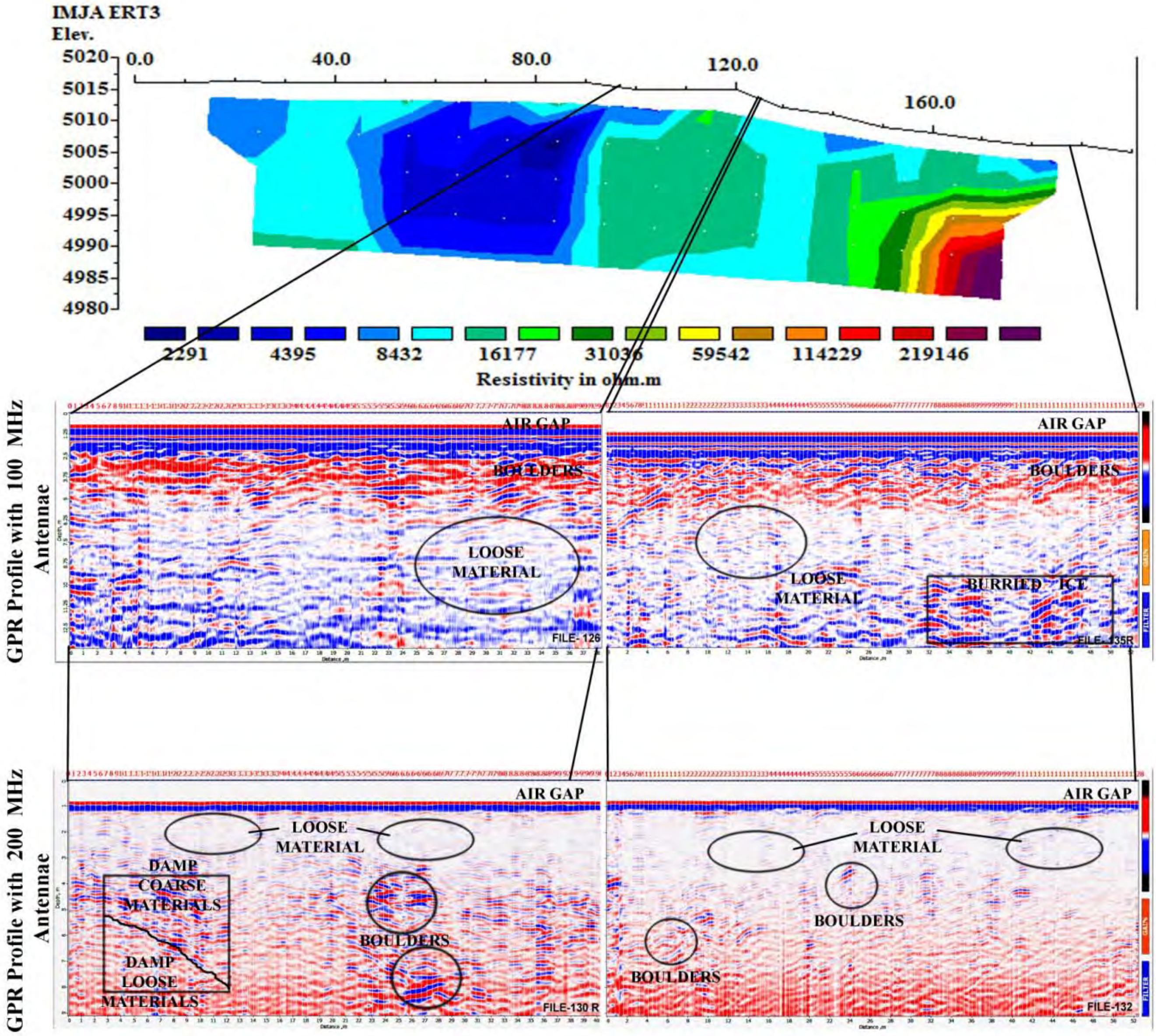

Figure 15: GPR profiles of 100MHz (middle; File-126, 135R) and 200MHz (below; File-130R, 132) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-3 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 4:

This GPR survey was carried out along ERT line 4 which was spread for nearly 160 m on the right side of the lake moraine deposit area. This line starts near the lake and crosses over the moraine to the other side in western direction. Because of the variation of topography of ERT profile line 4, the GPR surveys was carried out in sections and in total 11 profiles were taken using 100 MHz antennae and 9 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 171R, 172R and 173R were used from 100 MHz antennae while profile numbers 184, 183 and 182 were used from 270 MHz antennae. The direction of profile number 171, 172 and 173 were in the opposite direction with respect to that of ERT profiles. Hence these profiles were reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 173R (reverse) using 100 MHz antennae was obtained after 10m from the beginning of the whole profile sections, which starts from 10m and followed upto 90 m (10-90 m). Most of the upper subsurface layers show the mixture of loose sediments with boulders upto the depth of 13m. In this section, the materials are damp and present upto 5m. Using 270 MHz antennae, profile 182 was procured which shows presence of loose materials in top layer upto a depth of 2-3m. In the middle section upto a depth of 4-6m, damp materials is present as shown in Figure 16.

The GPR profile section 172R (reverse) collected using 100 MHz antennae represent the middle portion of ERT profile 4. It begins at 90m and ends at 118 m from the starting point of ERT line 4 and presents the data for a length of 28m. In this GPR profile, top layer seems to be composed of damp materials at a depth of 3 - 5.5m. Beneath this layer, loose sediments are present which can be demarcated from the above strata of boulders and damp materials as shown in Figure 17. At the beginning of this profile at a depth of 7-13m buried ice can be seen up to a distance of 23m of this profile. Similar observations are also seen in the profile 183 of 270 MHz antennae. The demarcations of damp material and buried ice can be clearly seen at depth of 3.5 – 5.5m and 6.5 – 7m respectively from the surface. The extent of buried ice is from 7m to 18m of this profile. These observations relates well with the finding of ERT along line 4.

The GPR profile section 171R (reverse) collected using 100 MHz antennae represent the end portion of ERT profile 4. It begins at 118m and ends at 156 m on ERT line 4. In this GPR profile, top layer seems to be composed of damp materials at a depth of 3 - 5.5m from the surface. Beneath this layer loose sediments are present which can be demarcated from the

above strata of boulders and damp materials as shown in Figure 18. At the beginning of this profile, at a depth of 7-13m buried ice can be seen from the beginning up to a distance of 13m of this profile. Similar observations are also seen in the profile 184 of 270 MHz antennae. The demarcations of damp material can be clearly seen at depth of 3-6m from the surface.

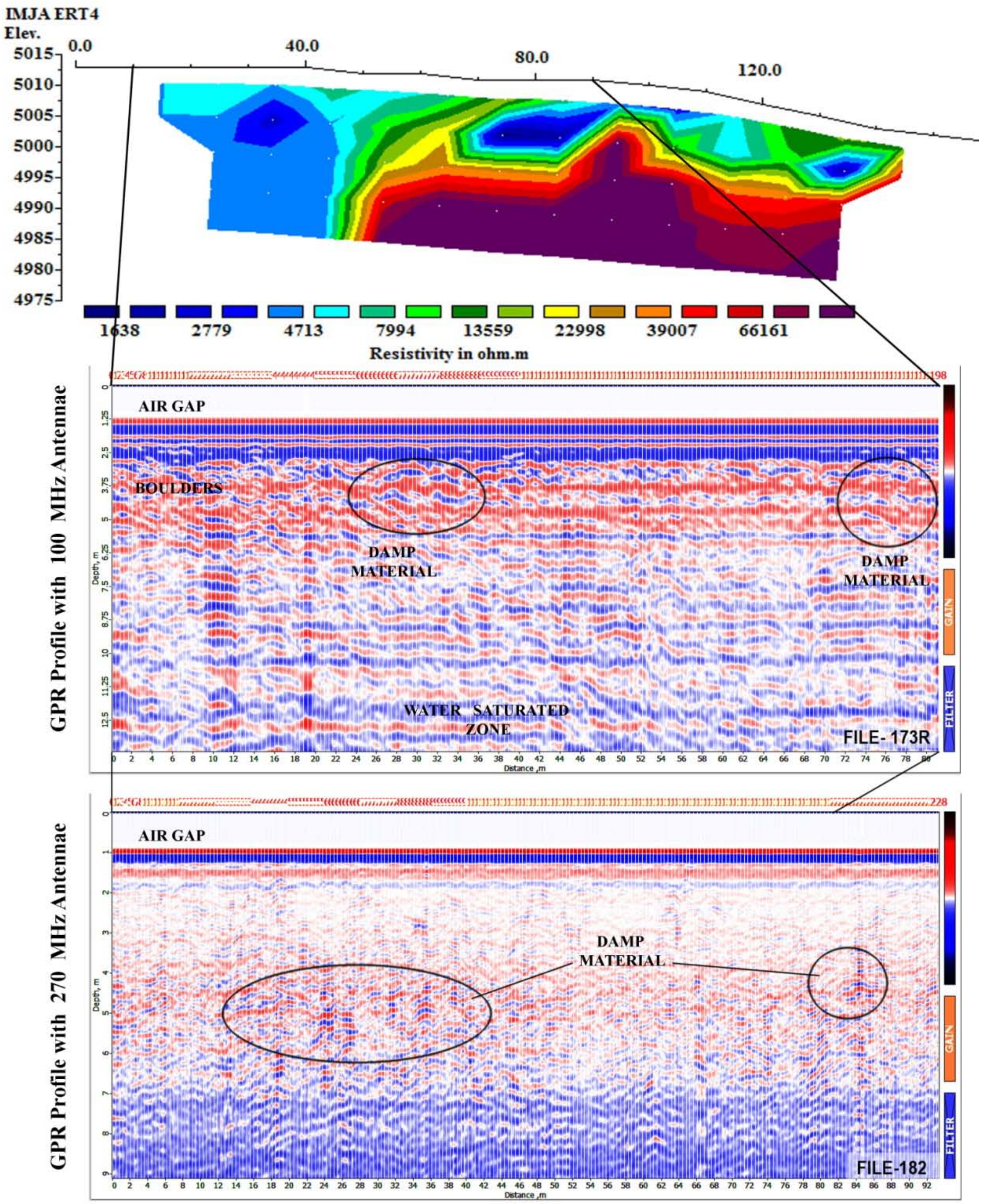

Figure 16: GPR profiles of 100MHz (middle; File-173R) and 270MHz (below; File-182) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-4 profile (top) carried out around right bank of Imja Lake moraine deposits.

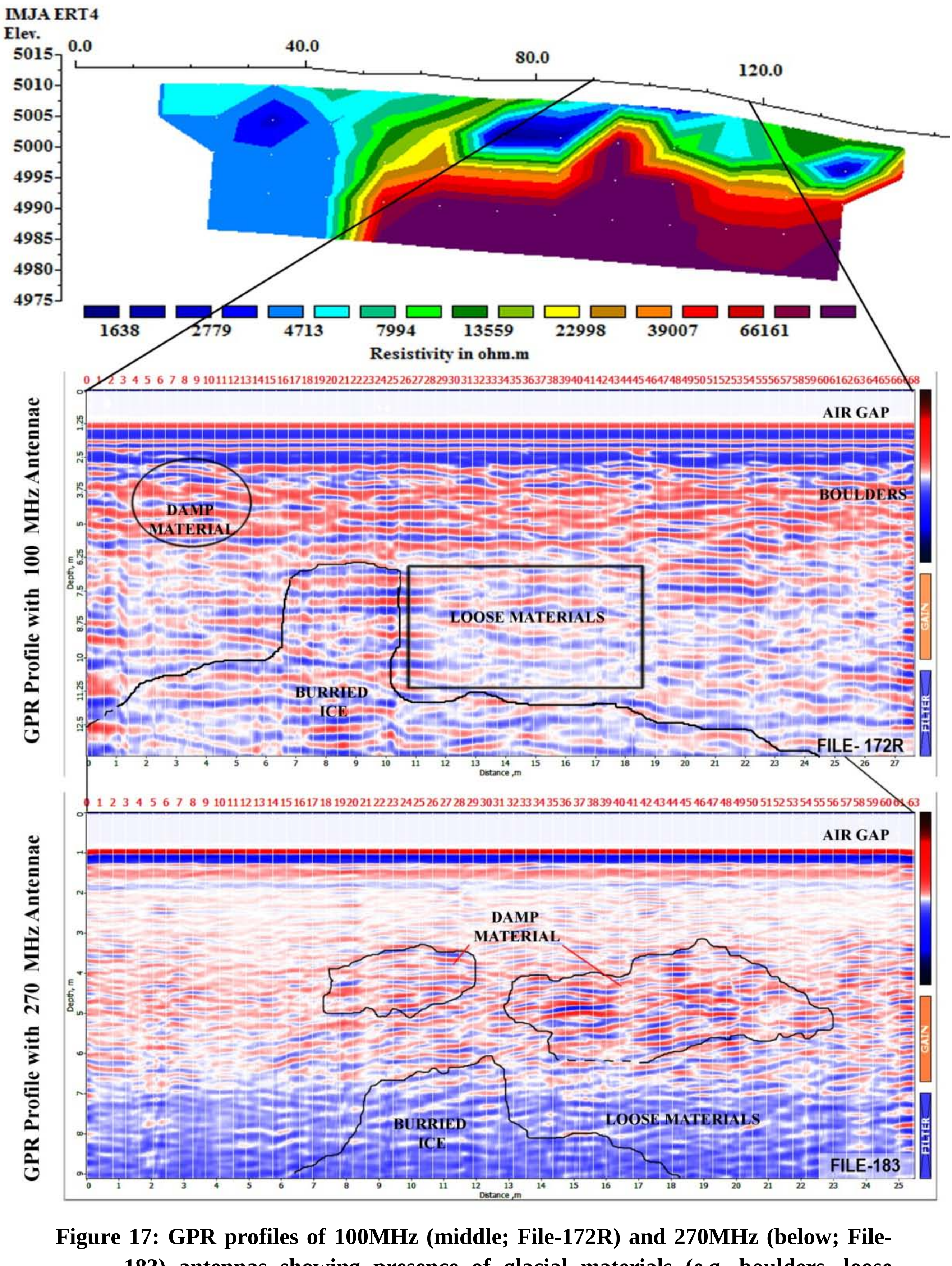

Figure 17: GPR profiles of 100MHz (middle; File-172R) and 270MHz (below; File-183) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-4 profile (top) carried out around right bank of Imja Lake moraine deposits.

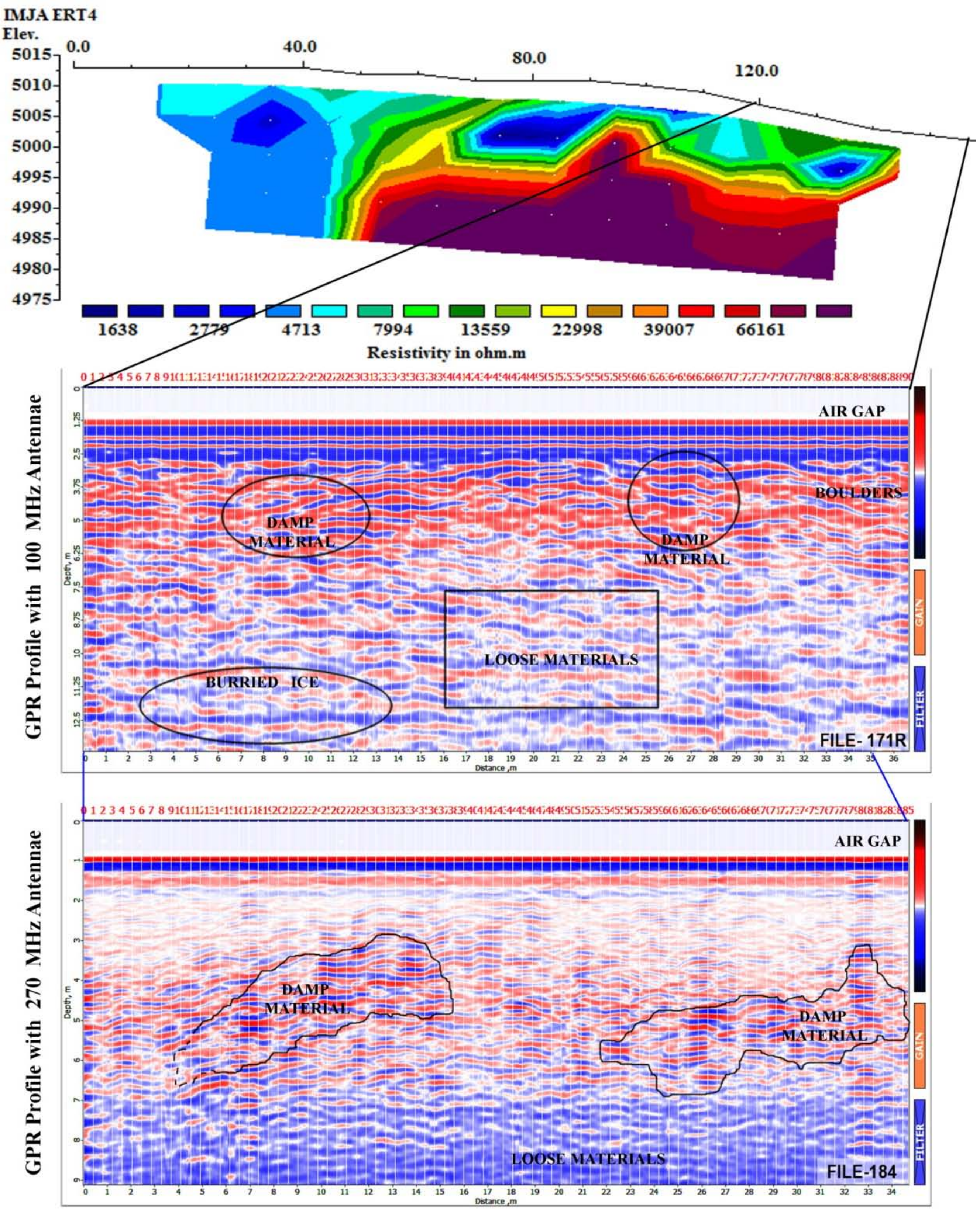

Figure 18: GPR profiles of 100MHz (middle; File-171R) and 270MHz (below; File-184) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-4 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 5:

This GPR survey was carried out along ERT line 5 which was spread for nearly 160m on the right side of the lake moraine deposit area in N-S direction. Because of the variation in topography of ERT profile line 5, the GPR surveys was carried out in sections and in total 8 profiles were taken using 100 MHz antennae and 6 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 136 and 137 were used from 100 MHz antennae while profile numbers 144 and 145 were used from 270 MHz antennae. The directions of all these profiles were in the opposite direction with respect to that of ERT profiles. Hence they were reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 137R (reverse) using 100 MHz antennae was obtained from the beginning of the whole profile sections, which starts from the same location as that of the starting points of ERT line and follow along the section up to 76m (0-76m). Most of the upper subsurface layers show the mixture of loose sediments with boulders up to the depth of 13m. In this section, at a distance of approximately 28 – 44m, loose materials are present at a depth of 7-10m from the surface. Similar observations are also seen in the profile 145R of 270 MHz antennae as indicated in Figure 19. The upper portion of this profile section shows the presence of loose materials after a depth of 3m, overlain by boulders. The resolution of this profile is better that 100 MHz, so demarcations within boulders and loose materials can be clearly visualized.

The GPR profile section 136R collected using 100 MHz antennae represent the end portion of ERT line 5. This profile begins at 78m and ends at 156 m. Boulders are present on top surface upto a depth of 5-6m as clearly demarcated on Figure 20. The upper portion of this profile section shows the presence of loose materials with boulders. In this profile, most of the upper subsurface layers show the mixture of loose materials with boulders upto the depth of 13m. Damp materials are present at a distance of 26m to 48m at a depth of 11-13m. However, at the end of the profile at a distance of about 58 – 78m of this profile, probable buried ice is present at a depth of around 7m. The demarcating line is marked in the Figure 20.

The profile 144R captured using 270 MHz antennae showed better resolution for demarcations among loose materials, damp materials, boulders and buried ice. Top layer of loose materials present at varying depths from 1.5 to 3 m from the top surface. Below this loose material, boulders are present which can be seen at various locations. In the middle (38 – 48 m) of the profile, damp materials are present at a depth of 5.5-6.5m, which can be differentiated from the

buried ice at bottom. There is a line present at a depth of 5-6m from the top surface which demarcates the presence of buried ice at the end of the profile that can be clearly seen in Figure 20.

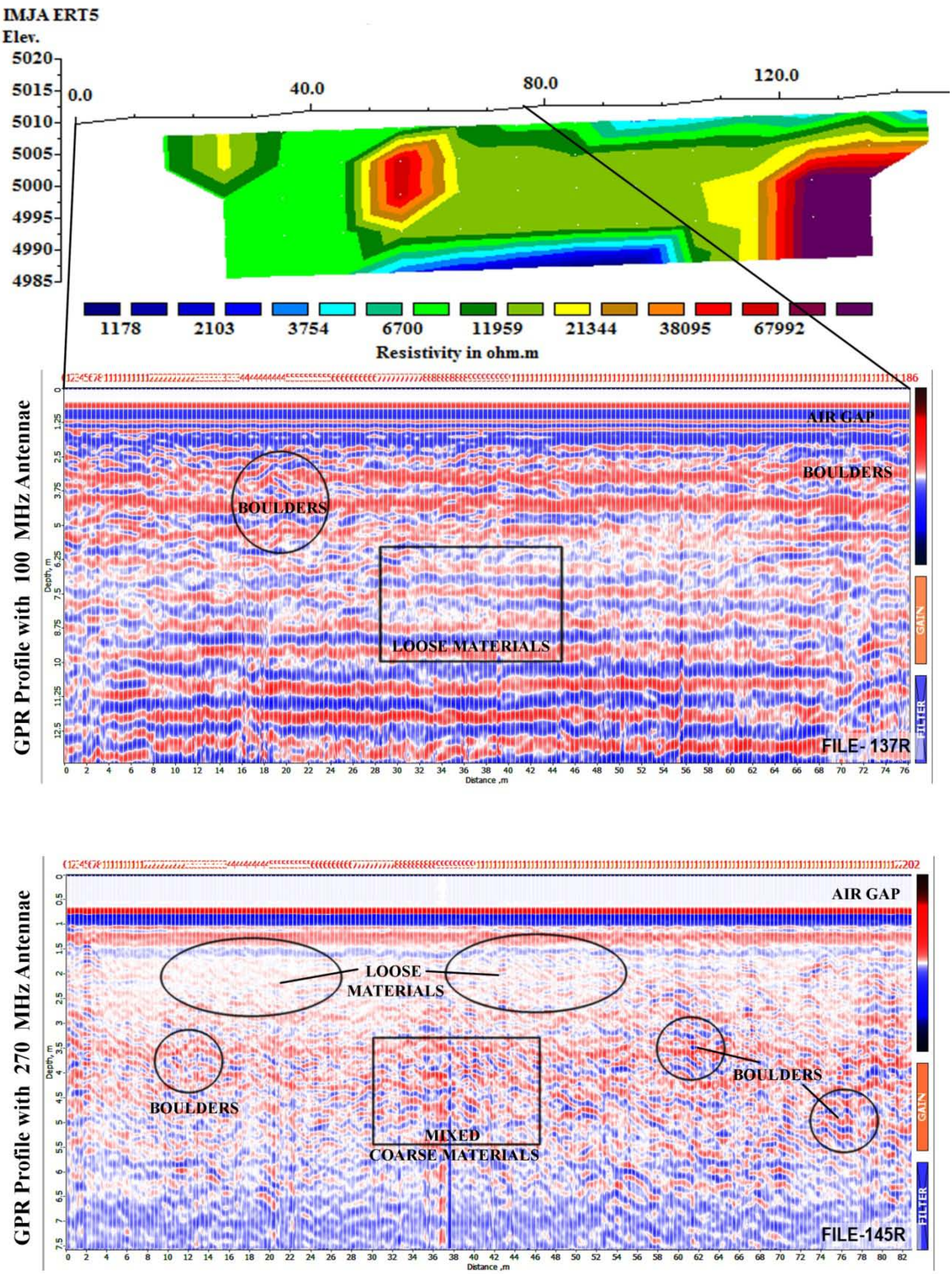

Figure 19: GPR profiles of 100MHz (middle; File-137R) and 270MHz (below; File-145R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-5 profile (top) carried out around right bank of Imja Lake moraine deposits.

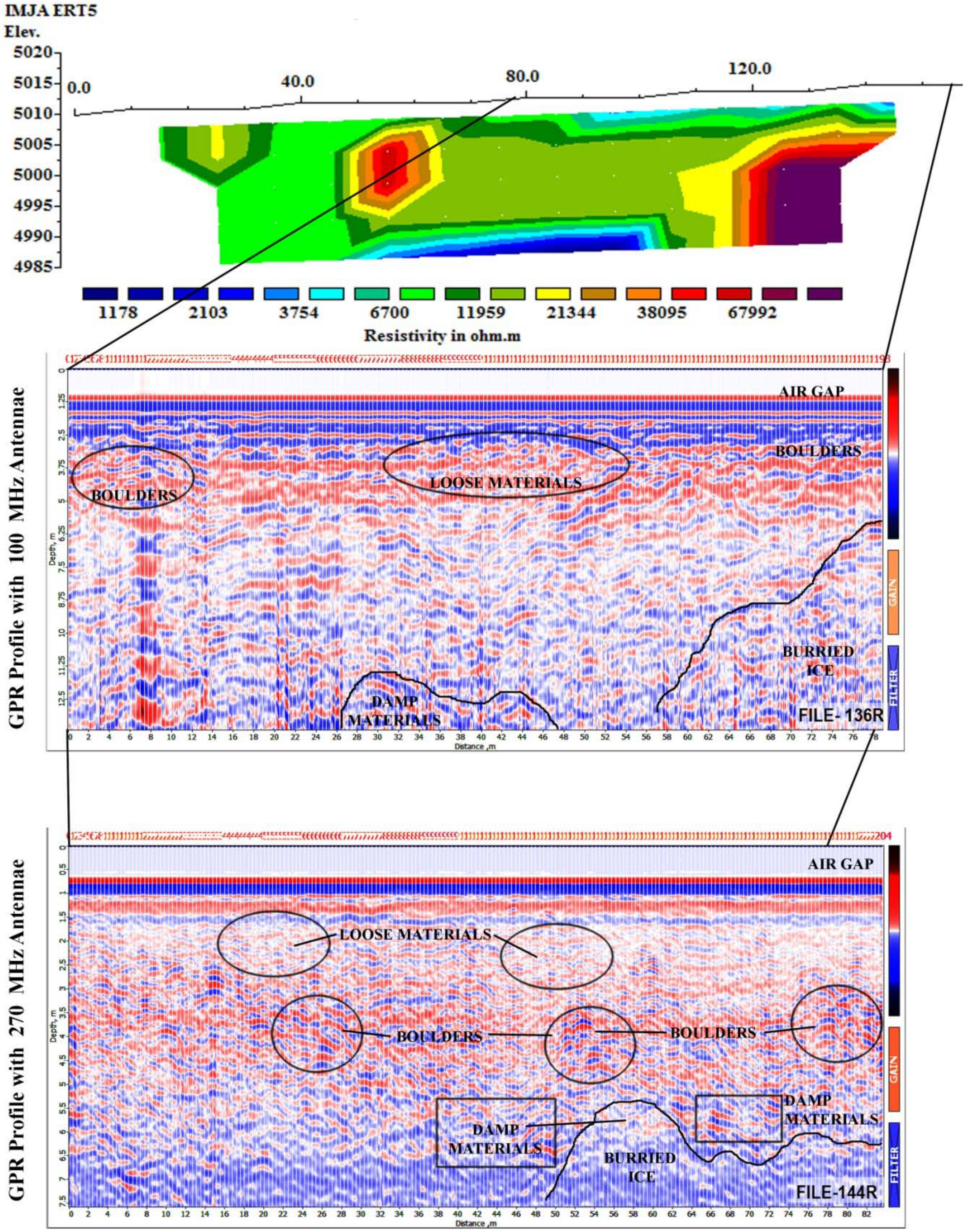

Figure 20: GPR profiles of 100MHz (middle; File-136R) and 270MHz (below; File-144R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-5 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 6:

This GPR survey was carried out along ERT line 6 which was spread for nearly 160m on the right side of the lake moraine deposit area in NW-SE direction. Because of the variation in topography of ERT profile line 6, the GPR surveys was carried out in sections and in total 2 profiles were taken using 100 MHz antennae and 9 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 170 was used from 100 MHz antennae while profile numbers 158 was used from 270 MHz antennae. These profiles are relatable with ERT profile.

The GPR profile 170 using 100 MHz antennae was obtained after 30m from the beginning of the whole profile sections, which starts from 30m from the starting points of ERT line and follow along the section upto 135m (30-135m). Most of the upper subsurface layers show the mixture of loose mixed materials with boulders/ coarse materials upto the depth of 13m. In this section, at a distance of approximately 75 – 85m, loose materials are present at a depth of 5-7.5m. At the end of the profile (75m- 105m), water saturated zone is present which can be demarcated very easily due to its reflectance signature. This zone is present at a depth of 11m and decrease to 8m towards the end of the profile as shown in Figure 21.

The profile 158 captured using 270 MHz antennae showed better resolution for demarcations among loose materials, filled coarse materials, and boulders. Top layer is of loose materials present at varying depths from 1.5 to 3 m. Below this loose material, boulders are present which can be seen at various locations. From the beginning to the middle (10 – 60 m) of the profile, filled coarse materials are present at a depth of 3.5-5m, which can be differentiated from the loose materials at top as shown in Figure 21. The resolution of this profile is better that 100 MHz, so demarcations within boulders and loose materials can be clearly seen.

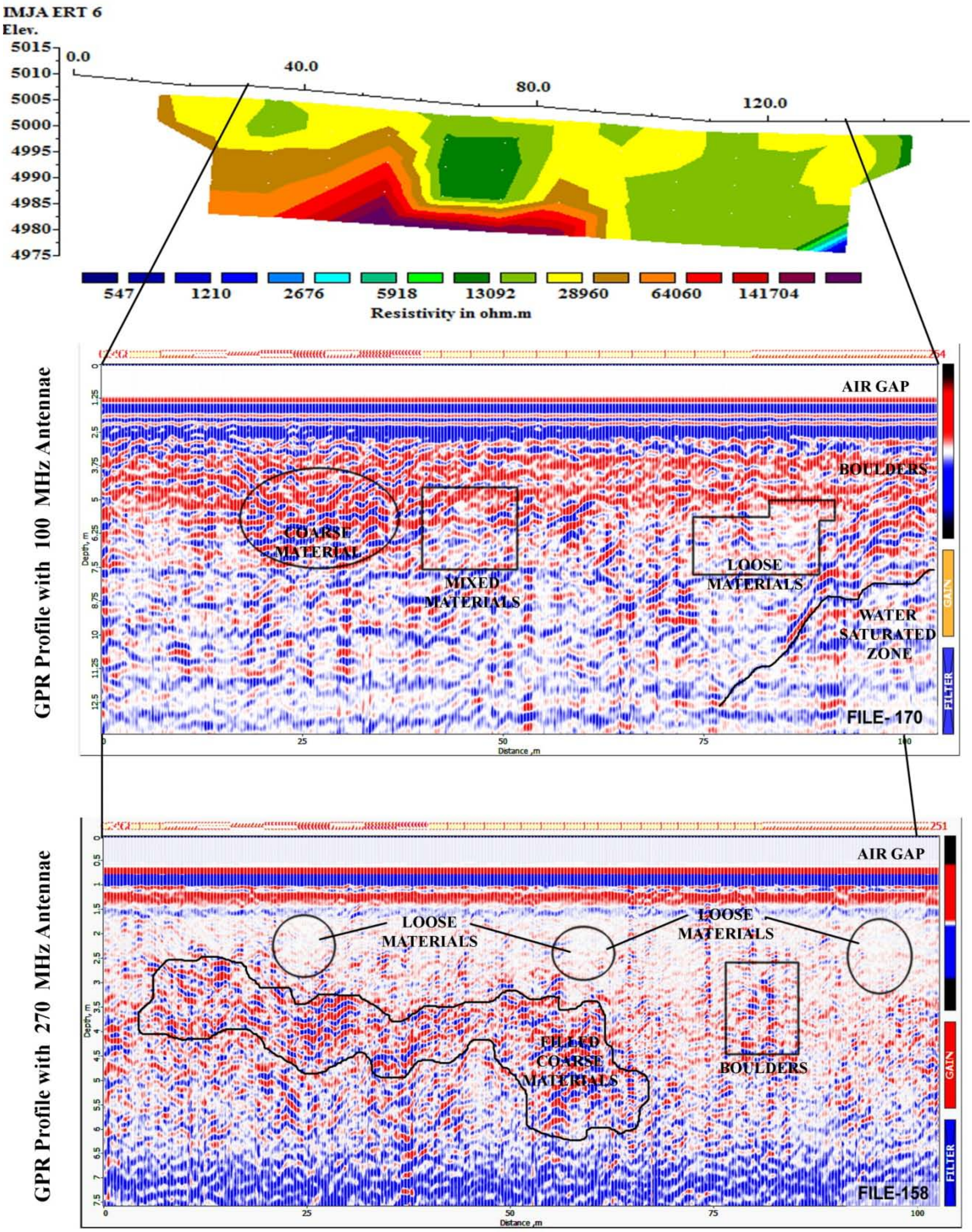

Figure 21: GPR profiles of 100MHz (middle; File-170) and 270MHz (below; File-158) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-6 profile (top) carried out around right bank of Imja Lake moraine deposits.

Along ERT Line 7:

This GPR survey was carried out along ERT line 7 which was spread for nearly 160 m on the right and left side of the lake moraine deposit area in approximately NW-SE direction. This profile crosses the outlet at around 80m i.e. mid way, hence for GPR survey two separate lines were marked. One was on right side of the outlet stream and other on the left side. Hence around 30-35m length of the middle was not covered by GPR. The GPR surveys was carried out in sections and in total 8 profiles were taken using 100 MHz antennae and 11 profiles were taken using 200 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 218 and 219 were used from 100 MHz antennae while profile numbers 232 and 223R were used from 270 MHz antennae. The direction of profile number 223R was in the opposite direction with respect to that of ERT profiles. Hence profile 223R of 270 MHz was reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 218 using 100 MHz antennae was obtained from the beginning of the whole profile sections, which starts from the same location as that of the starting points of ERT line 1 and follow the section up to 55 m (0-55 m). Most of the upper subsurface layers show the mixture of loose sediments with boulders up to the depth of 13m. In this section, damp material is present at the top, and below that loose material is present. At the end of the profile around 34m to 55m, probable buried ice/ hard rock is present at a depth of 9-13m. This demarcation can be clearly visible in Figure 22. Using 270 MHz antennae profile 232 was procured which shows presence of damp materials in the beginning of the profile (at a distance of 7-11m) in top layer up to a depth of 2-4.5m. Beneath this layer of loose materials can easily be seen.

The GPR profile section 219 collected using 100 MHz antennae represent the end portion of ERT profile 7. It begins at 92m and ends at 182 m along the ERT line 7. In this GPR profile, top layer seems to be composed of boulders at a depth of 2.5 - 5m. Beneath this layer loose sediments are present which can be demarcated from the above strata of boulders. At the beginning of this profile at a depth of 7-13m damp material is present. Next to this is probable buried ice which is present in two pockets one between 24m -50m and another between 60m – 90m at the bottom of the profile. This probable buried ice can be seen around 8 – 13 m as shown in Figure 23. Similar observations are also seen in the profile 223R (reverse) of 270 MHz antennae. The resolution of this profile is better that 100 MHz, so demarcations within boulders and buried ice can be clearly seen. The upper portion of this profile section shows the

presence of loose materials upto a depth of 5m. Around this layer, probable damp material strata are present at a depth of around 3 to 6.5 m. Beneath this layer, probable buried ice is present in the beginning of the profile at a depth of around 6-8m. These observations relates well with the finding of ERT along line 7 and are visualised in Figure 23.

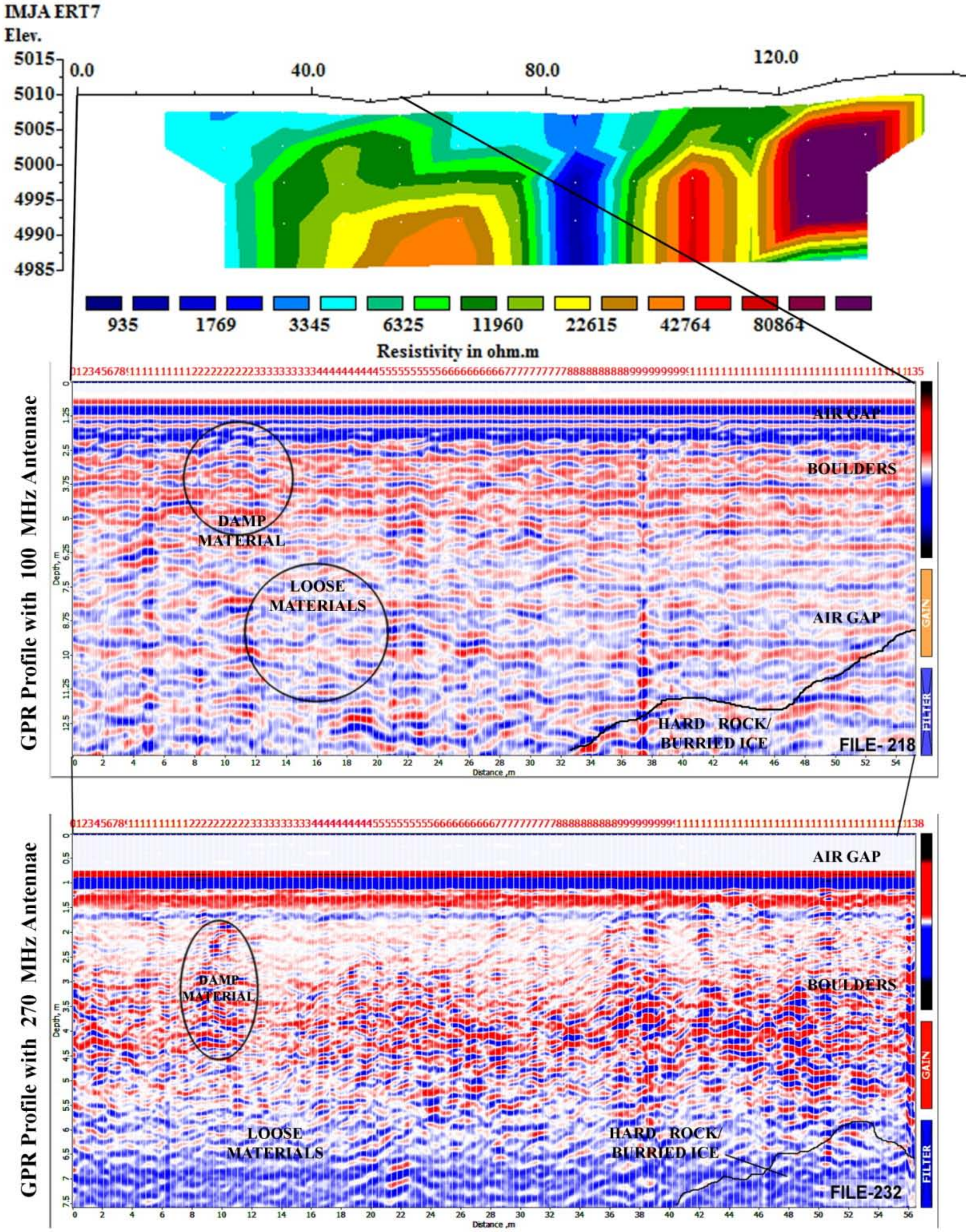

Figure 22: GPR profiles of 100MHz (middle; File-218) and 270MHz (below; File-232) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-7 profile (top) carried out around right bank of Imja Lake moraine deposits.

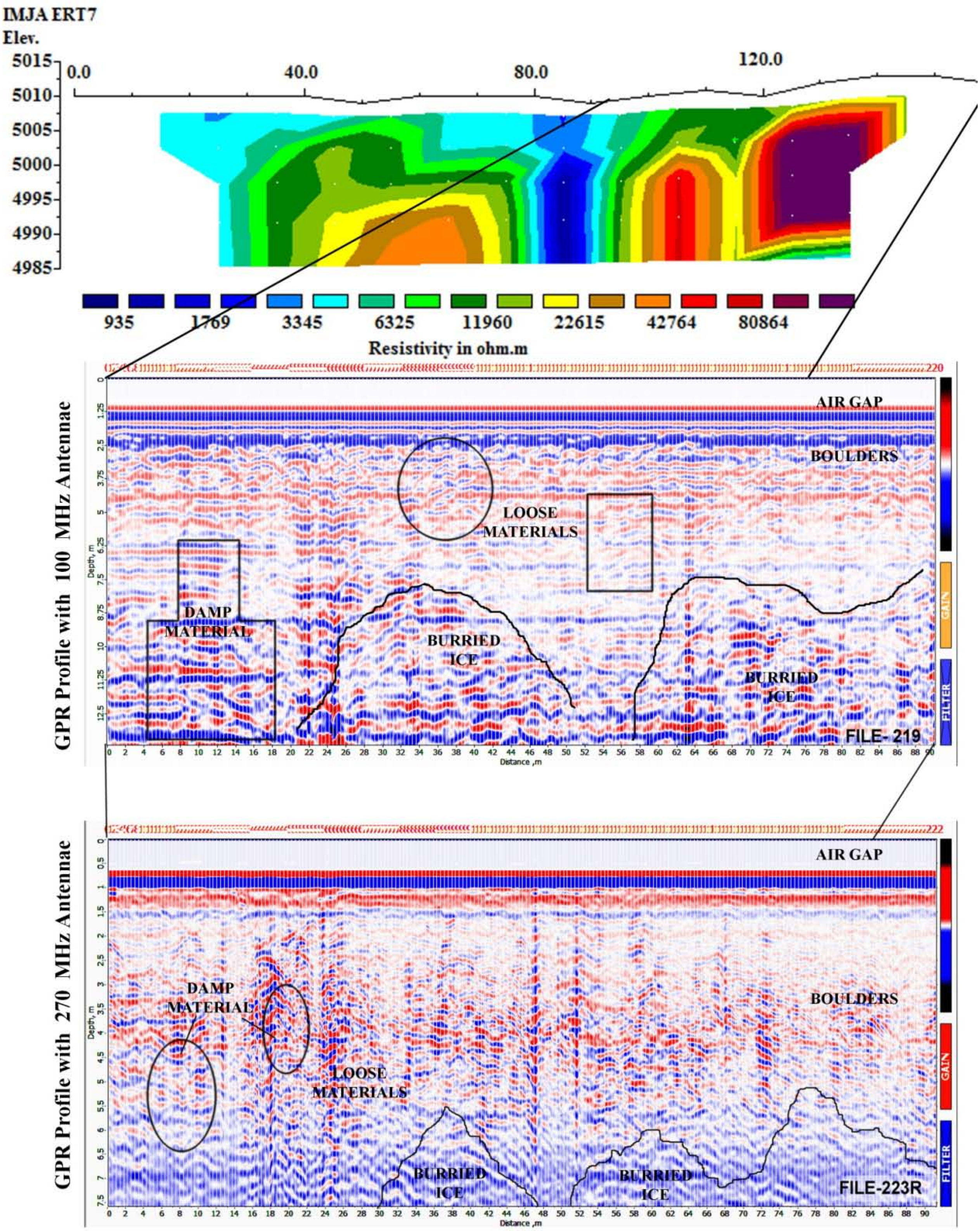

Figure 23: GPR profiles of 100MHz (middle; File-219) and 270MHz (below; File-223R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-7 profile (top) carried out around left bank of Imja Lake moraine deposits.

Along ERT Line 8:

ERT line 8 was carried out on the left side of the lake moraine just next to the stream outlet. It followed nearly a western direction, then over the top of the moraine sediment, the ERT line was changed towards Southern direction. Since the ERT line was curved and not straight, hence for GPR profile, was carried out along the present channel on both the sides. The profile on the left side of the channel are profile number 240, 241 and 242 using 100 MHz antennae and 237, 238, 239 using 270 MHz antennae. The right side of the channel was covered in profiles 243 and 244 of 100MHz and 236 and 235 using 270 MHz antennae. Out of all these profiles, 240, 241, 242 and 235 were in opposite direction, so they were reversed and hence their nomenclature was changed to 240R, 241R, 242R and 235R. All these profiles were used for interpretation. The GPR profiles that were taken on the left side of the stream were matched with the ERT-line 8 and surprisingly good correlations were found.

The GPR profile 242R (reverse) using 100 MHz antennae was obtained after 8m from the beginning of the whole profile sections, which starts from 8m of ERT line 8 and follow the section upto 75 m (8-75 m). Most of the upper subsurface layers show the mixture of loose materials with boulders and probable buried ice at deeper reaches upto the depth of 13m. In the beginning of the section between 10-18m probable buried ice is present at a depth of 9-13m. Towards the end of the profile between 34-56m, there seems to be a demarcation between damp material, present at the top, and probable buried ice present in the bottom layer at a depth of 8-13m. This demarcation can be clearly presented in Figure 24. Using 270 MHz antennae profile 237 was collected which shows presence of damp materials in middle layer upto a depth of 3.5-5m. The top layer is mostly loose material while in the bottom at depth of 6-8m probable buried ice is visible in two small pockets. They are at a distance of 20-28m and 36 to 56m while in the middle section upto a depth of 4-6m, damp coarse materials mostly composed of boulders is clearly seen.

The GPR profile section 241R collected using 100 MHz antennae represent the middle portion of ERT profile 8. It begins at 75m and ends at 154 m along the ERT line 8. In this GPR profile, top layer seems to be composed of boulders at a depth of 5.5 - 6.5m. Beneath this layer loose materials are present which can be demarcated from the above strata of boulders as shown in Figure 25. At the end of this profile between 42-64m, clear demarcation between damp coarse material on top and loose material at bottom. Similar observations are also seen in the profile 238 acquired using 270 MHz antennae. The upper portion (1.5 – 3m) of this profile section

shows the presence of loose materials upto a depth of 3m. Beneath this layer, coarse materials, probable damp boulder strata are present at a depth of around 3.5 to 6 m. Beneath this layer of loose materials, are present in the first half of the section at a depth of around 7-8m.

The GPR profile section 240R collected using 100 MHz antennae represent the end portion of ERT profile 8. It begins at 154m and ends at 197 m from the beginning of ERT line 8. In this GPR profile, top layer seems to be composed of boulders at a depth of 5.5 - 6.5m. Beneath this layer loose materials are present which can be demarcated from the above strata of boulders as shown in Figure 25. In the middle of this profile between 10-30m, clear demarcation between damp coarse material on top and loose material at bottom. Similar observations are also seen in the profile 239 acquired using 270 MHz antennae. The upper portion (1.5 – 3m) of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, coarse materials, probable damp boulder strata are present at a depth of around 3.5 to 6 m. Beneath this layer of loose materials, are present in the first half of the section at a depth of around 7-8m.

The GPR profiles 243, 244 taken using 100 MHz antennae and 236, 235R acquired using 270 MHz antenna show good results but cannot be related with any ERT lines, as no survey was carried out in this section along the right side of the existing channel. In GPR profile 243, top layer seems to be composed of boulders at a depth of 2.5 - 5m and in the latter half of the section some depressed area is visible which seems to be filled with boulders and loose materials. This area is present between 60-70m upto a depth of 10m. In first half of the profile between 35-50m, probable buried ice is visible at a depth of 7-12m. Similar observations are also seen in the profile 236 taken using 270 MHz antennae. The upper portion (1.5 – 3m) of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, coarse materials, probable boulders are present at a depth of around 3.5 to 5.5 m. Buried ice between 30-55m is probably present at a depth of 6.5-8m. In the latter half of the profile between 75-85m similar depressed areas area present which seems to be filled with boulders and loose materials as clearly visible in Figure 26.

In GPR profile 244, top layer seems to be composed of boulders at a depth of 2.5 - 5m and in the first half of the profile between 2-16m, probable interface between damp materials present on top and loose materials, visible at bottom, are present at a depth of 6-12m. Similar observations are also seen in the profile 235R taken using 270 MHz antennae. The upper portion (1.5 – 3m) of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, coarse materials, probable damp boulders/ coarse materials are present

at a depth of around 3.5 to 5.5 m. In the beginning of the profile, the demarcation between coarse materials and loose material is clearly visible at a depth of 5-7m as seen in Figure 26.

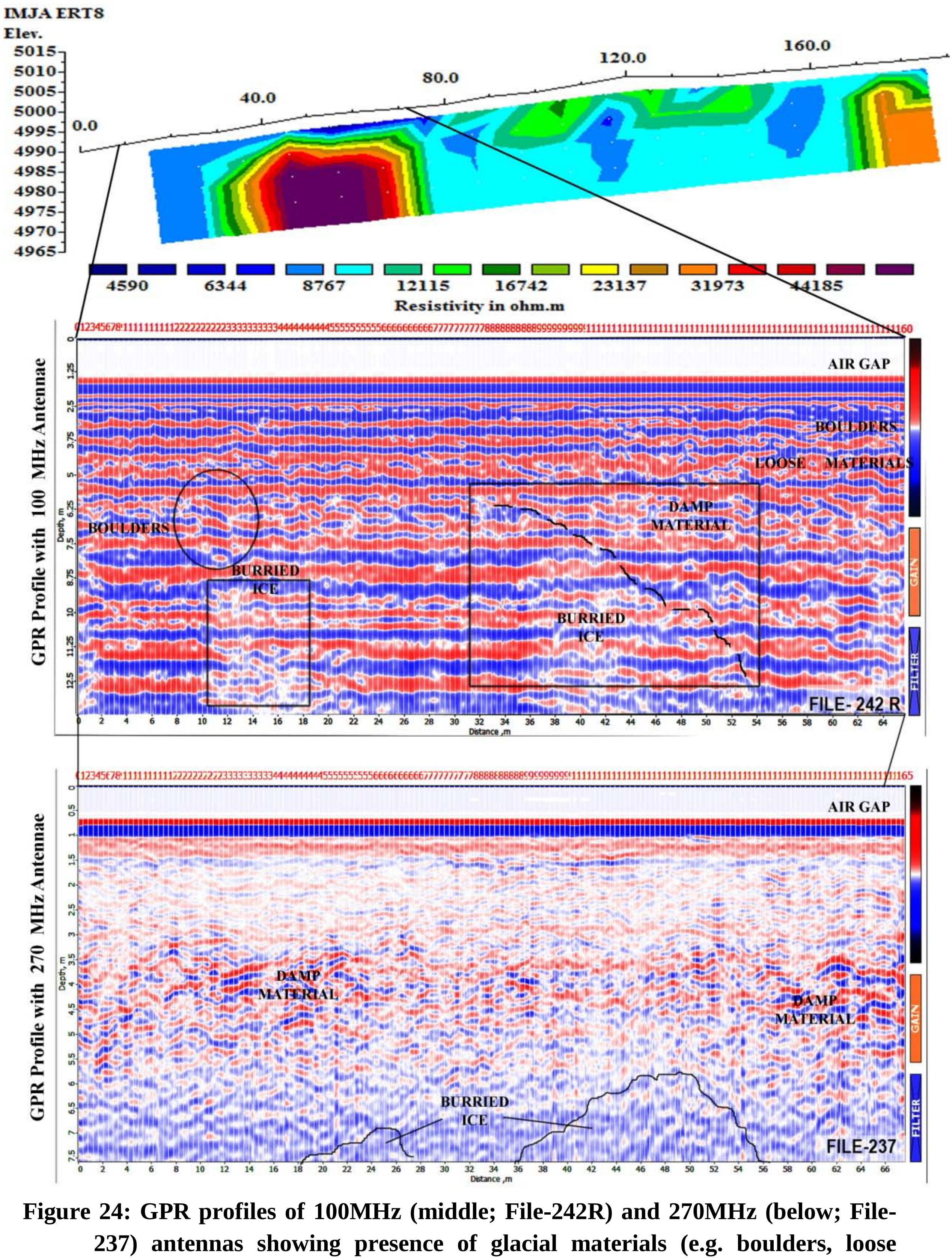

Figure 24: GPR profiles of 100MHz (middle; File-242R) and 270MHz (below; File-237) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-8 profile (top) carried out around left bank of Imja Lake moraine deposits.

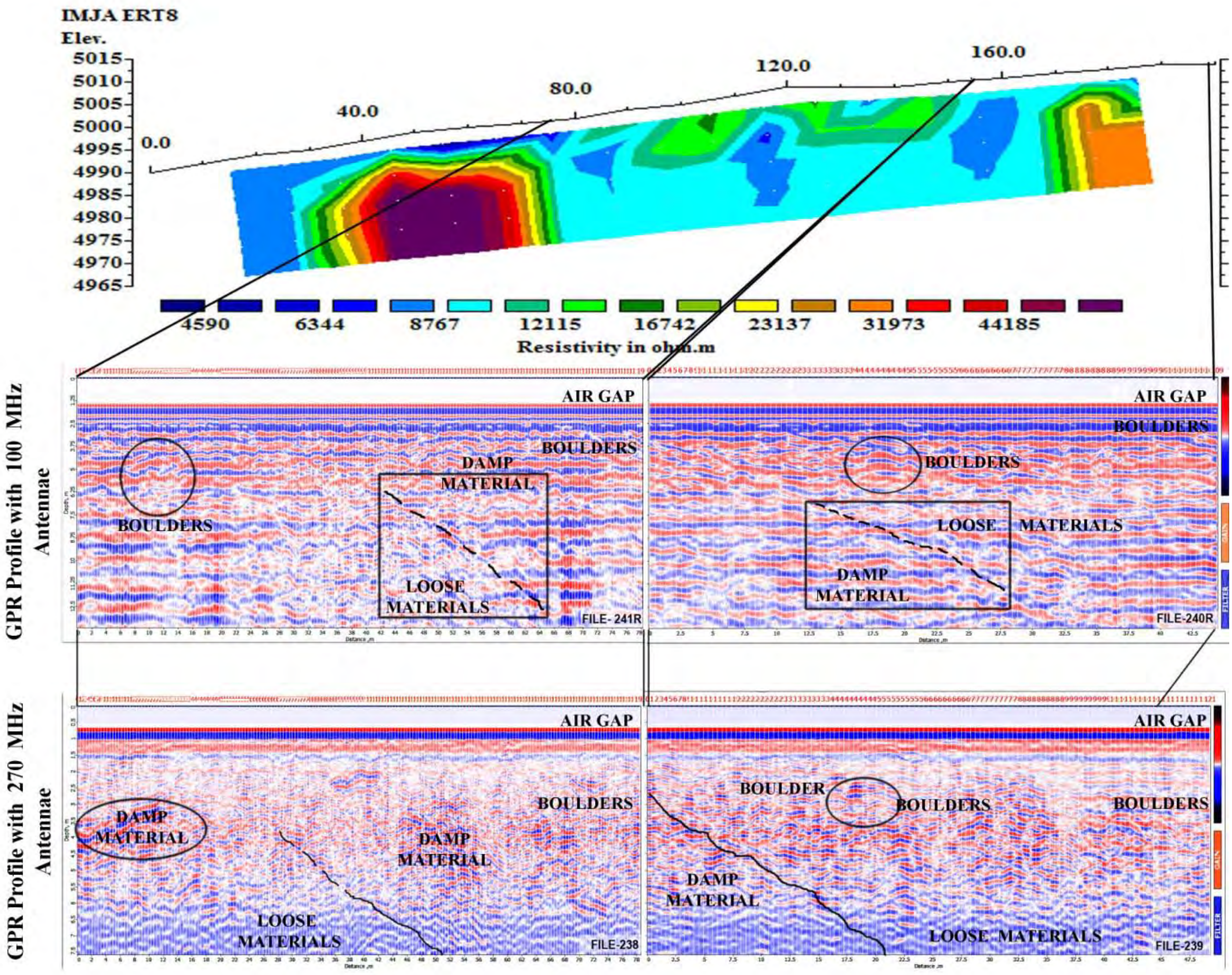

Figure 25: GPR profiles of 100MHz (middle; File-241R, 240R) and 270MHz (below; File-238, 239) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-8 profile (top) carried out around left bank of Imja Lake moraine deposits.

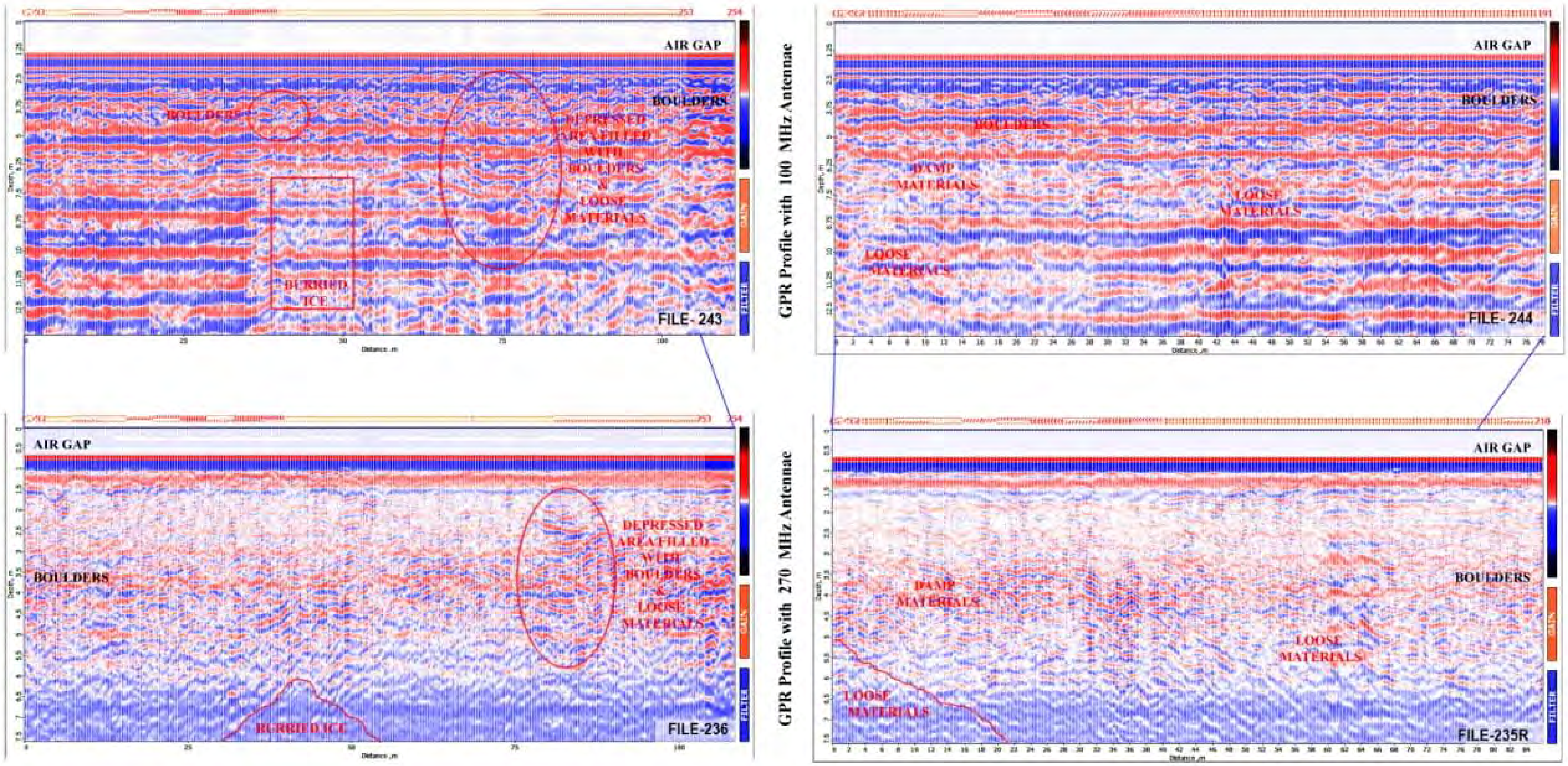

Figure 26: GPR profiles of 100MHz (above; File-243, 244) and 270MHz (below; File-236, 235R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) carried out along right bank of Imja Khola (along almost current channel) moraine deposits.

Along ERT Line 9:

This GPR survey was carried out along ERT line 9 which was spread for nearly 100 m on the left side of the lake moraine deposit area in approximately WNW-ESE direction. Because of the variation in topography of ERT profile line 9, the GPR surveys was carried out in sections and in total 10 profiles were taken using 100 MHz antennae and 11 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 249 and 252R were used from 100 MHz antennae while profile numbers 263 and 257 were used from 200 MHz antennae. The direction of profile number 252 was in the opposite direction w.r.t. that of ERT profiles. Hence profile 252 was reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 249 using 100 MHz antennae was obtained after 8m form the beginning of the whole profile sections, which starts after 8m from the same location as that of the starting points of ERT line 9 and follow along the section upto 50 m (8-50 m). Most of the upper subsurface layers show the mixture of loose sediments with boulders that are damp or water saturated upto the depth of 13m. In the first half of this section between 7-21m, a clear demarcation between water saturated/ damp material, present at the top, and boulders, present at the bottom, is distinctly visible. At the end of the profile around 30m to 40m, similar demarcation between water saturated materials and loose materials is visible. But in this section the direction is reverse, indicating a presence of stream channel at a depth of approximately 13m. These demarcations can be clearly seen in Figure 27. Similar results were obtained using 270 MHz antennae for profile 263, which also shows presence of damp/ water saturated materials in the beginning of the profile (at a distance of 7-20m) in top layer upto a depth of 2-6.5m. Beneath this, boulders and layer of loose materials can easily be seen. At the end of the profile around 33m to 40m, similar demarcation in opposite direction is visible, between water saturated materials on top and loose materials at bottom. Thus, the possibility of a stream channel (probably buried) cannot be ruled out.

The GPR profile section 252R collected using 100 MHz antennae represent the end portion of ERT profile 9. It begins at 54m and ends at 100 m along the ERT line 9. In this GPR profile, top layer seems to be composed of boulders at a depth of 2.5 - 5m. Beneath this layer, damp materials are present in which boulders and loose sediments are mixed. In the first half of the profile, between 10-25m a clear demarcating line between loose materials and hard rock or probably buried ice is present. These loose materials are preset on top at a varying depth of 7-

11m, while buried ice or hard rock is present at bottom at a depth varying from 7.5 to 13m. This probable buried ice can be seen around 8 – 13 m as shown in Figure 28. Similar observations are also seen in the profile 257 acquired using 270 MHz antennae. The resolution of this profile is better that 100 MHz, so demarcations within boulders, loose materials, damp materials and buried ice can be clearly seen. The upper portion of this profile section shows the presence of loose materials upto a depth of 3m from the surface. Around this layer, probable damp material strata are present at a depth of around 3 to 5.5 m from the top surface. Beneath this layer, probable buried ice is present in the beginning of the profile at a depth of around 4-8m. There is a clear demarcation between damp material and buried ice or hard rock in the first half of the profile between 6-16m. In the latter half of the profile, between 25.5 to 27.5 m there is some problem with the data so it is marked as system error. These observations relates well with the findings of ERT along line 9.

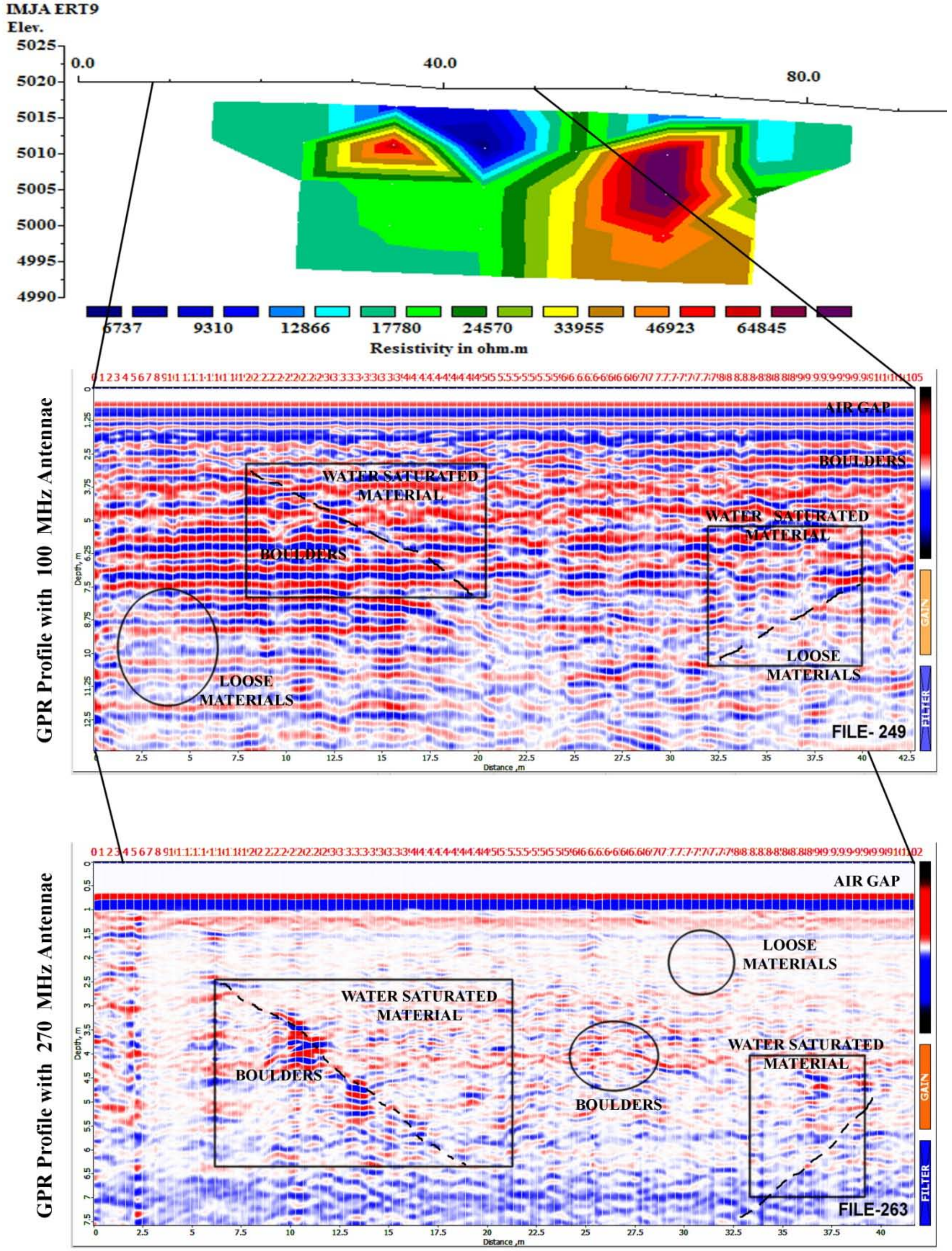

Figure 27: GPR profiles of 100MHz (middle; File-249) and 270MHz (below; File-263) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-9 profile (top) carried out around left bank of Imja Lake moraine deposits.

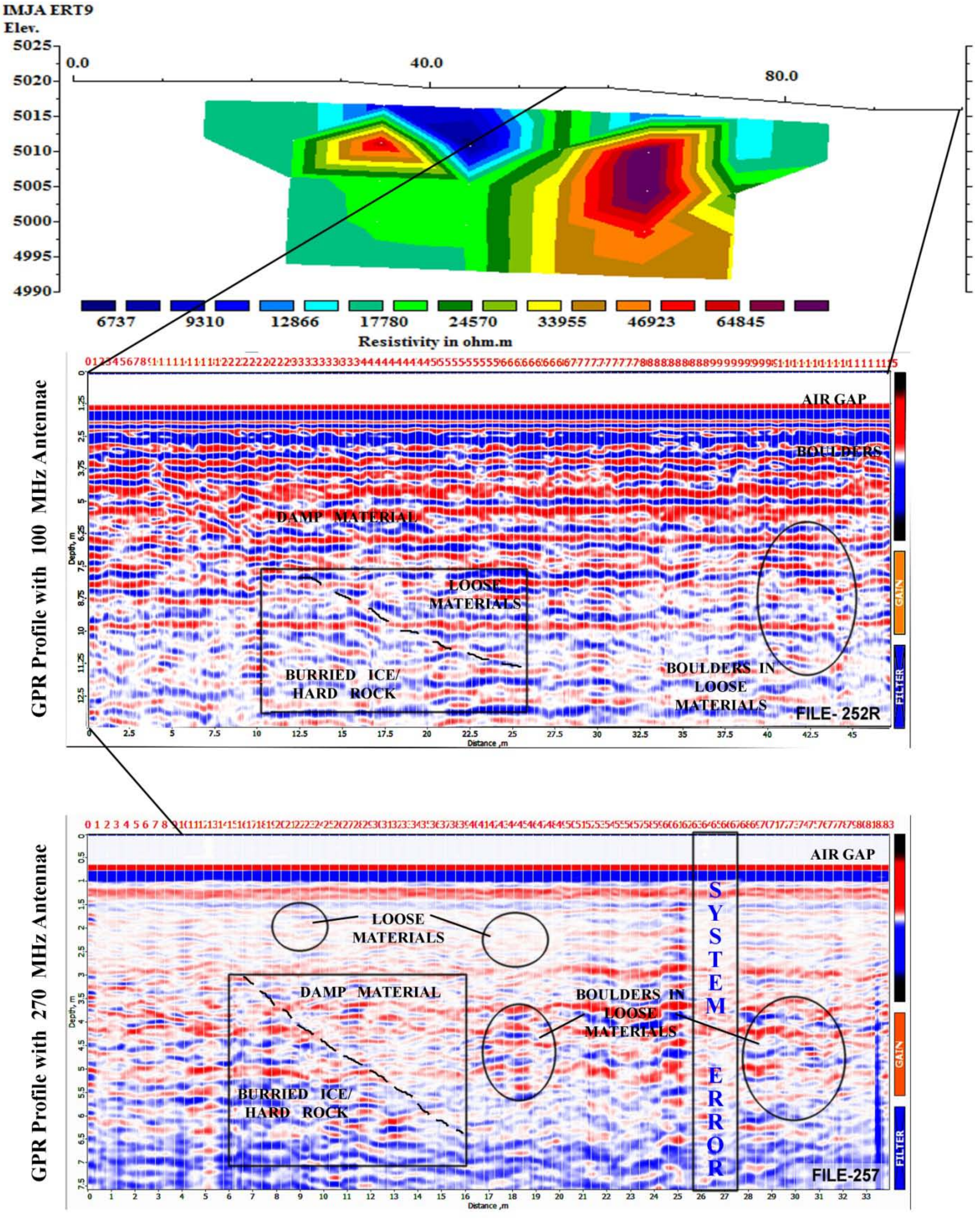

Figure 28: GPR profiles of 100MHz (middle; File-252R) and 270MHz (below; File-257) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-9 profile (top) carried out around left bank of Imja Lake moraine deposits.

Along ERT Line 10:

This GPR survey was carried out along ERT line 10 which was spread for nearly 160 m on the left side of the lake moraine deposit area in approximately N-S then NE-SW direction. Because of the variation in topography of ERT profile line 10, the GPR surveys was carried out in sections and in total 9 profiles were taken using 100 MHz antennae and 9 profiles were taken using 270 MHz antennae. Out of these, the best suited GPR profile lines were matched with the ERT profiles. In this section GPR profile no 272R and 280R were used from 100 MHz antennae while profile numbers 266 and 281R were used from 200 MHz antennae. The direction of profile number 272, 280 and 281 were in the opposite direction w.r.t that of ERT profiles. Hence these profiles were reversed to get the proper alignments that are relatable with ERT profile.

The GPR profile 280R using 100 MHz antennae was obtained after 14m form the beginning of the whole profile sections, which starts after 14m from the same location as that of the starting points of ERT line 10 and follow along the section upto 50 m (14-80 m). Most of the upper subsurface layer is dominated with boulders that may be damp upto the depth of 8m. In the latter half of this profile between 28-41m, a clear demarcation between coarse materials, present at the top, and buried ice or hard rock, present at the bottom, is distinctly visible. In the middle of the profile around 14m to 22m, and in the end of the profile around 52-58m, loose materials are present at higher depths varying from 9-13m. Similar demarcation between coarse materials and buried ice or hard rock is visible in the GPR profile no 281R acquired using 270MHz antennae. These demarcations can be clearly seen in Figure 26. The resolution of this profile is better than that acquired by using100 MHz, so demarcations within boulders, loose materials, and buried ice can be clearly seen. The upper portion of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, boulders and probable buried ice or hard rock (at a distance of 28-50m) is present in this profile at a depth of around 4-8m. There is a clear demarcation between coarse material and buried ice or hard rock in the middle of the profile between 28-50m. These observations relates well with the finding of ERT along line 10.

The GPR profile section 272R collected using 100 MHz antennae represent the end portion of ERT profile 10. It begins at 80m and ends at 156 m from the beginning of ERT line 10. In this GPR profile, top layer seems to be composed of boulders at a depth of 2.5 – 7.5m. Beneath this layer damp or water saturated materials are present in which boulders and loose sediments are

mixed. This demarcation is present between 37-54m at a varying depth of 6-11m. In this demarcation, boulders are present on top while water saturated materials are present at bottom of the profile. Loose materials are present at bottom between 9-12m as shown in Figure 30. Similar results are visible in GPR profile 266 acquired using 270 MHz antennae. The resolution of this profile is better that 100 MHz, so demarcations within boulders, coarse materials and water saturated materials can be clearly seen. The upper portion of this profile section shows the presence of loose materials upto a depth of 3m. Beneath this layer, boulders are present upto a depth of 5m. At a distance of 38-62m, damp coarse material, which is present on top, can be distinguished from water saturated materials present at bottom. Around this layer, probable damp material strata are present at a depth of around 3 to 6.5 m. Beneath this layer, probable water saturated material is present at a depth of around 5-8m. These observations relates well with the finding of ERT along line 10.

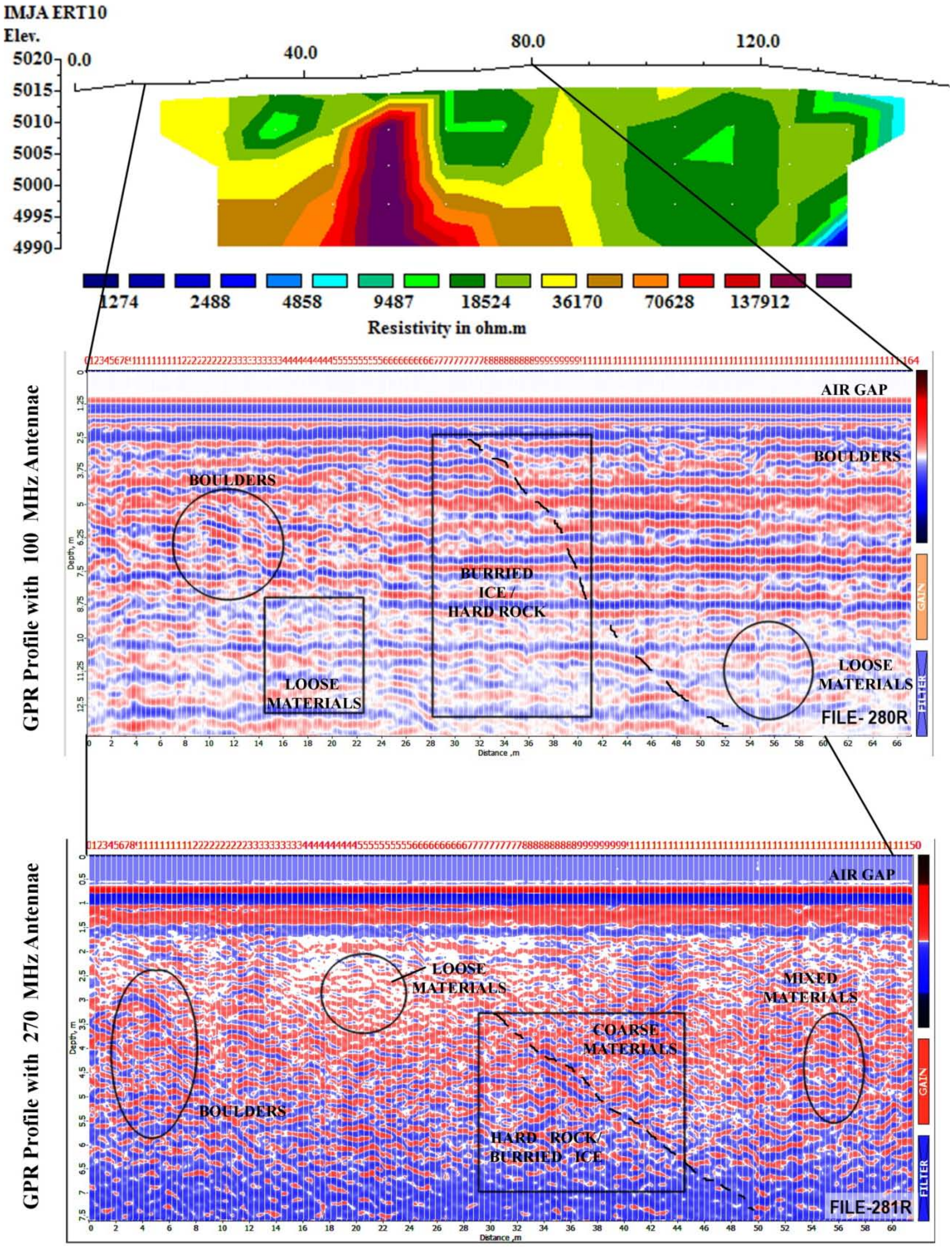

Figure 29: GPR profiles of 100MHz (middle; File-280R) and 270MHz (below; File-281R) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-10 profile (top) carried out around left bank of Imja Lake moraine deposits.

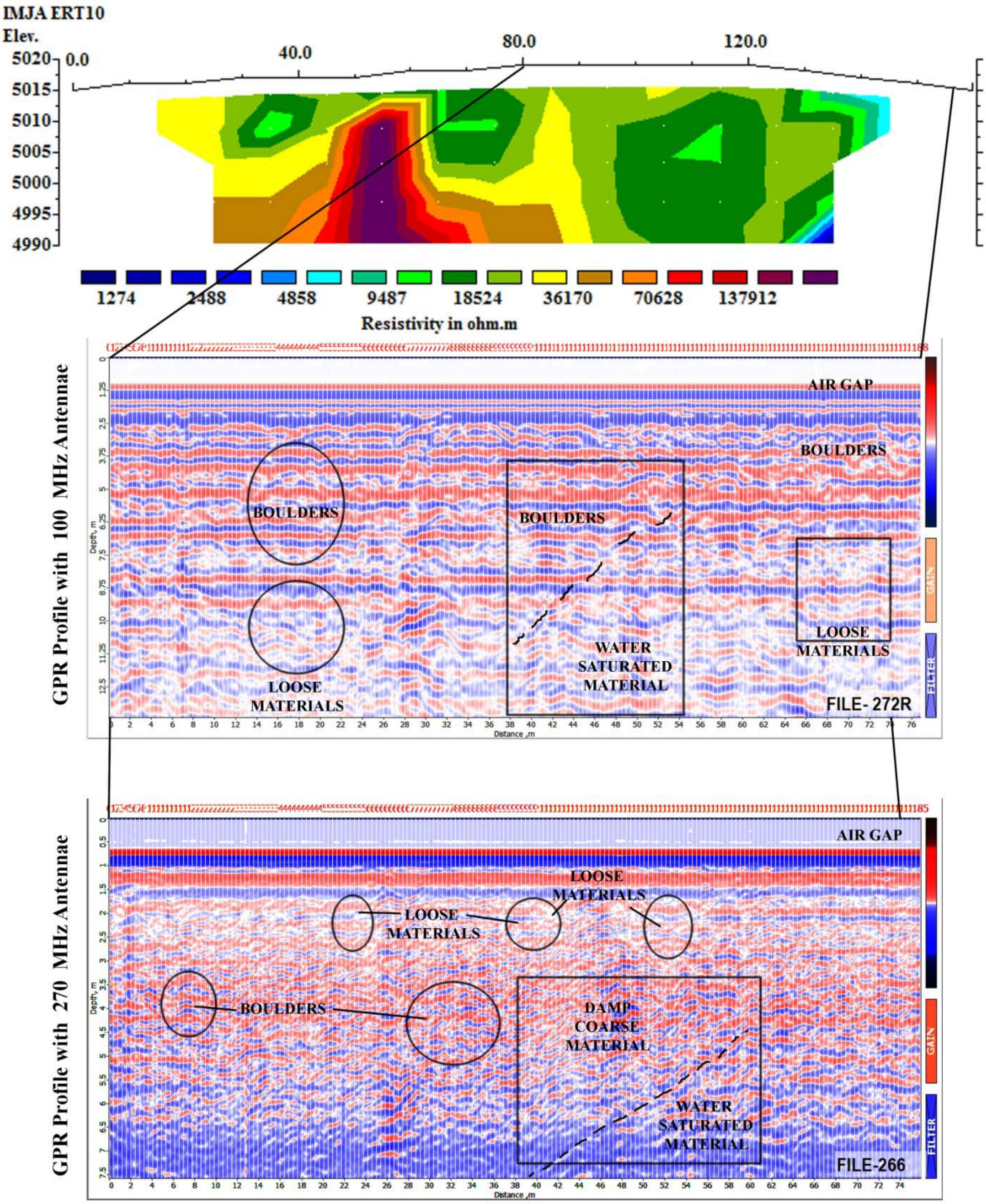

Figure 30: GPR profiles of 100MHz (middle; File-272R) and 270MHz (below; File-266) antennas showing presence of glacial materials (e.g. boulders, loose materials, buried ice, etc.) related with ERT-10 profile (top) carried out around left bank of Imja Lake moraine deposits.

5. DISCUSSIONS AND CONCLUSIONS

The inference has been made from the interpretation of each GPR profiles and thus comparing those with respect to the materials present there, focusing mainly on the shape, size of the buried ice. The properties of each finalized profiles (i.e. 52 profiles) can be made in tabular form so that the materials found in them can easily be compared and give a clear view for choosing one particular channel which is suitable for the concerned project work to be carried out in future. Also, the GPR data were correlated with the ERT data so it can be further verified.

Table 4: GPR & Corresponding Geological facies around the Imja Lake

GPR Profile Antenna Used	Chainage[#] (m)	Depth (m)	GPR Facies	Geological Facies	Lithological Interpretation (as Marked in the GPR Profile)	Size, Area* and Depth of Buried Ice (If Marked)
GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 1						
FILE-055 (100MHz)	21-53m and 63.5-78m	3-5m	High frequency parabolic shapes with meso-scale diffraction	Glacial till with unsorted boulders	Large boulders are marked in the profile by very high frequency	Not found up to the depth of penetration
	37-47m	8.5-10m	Chaotic or poorly defined	Matrix rich debris, damp	Damp materials marked by the high reflections (with darker patches) as compared from the surroundings	
	67-84m	6m	Chaotic or poor diffraction	Loose materials	Loose materials demarcated by low reflections (light coloured patches)	
	8.5-12m and at places	3-4m	Trough shaped	Glacial fill	Bow down (concave) structure with blue colored continuous reflection	

FILE-097R (200MHz)	29-37m and 44-53m	4-5m	Parabolic meso-scale diffraction	Unsorted boulders	Large number of parabolic shapes of boulders throughout the profile due to moraine.	Not found up to the depth of penetration
	About 20m and 56-82m	3.5-6m	Chaotic or poorly defined	Matrix rich debris, damp materials	Damp loose materials with slightly higher reflectance due to presence of moisture.	
	20.5-27m and 67-73.5m	1.7-3m	Chaotic or poor diffraction	Loose materials	At some parts below the boulders light coloured zone can be demarcate again.	
	98-102m	6-8.5m				
	8-19m	2-3.5m	Trough shaped	Glacial fill	A layer of loose sediments (with low reflectance or lighter patches) present above the continuous line of high reflectance.	
FILE-074 (100MHz)	6.5m-17m; about 22m about 38-44m	About 7m to 10.5m	Reflection free	Buried ice	Buried ice marked by low conductivity (appears very light; generally $<0.01Sm^{-1}$) with dielectric relaxation centered at 9GHz (still way above GPR bandwidths).	Present after 7m depth of an area around $10m^2$.
	8-12m; 32-38m and 76-81m	2 to 6.5m	Parabolic meso-scale diffraction	Unsorted large boulders	Layer of boulders marked by red parabolic forms.	
	37-52m and 74-79m	6-9m	Chaotic diffraction	Loose debris material	The light coloured low reflectivity patches of loose materials found.	
FILE-100R (200MHz)	Start point to 43m	6m to depth of penetration	Reflection free	Buried ice	Buried ice marked by low conductivity and appears very light.	Present at about 6m depth with an area of about $84m^2$.
	Along 0-58m and 60-80m	3 to 6m	Parabolic meso-scale diffraction	Unsorted large boulders with damp material	Layer of boulders marked by red parabolic forms.	
	32-41m and 66-68m	2-3.5m	Chaotic diffraction	Loose materials	Coarse damp materials with larger size and slightly higher reflectance due to presence of moisture.	
	50-65m	6.5-8m				

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 2						
FILE-208 (100 MHz)	11-25m	about 5m	Parabola of continuous or parallel reflection	Probably hard rock layer	A marking like intact rock is found with larger parabolic shapes of high frequency.	Not found up to the depth of penetration
	21-38m	2.5-3.75m	High frequency meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders throughout the profile due to moraine.	
	about 37-46.5m	8-11m	Discontinuous or hummocky diffraction	Loose debris	Light coloured low resistivity patches of probable loose materials.	
FILE-209 (100 MHz)	0-23m	5-7.5m	Horizontally continuous	Probable damp soil layer	A marking line of probable damp soil layer show high frequency.	Not found up to the depth of penetration
	2-4m; 6-13m and 20-31m	2.5-5m	High frequency meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders throughout the profile due to moraine.	
	21-28m	7-10.5m	Discontinuous or hummocky diffraction	Loose debris	Light coloured low resistivity patches of probable loose materials.	
FILE-197 (200 MHz)	All along the scanned line	2.5 to up to 5m	High frequency meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders can be spotted throughout the profile.	Not found up to the depth of penetration
	13-28m	about 4.5m	Parabola of continuous or parallel reflection	Hard rock	A margin of high frequency probable of intact rock.	
FILE-198 (200 MHz)	18-22m	6m	Reflection free	Buried ice	Scattered buried ice can be differentiated from the surrounding layer with low EM reflection and high resistivity.	Scattered buried ice can be spotted at a depth of 6m.
	2-5m and 7.5-12.5m	3-5.5m	High frequency meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders can be spotted throughout the profile.	
	8-14m	2.5-4m	Discontinuous or hummocky diffraction	Loose debris	Large number of parabolic shapes of moraine throughout the profile.	

FILE-210 (100 MHz)	0-21m	About 7.5m to depth of penetration	Reflection free	Buried ice	Buried ice marked by high resistivity darker variation patches, the portion where radar signal dies out and appears very light	At the depth of about 7.5m and 20m length along the profile in 120m² area approx.
	22-46m	5.5-8.5m	Chaotic or poor diffraction	Loose debris with damp material.	Damp loose materials with slightly higher reflectance due to presence of moisture. Large number of parabolic shapes of boulders.	
FILE-199 (270 MHz)		about 6m	Reflection free	Buried ice	Buried ice marked by high resistivity and appears very light.	Present as hummock at a depth of 6m and for 12m length along the profile with approx. 12m² area.
	0-12m	3 to 5m	Parabolic meso-scale diffraction	Unsorted boulders	A cluster of parabolic shapes of boulders present.	
	14-67m	1.5 to up to 4.2m	Chaotic diffraction	Loose debris	Light coloured low resistivity patches of loose materials found above the high reflectivity zone of boulders.	
FILE-202 (100MHz)	1.5-18m and 108-132m	2.5-6m	Parabolic macro and meso-scale diffraction	Unsorted large boulders	Large parabolic curve of boulder with other smaller boulders.	Not found up to the depth of penetration
	25-92m	2.5-5.5m	Chaotic diffraction	Damp and loose materials	Damp loose materials with slightly higher reflectance due to presence of moisture.	
FILE-200 (270MHz)	Along scan length	about 2.5-5.3m	Parabolic macro and meso-scale diffraction	Unsorted large boulders	Large parabolic curves of boulders easily observable throughout the profile line.	Not found up to the depth of penetration
	26-48m and 97-117m	1.5-2.4m	Chaotic or poor diffraction	Damp and loose materials	Light coloured low resistivity patches of loose materials found.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 3						
FILE-124 (100 MHz)	10-40m and 54-65m	3.5-7.5m	Discontinuous or hummocky diffraction	Loose debris	Parabolic shapes of boulders present at the upper layers at some parts. Light coloured patches of loose materials also marked.	Not found up to the depth of penetration
	25-56m	10.5m to approx 12m	Poorly defined	Damp soil	At the lower depth of profiles low resistivity and high reflections show like the presence of water or soil moisture.	
FILE-122 (200 MHz)	10-16m; 42-56m; 64-76m and 88-96m	3.5-7m	High frequency meso-scale chaotic	Cluster of boulders	Scattered parabolic shapes can representative of boulders.	Not found up to the depth of penetration
	14-22m; 38-50m; 64-70m and 78-90m	1.5-3.5m	Discontinuous or hummocky diffraction	Loose debris	Light coloured patches can be spotted of probable loose materials found above the high reflectivity zone of boulders.	
FILE-126 (100 MHz)	Almost along entire scan length	2.5-6m	High frequency chaotic	Cluster of boulders	Clusters of parabolic curves of probable boulders can easily be observed throughout the profile line.	Not found up to the depth of penetration
	13-22m and 25-36m	6.5-10m	Chaotic diffraction	Loose debris material	Light coloured low resistivity patches of loose materials found below the boulders.	
FILE-135R (100 MHz)	About 32-46m	9 to up to depth of penetration	Parallel reflections	Stratified ice	Parallel bands of very low conductivity can be seen of probable buried ice.	Buried ice at a depth of 9m with a covering area in the profile of approx. $72m^2$
	Almost along entire scan length	2.5-6m	High frequency chaotic	Cluster of boulders	Clusters of parabolic curves of probable boulders can easily be observed throughout the profile line.	
	10-15m; 20-24m and 32-44m	6.5-10m	Chaotic diffraction	Loose debris material	Light coloured low resistivity patches of loose materials found below the boulders.	

FILE-130R (200 MHz)	7-13m and 22-40m	1.3-3.5m	Low frequency discontinuous	Loose material or boulders	Light coloured patches of probable loose materials can be seen at shallow depth.	Not found up to the depth of penetration
	22-31m	2-9m	High frequency chaotic	Cluster of boulders	The boulders with their typical parabolic reflections found at depth similar to the damp materials.	
	0-13.5m	3-5.5m	Horizontally parallel with high frequency	Damp material	Pods of high reflection discontinuous layers of probable damp material can be seen in the GPR profile.	
FILE-132 (200 MHz)	2-20m and 32-52m	1.5-4m	Low frequency discontinuous	Loose rock	Light coloured patches of probable loose materials can be seen at shallow depth.	Not found up to the depth of penetration
	4-9m	5-6.5	Horizontally parallel with high frequency	Cluster of boulders	The boulders with their typical parabolic reflections found at depth similar to the damp materials.	
	22-27m	3-4.5m				
GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 4						
FILE-173R (100MHz)	22-36m	6-7.5m	Horizontally discontinuous	Damp material	Pods of high reflection can be seen in the GPR profile at the depth range of about 4m.	Not found up to the depth of penetration
	70-80m	2.5-5.5m	High frequency chaotic	Cluster of boulders	A cluster of parabolic shapes of boulders.	
FILE-182 (270MHz)	12-38m and 76-87m	4.5-6.5	Horizontally discontinuous	Damp material	Patches of high reflection of probable moisture content visible within chaotic strata.	Not found up to the depth of penetration
	14-22m; 32-38m; 44-52m and about 86m	2-3.5m	High frequency chaotic	Cluster of boulders	Chaotic parabolic shapes of high reflection of probable boulder strata can be seen in the GPR profile.	

FILE-172R (100MHz)	0-24.5m	After 6m	Reflection free	Buried ice	Very low reflections with high resistivity showing presence of probably buried ice	Found after a depth of 6.25m and about the length of 25m thus approx. with an area of about 150m²
	Along the scanned length	2.5 to 5.5m	High frequency discontinuous	Boulders with moisture	Reflection of high gain showing probable presence of moraines with moisture content.	
	11-18.5m	after about 5m	Discontinuous or hummocky diffraction	Loose debris	Light coloured patches of probable loose materials can be seen at shallow depth.	
FILE-183 (270MHz)	7-12m and 13-22.5	3-6m	Hummocky diffraction	Boulders with moisture	Reflection of high gain indicating probable presence of moraines with moisture content.	Buried ice found after a depth of 6m and about an area covered of about 35m².
	3-7.5m and 19-25m	2-3.5m	High frequency discontinuous	Loose debris	Light coloured patches of probable loose materials seen at deeper depth.	
	3-5.5m	5-7m				
	6.5-18.5m	After 6m	Reflection free	Buried ice	Layer of low reflections with high resistivity show present probable buried ice.	
FILE-171R (100MHz)	Along entire scan length	2.5-5.5m	Hummocky diffraction	Boulders with moisture	Reflection of high gain showing probable presence of moraines with moisture content.	Buried ice at a depth of 11m present covering an area of about 20m².
	16.5-27m	about 7-10.5m	High frequency discontinuous	Loose debris	Light coloured patches of probable loose materials seen at deeper depth.	
	3-11.5m	After 10.5m	Reflection free	Buried ice	Layer of low reflections with high resistivity indicate presence of probable buried ice.	
FILE-184 (270MHz)	Along scanned length	After 7m	High frequency discontinuous	Loose debris with moisture	Light coloured pods or patches of probable moisture content in moraine seen at deeper depth.	Not found up to the depth of penetration
	3.5-15.5m and 22-35m	3-6.5m	Hummocky diffraction	Boulders with moisture	Reflection of high gain showing probable presence of moraines with moisture content.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 5						
FILE-137R (100MHz)	14-24m and 63-76m	2.5-5m	Hummocky diffraction	Scattered boulders	Reflection of high gain probable indicating presence of boulders of up to 2m.	Not found up to the depth of penetration
	Along scanned length	5-8.5m	Chaotic diffraction	Loose debris	Light coloured patches of probable loose materials seen after the boulder strata.	
FILE-145R (270MHz)	6.5-24.5m and 38-54.5	1.5-2.8m	Chaotic diffraction	Loose moraines strata	Light coloured reflections of probable loose materials over compact boulder strata.	Not found up to the depth of penetration
	Along scanned length	3-4.5m	Hummocky diffraction	Scattered boulders	Pods of boulders with high gain within moraine strata.	
	31-46m	3.5-6m	Chaotic hummocky diffraction	Mixed coarse material	The coarser material strata can be noticed.	
FILE-136R (100MHz)	26-48m and 57-78.5m	After 6m and 11.3m	Reflection free	Buried ice	Buried ice marked by low conductivity and appears very light.	Demarcated after the depth of 6.5m near the end of profile length covering the area of approx. 100m²
	0-12m and 62-78.4m	3-5m	Parabolic meso-scale diffraction	Unsorted large boulders	Layer of boulders marked by red parabolic forms.	
	30-54m	2.5-4m	Chaotic diffraction	Loose materials	Coarse damp materials with larger size and slightly higher reflectance due to presence of moisture.	
FILE-144R (270MHz)	49-83.2m	After 5m	Reflection free	Buried ice	Buried ice marked by low conductivity and appears very light.	Demarcated at the depth of 5.5m at the end of profile and covering an area of about 45m².
	Along scanned length	2.5-4.5m	Parabolic meso-scale diffraction	Unsorted large boulders	Layer of boulders marked by red parabolic forms.	
	14-26m and 46-58m	1.5-3m	Chaotic diffraction	Loose materials	Coarse damp materials with larger size and slightly higher reflectance due to presence of moisture.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 6						
FILE-170 (100MHz)	Along scanned length and deeper at 18-31m	2.5-6.5m	Hummocky diffraction	Boulders in moraine strata	Pods of boulders of high gain within moraine strata.	Not found up to the depth of penetration
	35-52m	4-7m	Discontinuous diffraction	Mixed material	The coarser material strata.	
	73-88m	4-7.5m	Chaotic diffraction	Loose dump material	Light coloured patches of probable loose materials can be seen at shallow depth.	
	75-103m	After 7.5m	Oblique continuous diffraction	Water saturated zone	Layered strata with very high conductivity can be predicted as presence of water content.	
FILE-158 (270MHz)	5-68m and 76-92m	2.5-6m	Discontinuous or hummocky diffraction	Boulders in moraine strata	Shape and size range of the reflection shows the presence of probable boulders or coarse material of high gain within moraine strata.	Not found up to the depth of penetration
	18-26m; 53-62m and 88-102m	1.5-2.5m	Chaotic diffraction	Loose debris	Very light coloured patches of probable loose materials can be seen at shallow depth.	
GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 7						
FILE-218 (100MHz)	33-55.5m	After 9m	Horizontally continuous or parallel	Hard rock or buried ice	A marking of high gain with inclined continuous layers can be intact rock or buried ice.	It is demarcated at depth of 9.5m and covering an area of about $40m^2$.
	8-14m; 30-37.5m and 50-55.5m	1.5-5m	Meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders can be spotted throughout the profile at the shallow depth.	
	12-19m	5-11m	Chaotic diffraction	Loose debris	Light coloured patches of probable loose materials seen after the boulder strata.	

FILE-232 (270MHz)	40.5-56.5m	After 6m	Horizontally continuous or parallel	Hard rock or buried ice	A marking of high gain with inclined continuous layers can be intact rock or buried ice.	Buried ice is demarcated at the depth of 6m covering an area of about 15m².
	7-12m	1.5-3.5m	Discontinuous diffraction	Damp material	Damp boulder material.	
	Along scanned profile length	2.5-5.5m	Meso-scale chaotic	Cluster of boulders	Large number of parabolic shapes of boulders can be spotted throughout the profile at the shallow depth.	
	4-8.5m; 12-18m and 34-46m	5.5-6.5m	Chaotic diffraction	Loose debris	Light coloured patches of probable loose materials seen after the boulder strata.	
FILE-219 (100MHz)	20-52m and 58-90.2m	After 7.5m	Continuous or parallel	Hard rock or buried ice	A marking like intact rock is found with larger parabolic shapes of high frequency but at much deeper depth.	Large amount of Buried ice found after a depth of 6.5m and about the length of 60m thus approx. with an area of about 300m²
	Along scanned profile length	2-4m	Scattered parabolic shapes	Unsorted boulders	Large boulders are marked in the profile by high gain.	
	14-20m; 34-58m and 66-87m	5.5-8.5m	Chaotic or poorly defined	Matrix rich debris, damp and loose materials	Damp materials marked by the high reflections (with darker patches) as compared from the surroundings while loose materials demarcated by low reflections (light coloured patches) in shallow depth.	
FILE-223R (270MHz)	30-48m and 51-90.5m	after 5m	Continuous or parallel	Hard rock or buried ice	A marking like intact rock is found with larger parabolic shapes of high frequency but at much deeper depth.	The buried ice found at depth of 5m and about the length of 50m along the profile at an area of about 75m².
	Along scanned profile length	2-4.5m	Scattered parabolic shapes	Unsorted boulders	Large boulders are marked in the profile by high gain.	
	5-12m; 26-38m and 52-90.5m	1.5-3m and 4.5-5.5m	Chaotic or poorly defined	Matrix rich debris, damp and loose materials	Damp materials marked by the high reflections (with darker patches) as compared from the surroundings while loose materials.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 8						
FILE-242R (100MHz)	50-65.5m	4-6.5m	Discontinuous or hummocky diffraction	Loose debris	Boulders are mainly found in the upper portions of the profile however few boulders are seem to be present at greater depths with much bigger size having large parabolic curves.	Demarcated at the depth of 6m of the profile, covering an area of about 80m².
	7.5-12.5m and 55-65.5m	5-8m	Scattered parabolic shapes	Unsorted boulders	Large boulders are marked in the profile by high gain.	
	10-18m and 36-47m	After 8m	Reflection free	Buried ice	The buried ice marked by high resistivity darker variation area at some parts of the lowest depths and in GPR it is the portion where signal dies out. Hence they appear very light.	
FILE-237 (270MHz)	Along scanned profile	1.5-3.5m	Discontinuous diffraction	Loose debris	High electromagnetic reflections with darker patches as compared from the lower depths.	Demarcated at the depth of 6m of the profile, covering an area of about 20m².
	10-22.5m and 56-66.5m	3.5-5m	Hummocky diffraction	Damp Material	Damp materials at the upper surfaces are found by the higher resistivity	
	18-27m and 36-55.5m	After 6m	Reflection free	Buried ice	Large amount of Buried ice marked by high resistivity darker variation area and in GPR it is the portion where signal dies out. Hence they appear very light.	
FILE-240R (100MHz)	Along scanned profile length	about 3-5m	Parabolic meso-scale diffraction	Unsorted large boulders	The large parabolic shapes are formed throughout the upper surface of probable boulder strata.	Not found up to the depth of penetration
	5-9m and 20-32.5m	6.5-8m	Discontinuous diffraction	Loose materials	Loose materials are demarcated by low resistivity light coloured patches at greater depth	
	10-22.5m	8-11m	Chaotic diffraction	Damp materials	Damp materials above loose materials are demarcated by the high EM reflectance shown as darker patches.	

FILE-241R (100MHz)	Along scanned profile length	about 2.5-4.5m	Parabolic meso-scale diffraction	Unsorted large boulders	The large parabolic shapes are formed throughout the upper surface of probable boulder strata.	Not found up to the depth of penetration
	20-54m and 71-78m	5-13m	Discontinuous diffraction	Loose materials	Loose materials are demarcated by low resistivity light coloured patches at greater depth	
	50-64m	4-6.5m	Chaotic diffraction	Damp materials	Damp materials above loose materials are demarcated by the high EM reflectance shown as darker patches.	
FILE-238 (270MHz)	34-43m and 65-77m	2.5-4m	Parabolic meso-scale diffraction	Unsorted large boulders	The parabolic shapes formed indicating probable boulder strata throughout the upper surface.	Not found up to the depth of penetration
	Along scanned profile length	6-7.5m	Discontinuous diffraction	Loose materials	Light coloured patches show probable loose materials	
	0-13m and 44-57m	3-5.5m	Chaotic diffraction	Damp materials	Damp materials are demarcated by the high EM reflectance shown as darker patches.	
FILE-239 (270MHz)	4-33m	2-5.5m	Parabolic meso-scale diffraction	Unsorted large boulders	The parabolic shapes formed indicating probable boulder strata throughout the upper surface.	Not found up to the depth of penetration
	Along scanned profile length	6-7.5m	Discontinuous diffraction	Loose materials	Light coloured patches show probable loose materials	
	0-21m	2.5-7m	Chaotic diffraction	Damp materials	Damp materials are demarcated by the high EM reflectance shown as darker patches.	

FILE-243 (100MHz)	Along scanned profile length	2.5-5m	Chaotic or poorly defined	Matrix rich debris	Pods of parabolas (boulders) can be seen in probable moraine strata in the upper portions of the profile.	Demarcated after the depth of 6.25m of the profile. Covering the area of approx. 50m².
	65-80m	2-10m	Trough shaped	Glacial fill	Large syncline shaped depression marked with high reflectivity of boulders and low reflectivity of loose material.	
	30-52m	6-12.5m	Reflection free	Buried ice	The Buried ice marked by high resistivity darker variation area at some parts of the deeper depths.	
FILE-236 (270MHz)	Along scanned profile length	3.5-5m	Chaotic or poorly defined	Matrix rich debris	Boulders are mainly found in the upper portions of the profile having several parabolic curves.	Demarcated at the depth of 6m, covering an area of about 40m².
	77-92m	1.5-5.5m	Trough shaped	Glacial fill	Large syncline shaped depression marked with high reflectivity of boulders and low reflective areas of loose material.	
	28-53m	After 6m	Reflection free	Buried ice	Light reflections can be seen in the profile depicts probable presence of buried ice.	
FILE-244 (100MHz)	Along scanned profile length	2.5-4.5m	High frequency chaotic	Cluster of boulders	Clusters of parabolas with high reflectance can be representative of boulders.	Not found up to the depth of penetration
	3-14 and 40-52m	6.5-10m	High frequency discontinuous	Loose debris	Damp and loose materials are marked high and low reflectivity of electromagnetic reflections at particular areas.	
FILE-235R (270MHz)	Along scanned profile length	3-4.5m	High frequency chaotic	Cluster of boulders	Patches of parabolas represent parabola boulders in the shallow part of the profiles.	Not found up to the depth of penetration
	Along scanned profile length	1.5-3.2m and 5-6m	High frequency discontinuous	Loose debris	High and low reflectance in the vicinity shows probable presence of damp material in loose material.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 9						
FILE-249 (100MHz)	7-22m and 27.5-40m	2.5-7.5m	Oblique continuous diffraction	Water saturated zone	Layered strata with very high conductivity can be predicted as presence of water content.	Not found up to the depth of penetration
	2-5.5m; 17.5-30m and 35-42.5m	8.5-11m	Low reflection discontinuous	Loose debris	Light coloured pods or patches of probable moisture content in moraine observed after water saturated zone.	
FILE-263 (270MHz)	7-20m; 25-28m and 30-38m	2.5-5.5m	Oblique continuous diffraction	Water saturated zone	Layered strata with very high conductivity can be predicted as presence of water content.	Not found up to the depth of penetration
	Along scanned length	1.5-3.5m	High frequency discontinuous	Loose debris	Light coloured pods or patches of probable moisture content in moraine observed after water saturated zone.	
FILE-252R (100MHz)	5.5-19m	7.5-12.5m	Reflection free	Buried ice or hard rock	Inclined stratified material of low conductivity and high EM reflectance can be buried ice or hard rock.	Demarcated after the depth of 7.5m of the profile, covering the area of approx. 75m².
	0-11m; 20-24m and 41-45m	4-7m	Chaotic Parabolic meso-scale diffraction	Unsorted boulders with damp and loose materials	Layer of boulders marked by parabolic forms in the shallow depth range. The coarse damp materials with larger size and slightly higher reflectance due to presence of moisture.	
FILE-257 (270MHz)	5-14m	3-6.5m	Reflection free	Buried ice or hard rock	Inclined stratified material shown as light colour can be marked as buried ice or hard rock.	Demarcated after the depth of 5.5m of the profile, covering an area of about 40m².
	6-11m and 15-21m	1.5-3.5m	Chaotic diffraction	Loose materials	Light coloured pods moraine spotted after water saturated zone.	
	7-16m; 20-25m and 28-31.5m	2.5-6m	Chaotic Parabolic meso-scale diffraction	Unsorted damp boulders	Pods of boulders within moraine strata can be marked by parabolic forms in the shallow depth.	

GPR SURVEY PROFILES ALONG IMJA ERT PROFILE LINE 10						
FILE-280R (100MHz)	6-17m; 20-25m and 56-63m	3-8m	Hummocky diffraction	Boulders with moisture	Reflection of high gain indicating probable presence of moraines with moisture content.	Demarcated at the depth of 6m, covering the area of approx. 100m².
	14-22m and 53-57m	7-11m	Chaotic diffraction	Loose debris	Light coloured patches of probable loose materials seen at the deeper depth.	
	27-39m	about 5.5m	Reflection free	Buried ice	Presence of low reflection layer with high resistivity at very shallow depth indicating probable buried ice or hard rock.	
FILE-281R (270MHz)	28-44m	3-6.5m	Parallel reflections	Stratified ice/ hard rock	Parallel bands of very low conductivity can be seen of probable buried ice.	Demarcated after the depth of 4m of the profile, covering an area of about 42m².
	1-8m and 52-55m	2.5-6m	High frequency chaotic	Cluster of boulders	Clusters of parabolic curves of probable boulders can easily be observed throughout the profile line.	
	14-36m and 44-58m	1.5-3m	Chaotic diffraction	Loose debris material	Large patches of light coloured low resistivity patches of loose and coarse materials found between the boulders.	
FILE-272R (100MHz)	13-22m; 36-50m and 62-76m	2.5-6.5m	High frequency discontinuous	Boulders with moisture	Reflection of high gain indicating probable presence of moraines with moisture content.	Not found up to the depth of penetration
	14-22m and 66-73m	7.5-11m	Discontinuous or hummocky diffraction	Loose dump debris	Light coloured patches of probable loose materials can be seen at the deeper depth.	

FILE-266 (270MHz)	4-9m and 28-36m	3-5m	High frequency discontinuous	Boulders with moisture	Presence of probable moraines with moisture content show high reflectance and gain.	Not found up to the depth of penetration
	40-61m	3.5-6m	Chaotic diffraction	Damp or water saturated material	Large patches of light coloured low resistivity patches of loose and coarse materials found between the boulders.	
	19-24m; 37-42m and 50-54.5m	about 2-4m	Discontinuous or hummocky diffraction	Loose dump debris	Within the probable boulder strata light coloured patches show loose materials at shallow depth.	

*Chainage of the profile lines is provided according to the length of particular GPR profile line.*

***** *Note the area mentioned here is not the planar area as cross profiles were not taken. These are just the area in the profile defining the length and depth of the ice as seen in GPR profiles. Hence their direct interpretation in ice estimation should not be done. Though indirectly, it can be concluded that the profiles which has more buried ice area will have more buried ice volume and planar area of ice considering the normal deposition and melting of that ice. Thus those profiles which has highest amount of buried ice area as per GPR should not be considered as an option for channel alignments.*

Hence, keeping in mind the above data and especially the amount of buried ice, the most promising outlet among the suggested profile lines would undoubtedly be the profile along ERT-8, where almost no buried ice is present. The buried ice in ERT-8, comparison to all other profile lines has lowest area covered with keeping in mind the easy connectivity with the Imja Lake at the outlet and the much less laborious work for the construction of the outflow. There will be less excavation at this site as other areas has more overburden composed of big boulders within the matrix of loose sediments. The ERT-1 and ERT-9 profiles also seems to have less buried ice but the profile has been made on the lateral moraines with peaks at their one end which cannot serve as the outlet. And construction of channel along these lines would incur huge cost of excavation. Moreover along ERT-9, there seems to be a buried channel which causes the damp area in v-shape. This could be the seepage that across this profile which was visible on the other side of the moraine. Similar problems will be with the ERT-3 as of ERT-1. The ERT-2, ERT-4, ERT-5, ERT-7 and ERT-10 has large amount of buried ice which would be very dangerous and risky while constructing the outlet channel for lowering of Imja Lake. Large number of profiles of ERT-8 are been used in the interpretation so that this profile is studied very thoroughly for any kind of problems and buried ice determination at each section.

6. SELECTION OF SUITABLE SITE FOR THE CONSTRUCTION

Four alternatives traverses were selected for the detailed investigations around the Imja Lake based on the technical judgments from the various thematic team involved in the present study. The investigation is made to acquire geological, geotechnical and geophysical information of the area. The inputs from these studies will help the surveying and design persons to select the most suitable design of the artificial structure. The safety, remedial and the mitigating measures would also depend on these detailed investigations. The traverse which satisfies the following conditions at its best would be the most suitable site for the construction of the structure to lower down the level of the lake:

- The site should be free or less affected by the buried ice (also known as dead ice), seepage areas, voids, karsts and the great thickness of the moraines are unfavorable for the stability of the structure.
- Topographically depressed parts with gentle slopes were selected as far as possible so as to reduce the risk of ground destabilized during excavation and minimizing the depth of cutting.

- Location of minimum cross sectional area should be selected to reduce the cost of the structure.
- The alignment of the structure should intersect the paleo channels as far as possible as these serves as conduits for water flows out of the lake.

The suggested alignments of four alternative outlets are shown in the Google map image (Figure 7) and survey ERT profile map (Figure 8). These alignments are surveyed and accessed based on the GPR profiles. The survey transects R1 and R2 are located on the right bank of the Imja Khola while the R3 transect is oriented on the left bank. The C is placed near the present channel of the Imja Khola.

All the possible transects along the suggested alignments were analyzed and the one which best satisfies the criteria for favorable conditions should be selected for the construction of the artificial structure for the lake lowering. The analysis of the surveyed profiles along R1 and R2, reveal the presence of thick moraines, buried ice and steep slope gradient. Moreover the slopes are north facing (less sunlight) which favor the accumulation of snow on the slopes. In case of R3 alignment, the steep slopes and seepage of water (which may be from the buried ice or infiltration from the lake) make this transect unsuitable for the construction of structure.

The transect C, which is aligned along the present channel of the Imja Khola is free from buried ice and no seepage could be seen in the field. Moreover, this site is the lowest available natural channel for the outflow of water from the lake, so least excavation would be required to lower down the level of lake by 3m and the narrow valley would help in reducing the cost of the structure. So, based on the GPR study, the current channel (alignment C) is the best suitable location for the development of the structure to achieve the goals of the project.

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Annexure I

ALIGNMENT OF GPR PROFILES COLLECTED AROUND IMJA LAKE MORAINES

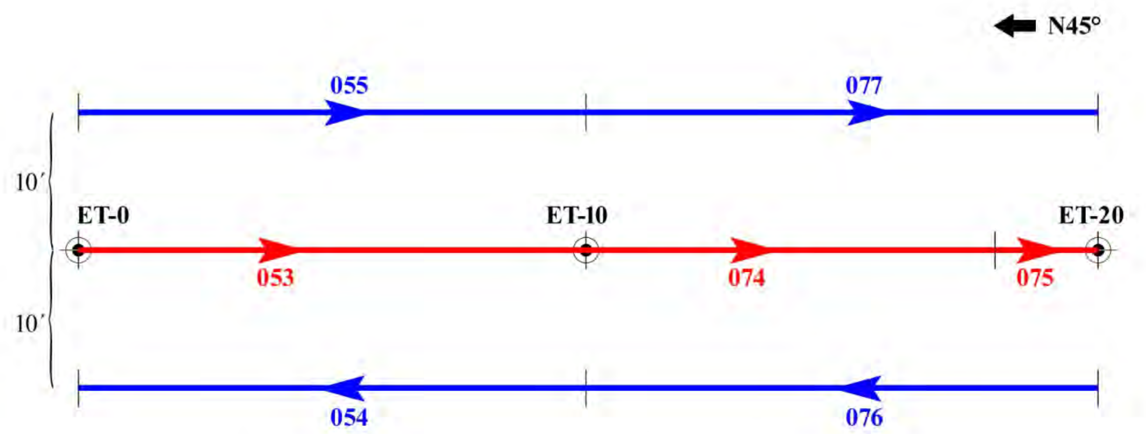
LEGEND

Alignment of ERT Profile Line (arrow showing direction of GPR profile line and File No.)

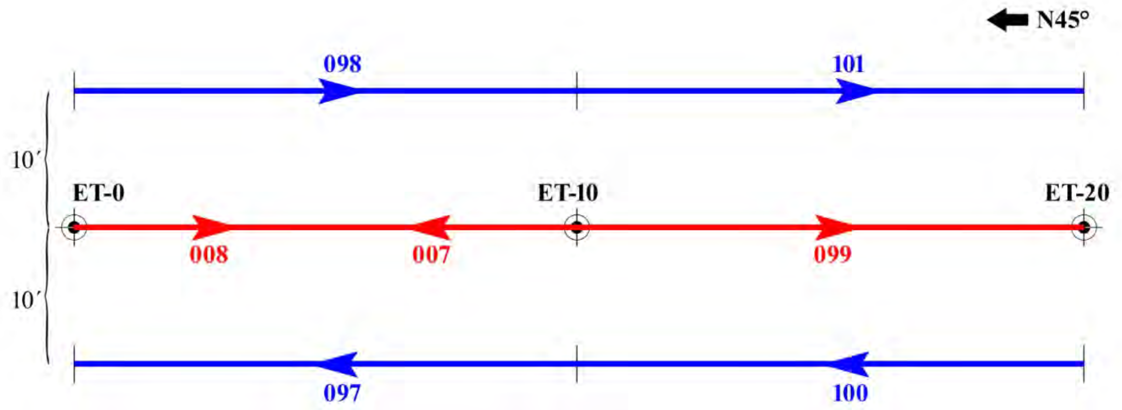
Buffer Line (at 10 feet) along ERT Profile Line (arrow showing direction of GPR profile line and File No.)

Obstruction (e.g. boulder with size) in the survey path

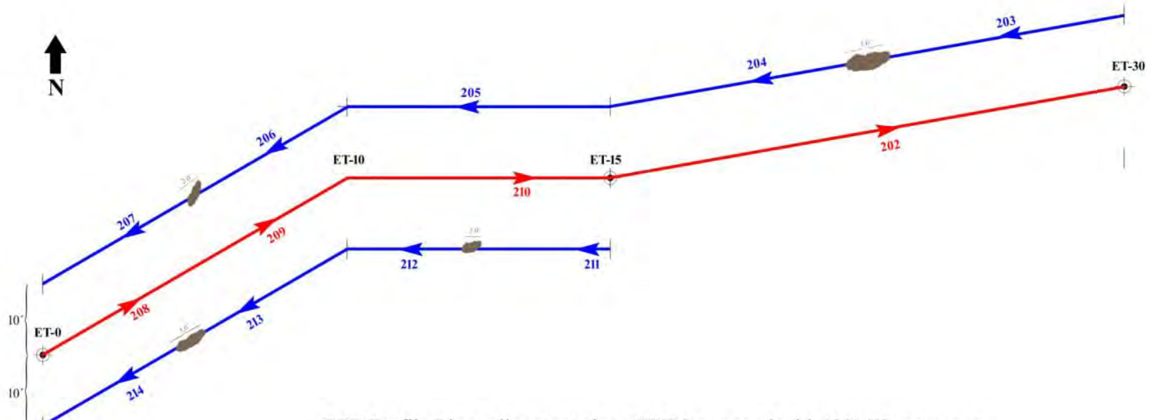
ET-0 ERT Survey Point (here, ET-0 is starting point, ET-8 is point at 80m, ET-10 is point at 100m and so on)



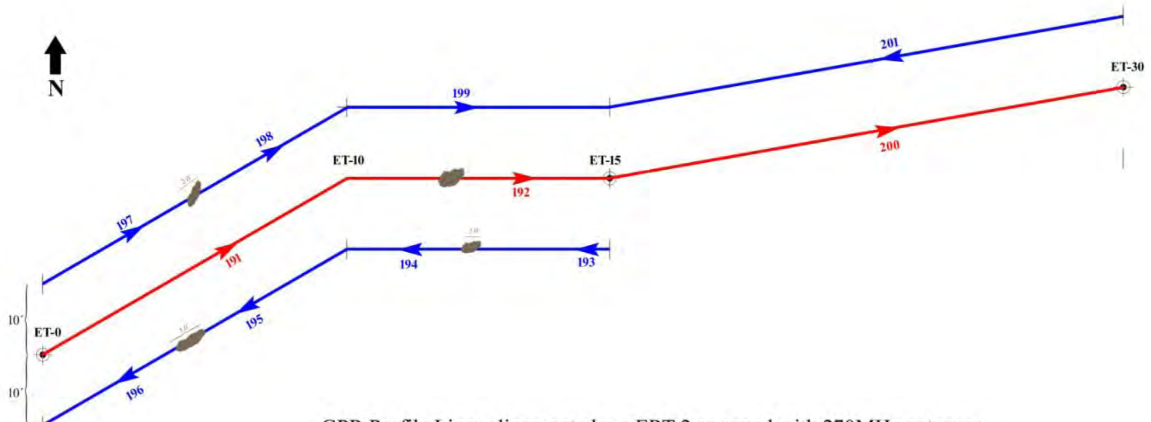
GPR Profile Lines alignment along ERT-1 with 100MHz antennas



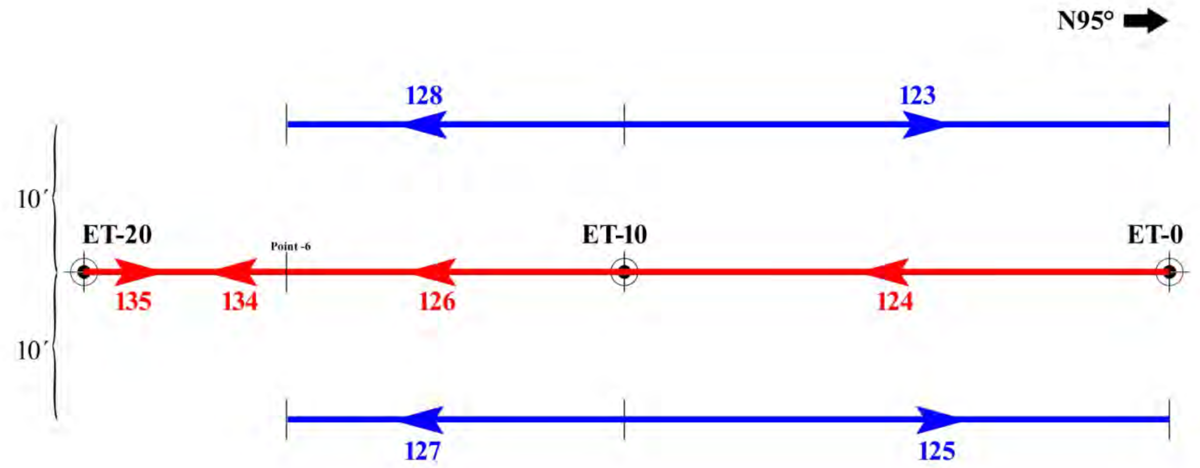
GPR Profile Lines alignment along ERT-1 with 200MHz antennas



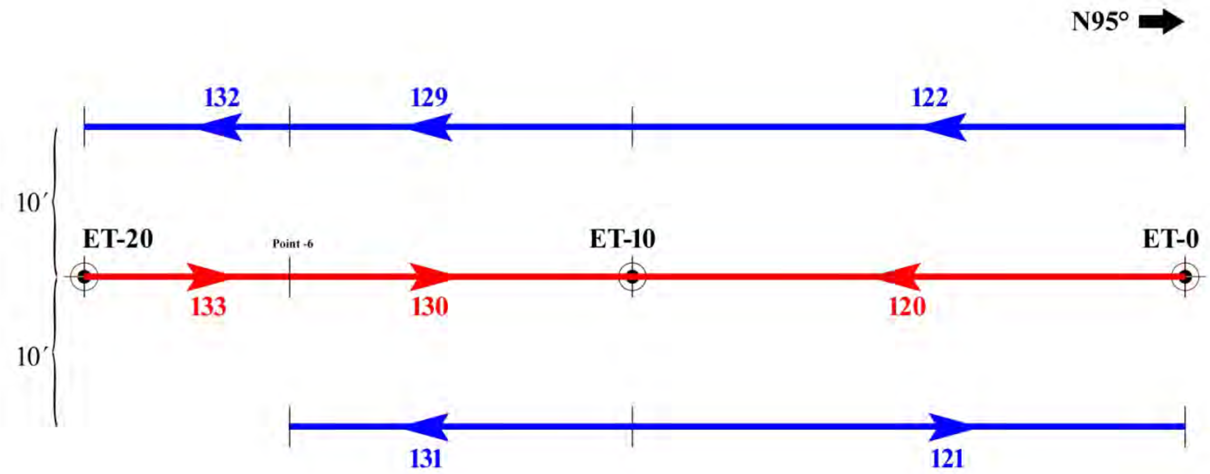
GPR Profile Lines alignment along ERT-2 sc anned with 100MHz antennas



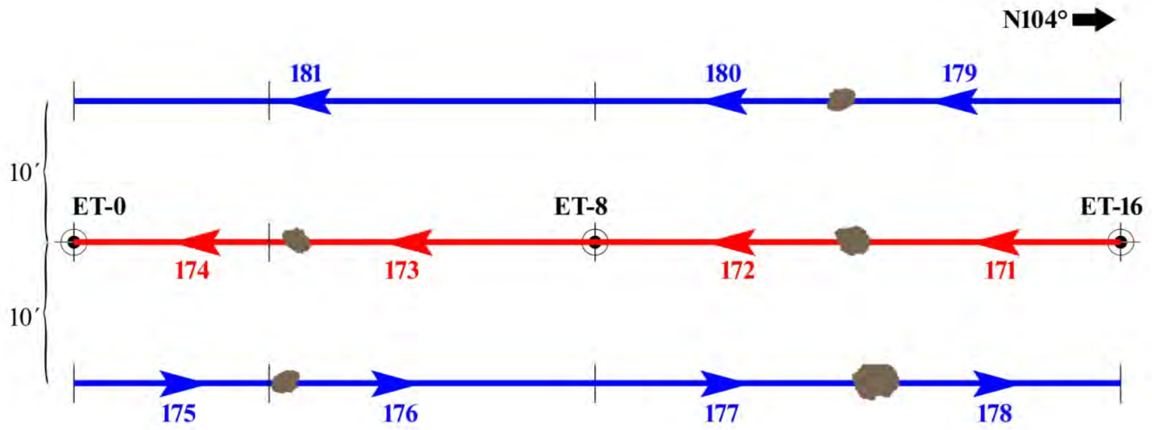
GPR Profile Lines alignment along ERT-2 sc anned with 270MHz antennas



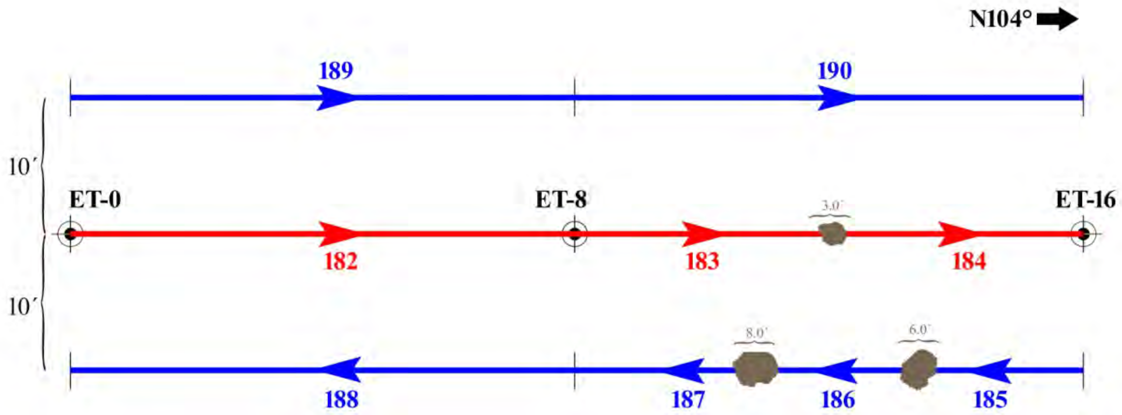
GPR Profile Lines alignment along ERT-3 with 100MHz antennas



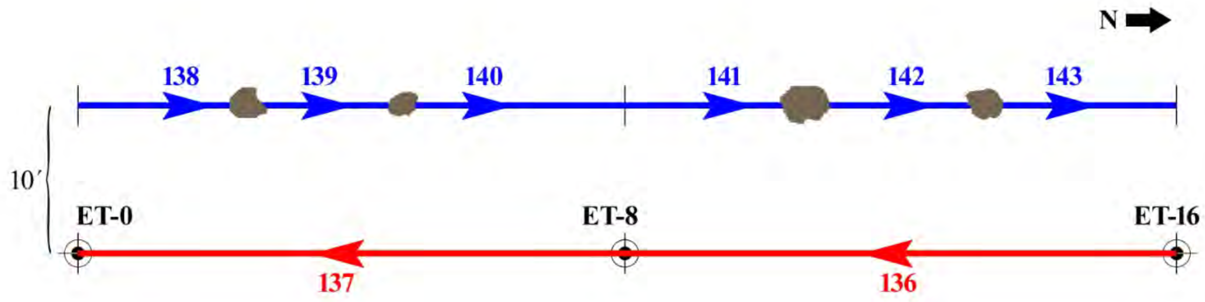
GPR Profile Lines alignment along ERT-3 with 200MHz antennas



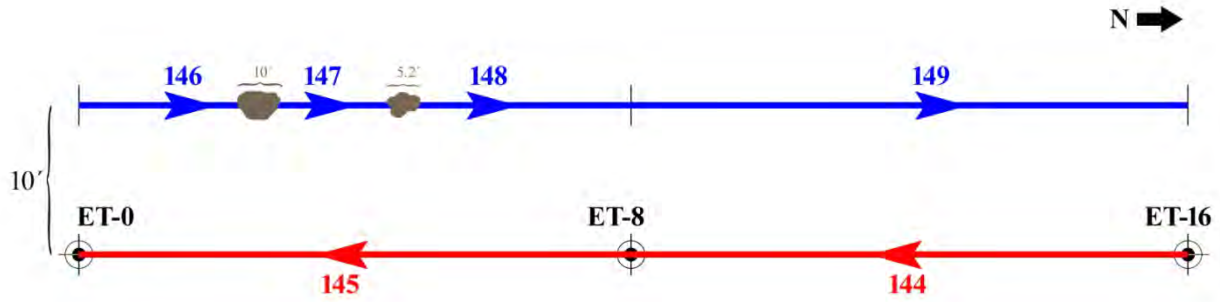
GPR Profile Lines alignment along ERT-4 with 100MHz antennas



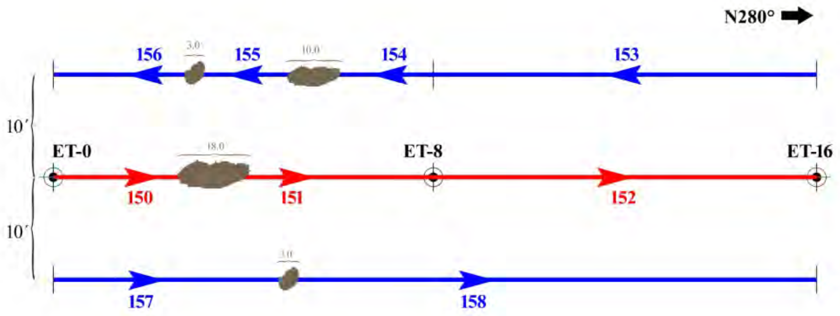
GPR Profile Lines alignment along ERT-4 with 270MHz antennas



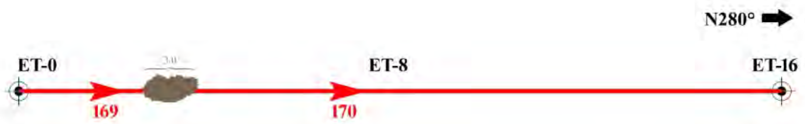
GPR Profile Lines alignment along ERT-5 with 100MHz antennas



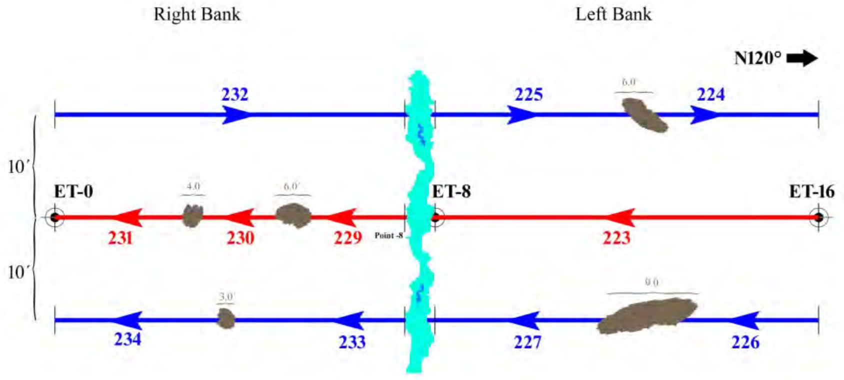
GPR Profile Lines alignment along ERT-5 with 270MHz antennas



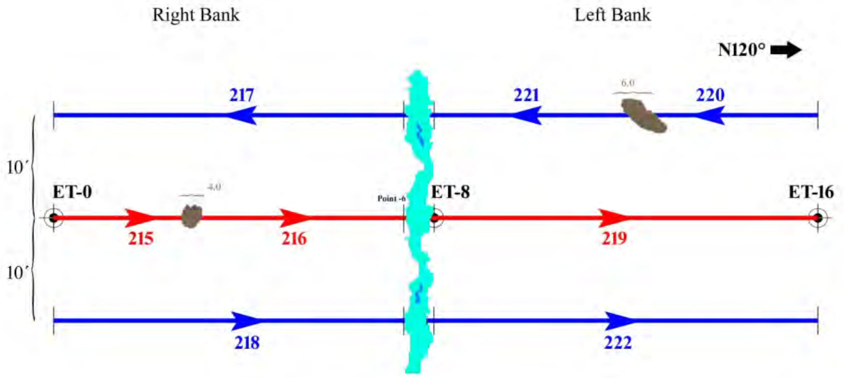
GPR Profile Lines alignment along ERT-6 with 270MHz antennas



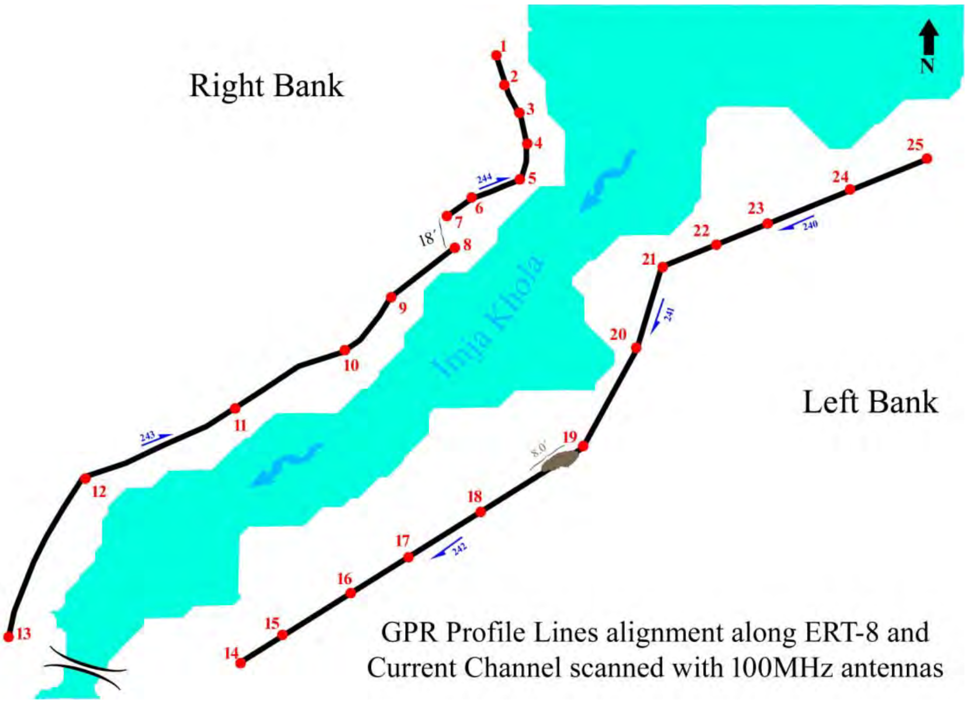
GPR Profile Lines alignment along ERT-6 with 270MHz antennas



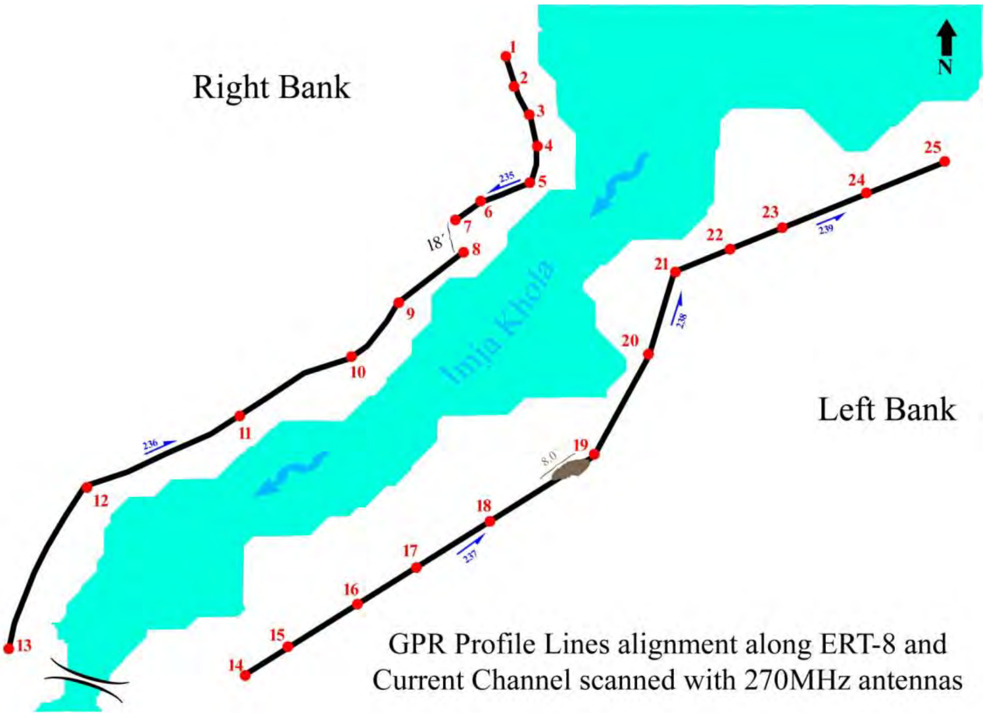
GPR Profile Lines alignment along ERT-7 with 270MHz antennas



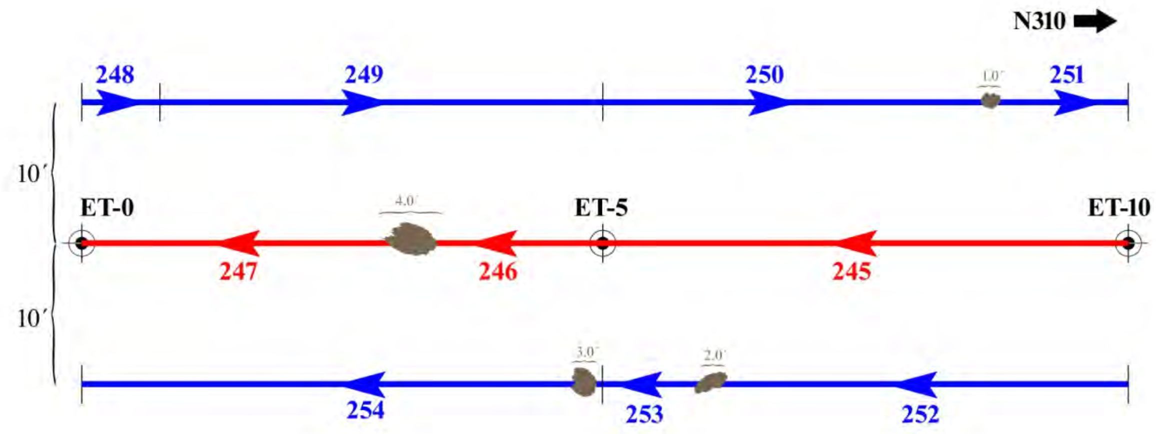
GPR Profile Lines alignment along ERT-7 with 100MHz antennas



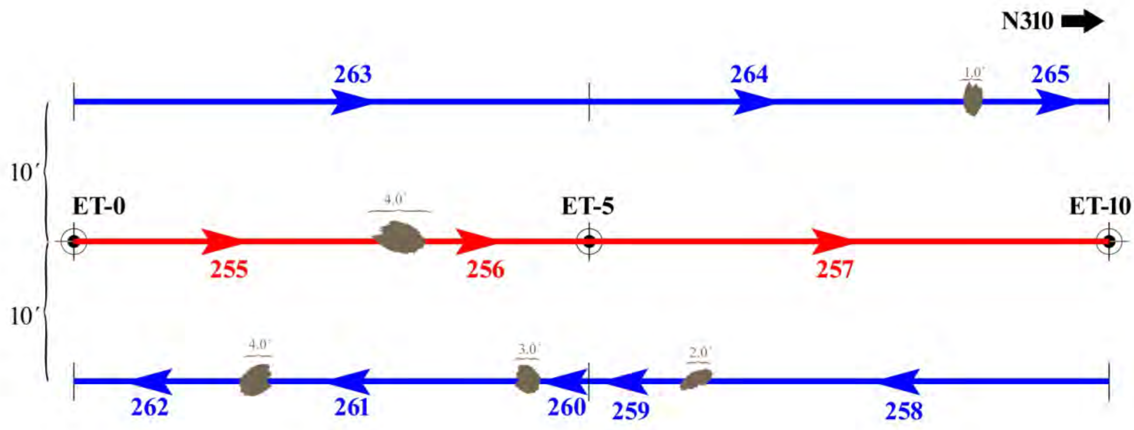
GPR Profile Lines alignment along ERT-8 and Current Channel scanned with 100MHz antennas



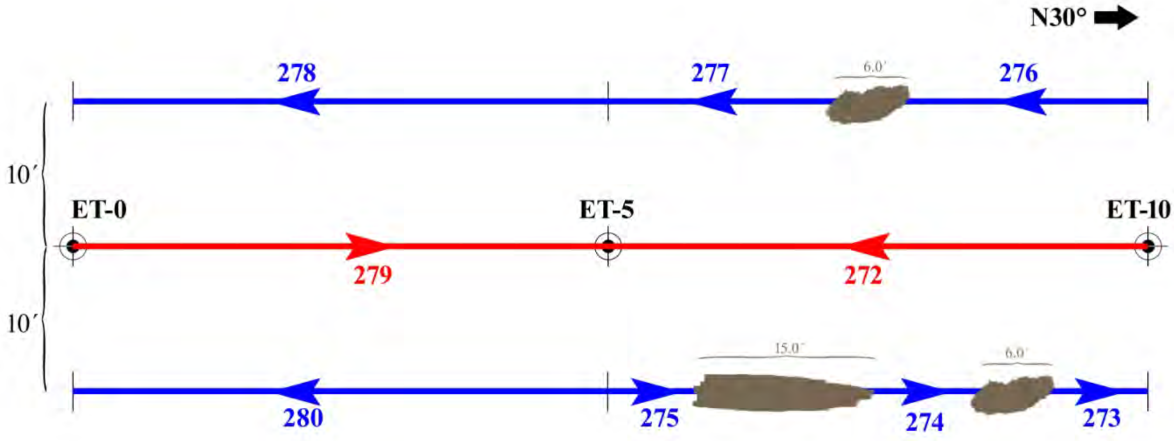
GPR Profile Lines alignment along ERT-8 and Current Channel scanned with 270MHz antennas



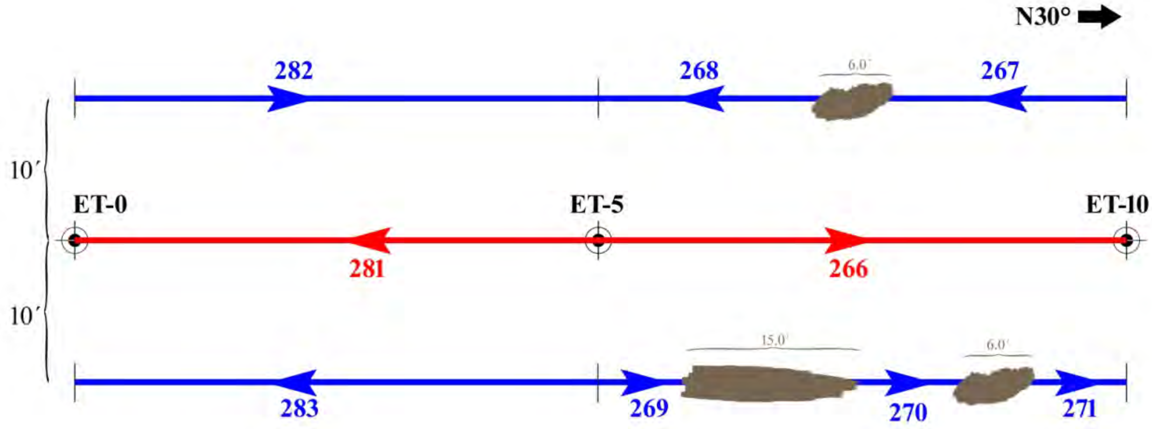
GPR Profile Lines alignment along ERT-9 with 100MHz antennas



GPR Profile Lines alignment along ERT-9 with 270MHz antennas



GPR Profile Lines alignment along ERT-10 with 100MHz antennas



GPR Profile Lines alignment along ERT-10 with 270MHz antennas

Annexure-II

GPR FIELD DATA COLLECTION SHEET

GPR DATA COLLECTION SHEET FOR …………………………………………………………………… PROJECT, 20….

Location Name : ______________________ (……….°………’………..”N; ……….°………’……….”E at …|………m/ft)

Landmark : ______________________ **Geology/Lithology** : ______________________

Geomorphology : ______________________ **Topography** : ______________________

Surface Soil Type : ______________ (Di-Electric Constant _________) **Sub-surface Condition** : ______________

Geological Structure : ______________________ **Water/Moisture** : ______________________

Folder Location : ______________________ **Photo Nos.** : ______________________

N

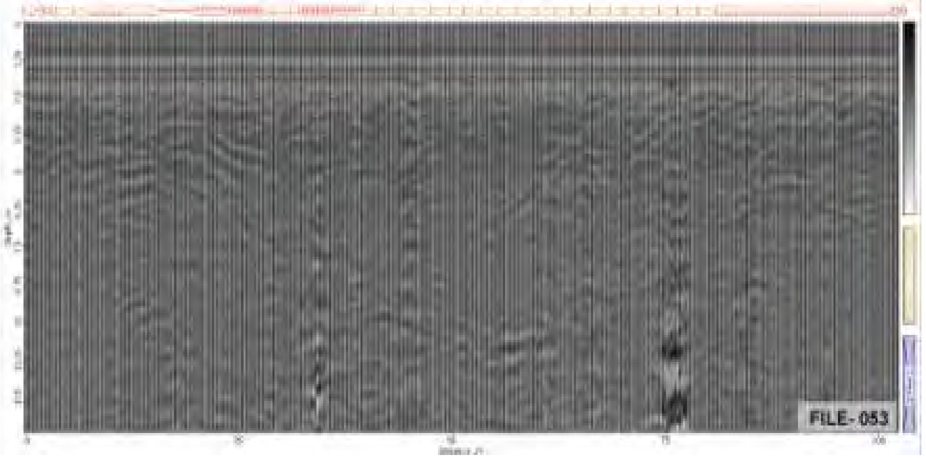
Plan Map of the Site: Not to Scale

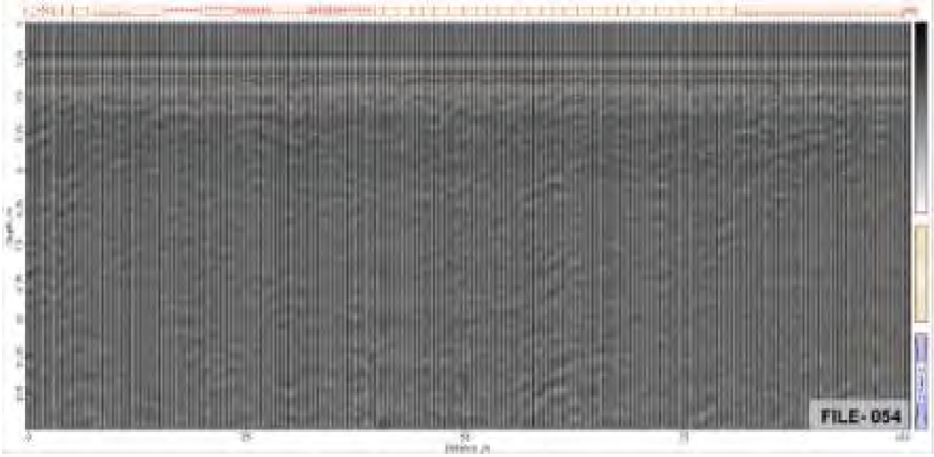
S. No.	Antenna	File Name	Start Position	End Position	Length (m)	Direction/ Bearing	Remarks

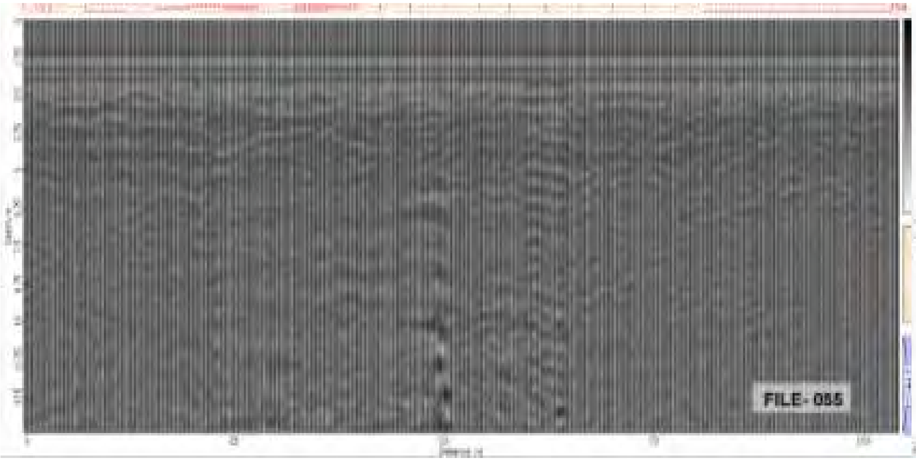
Annexure-III

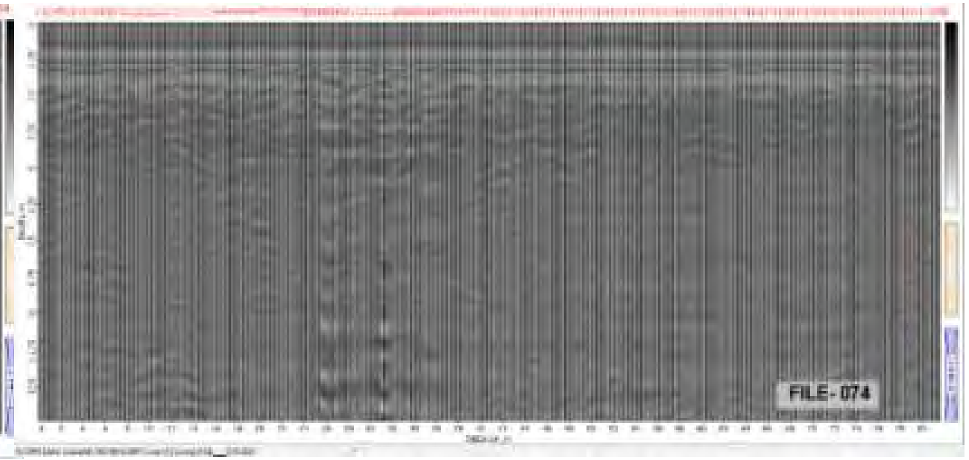
GPR PROFILES WITH 100 MHz ANTENNA (SAVED FROM PRISM-2.59 SOFTWARE)

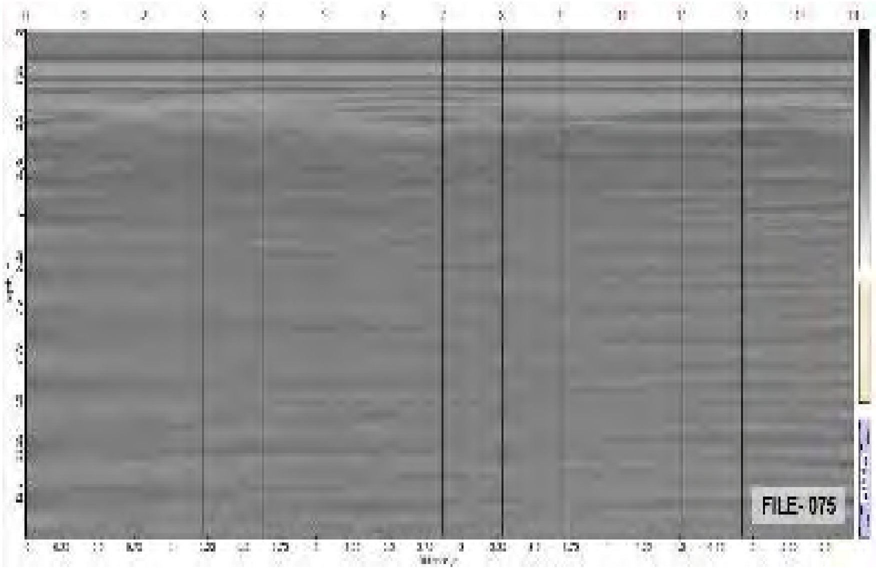
IMAGES OF GPR PROFILE SCANNED ALONG ERT-1







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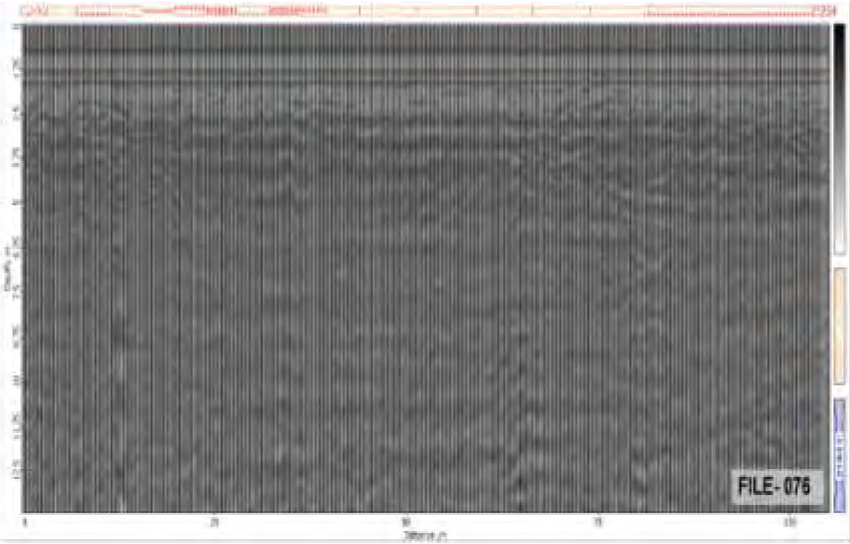
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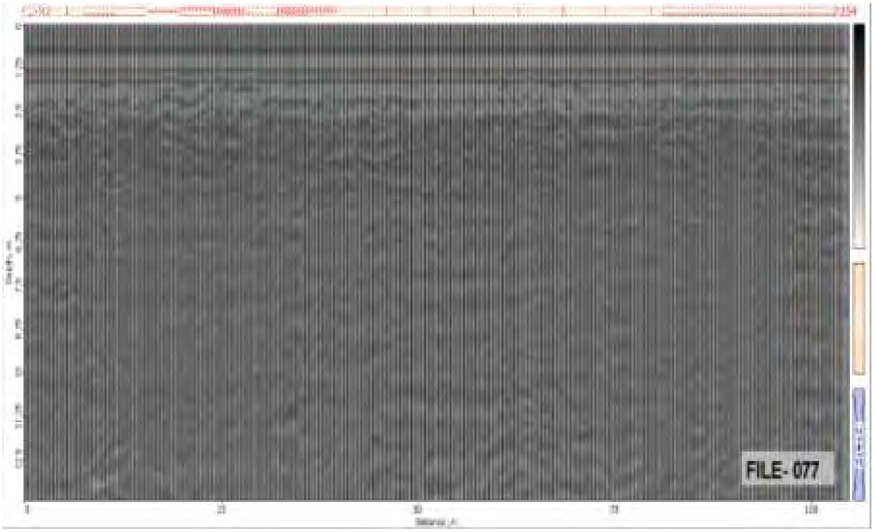
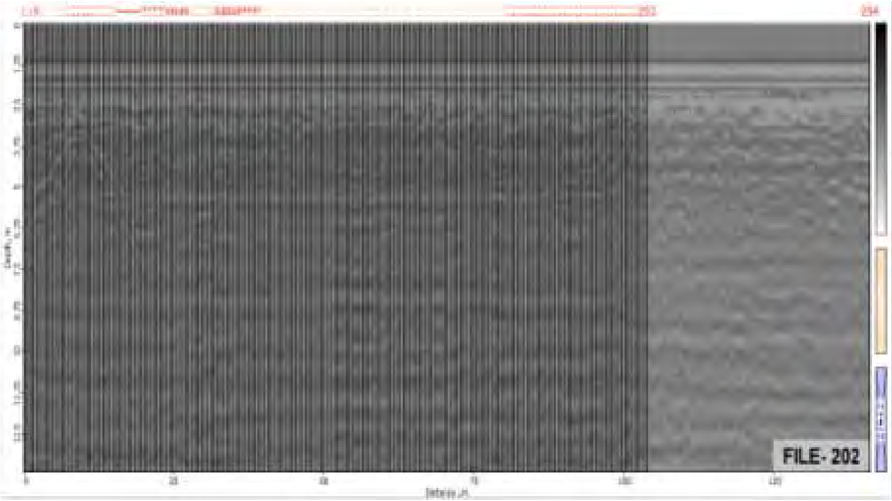
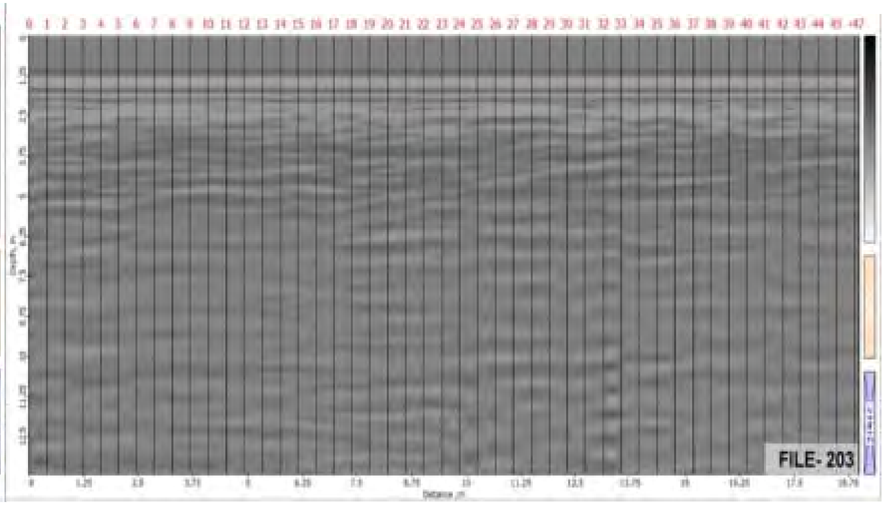
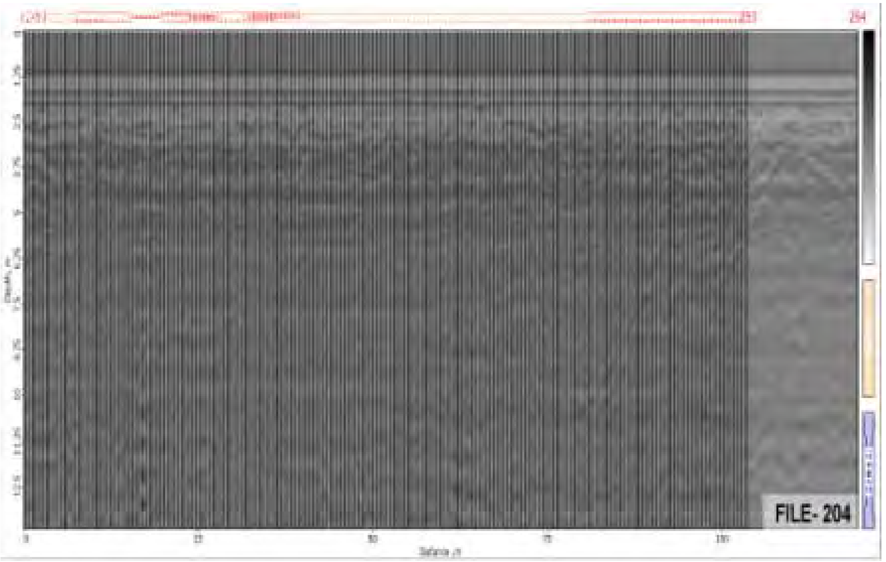
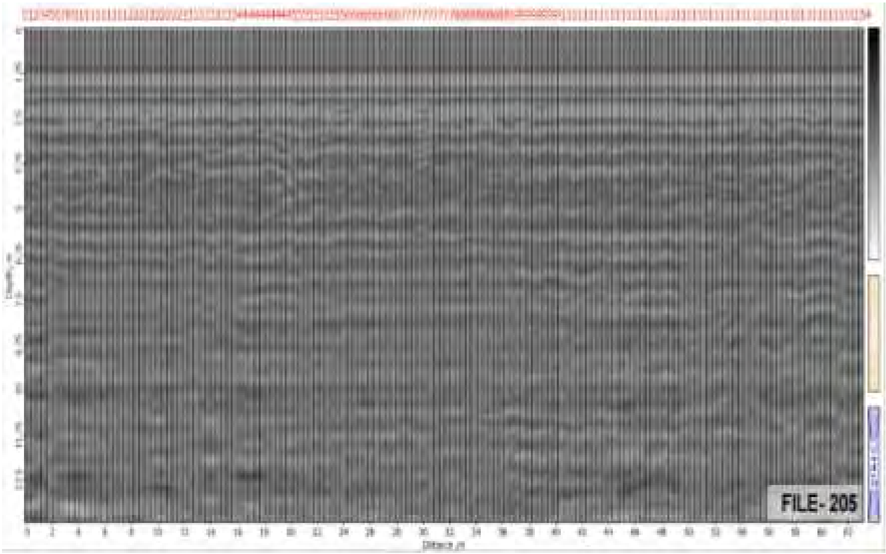

FILE- 077

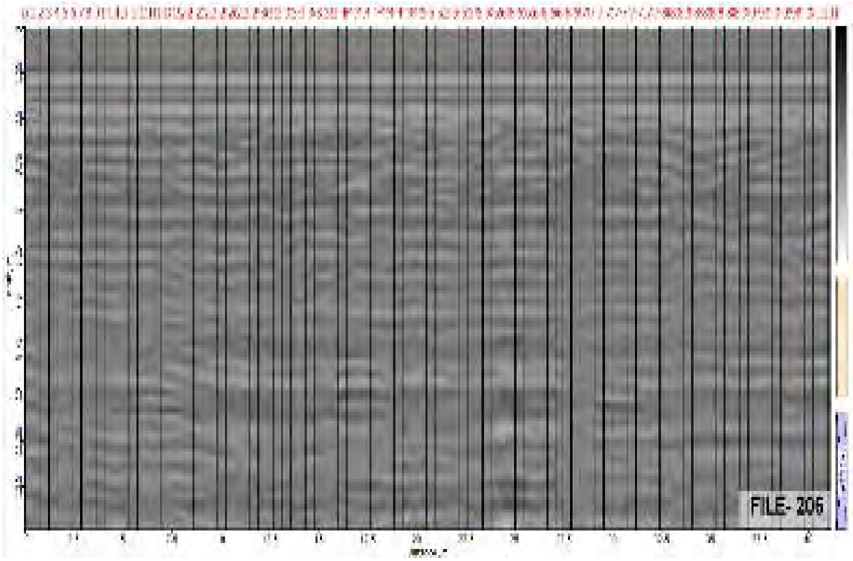
IMAGES OF GPR PROFILE SCANNED ALONG ERT-2







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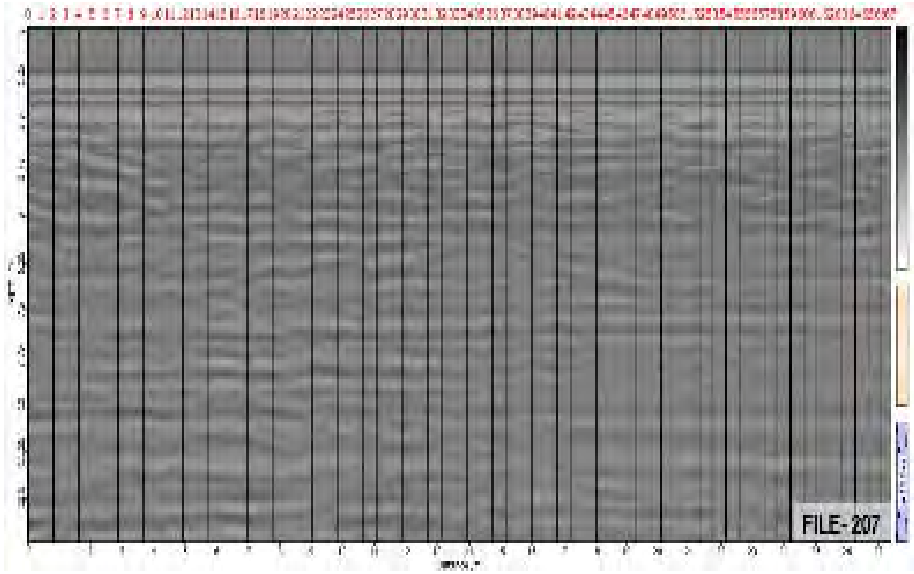
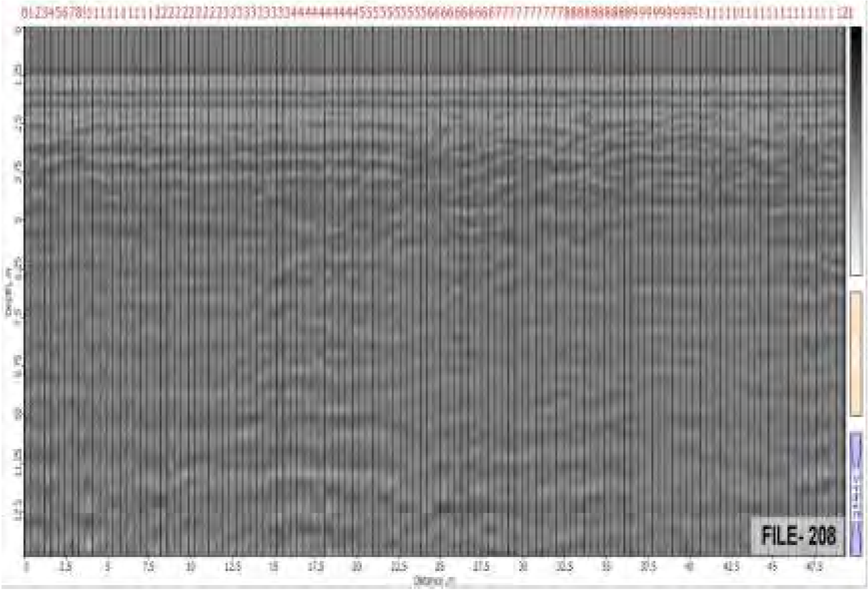

FILE- 207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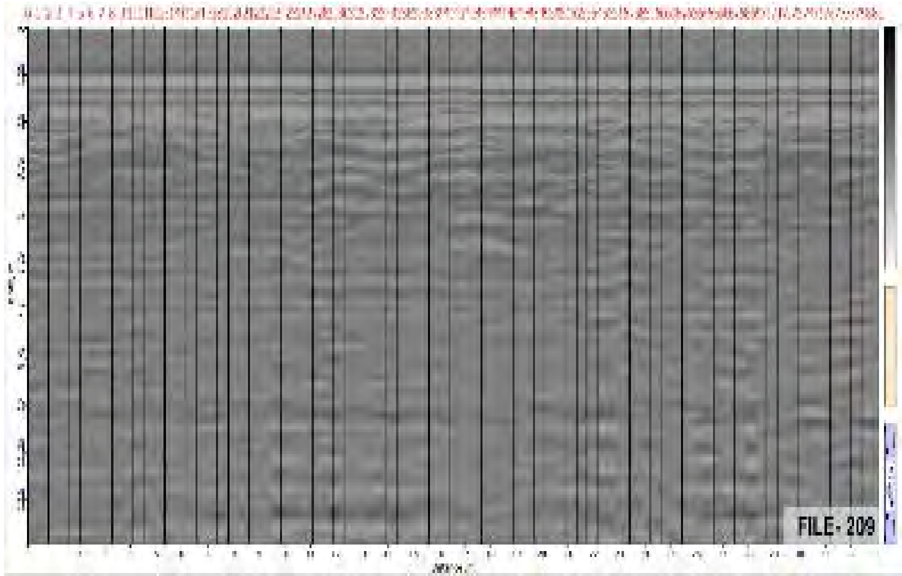
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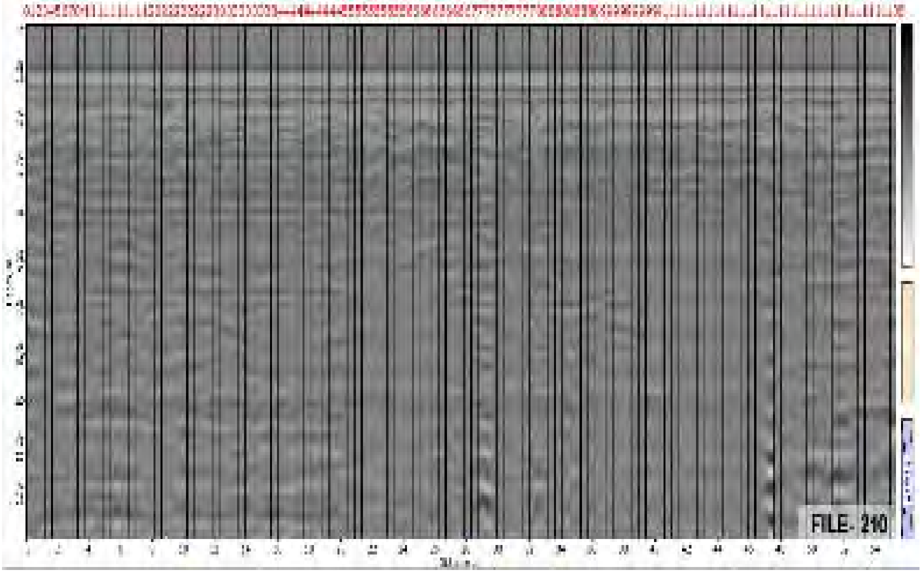
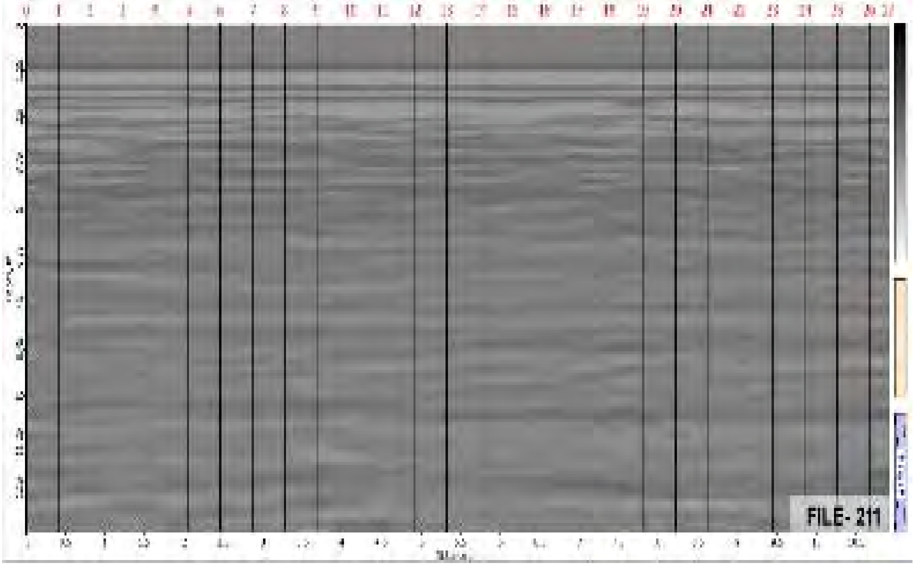
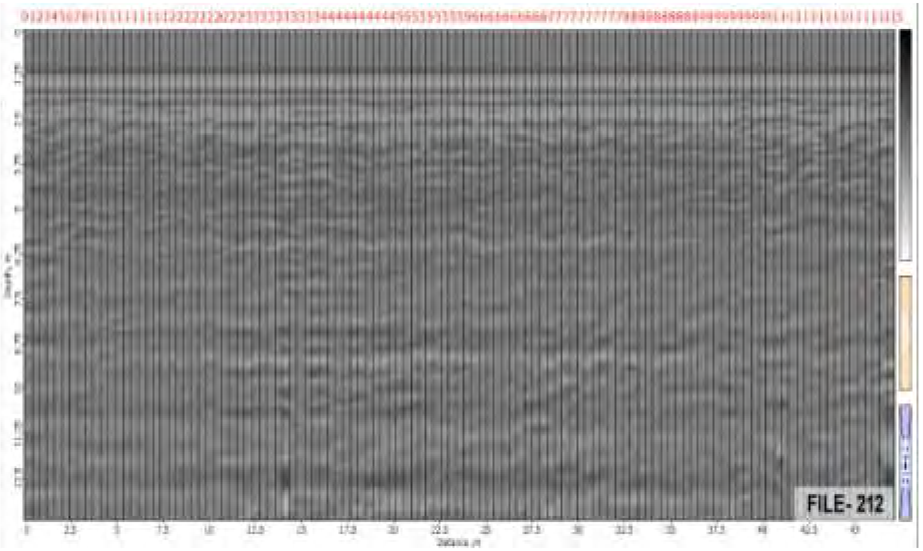
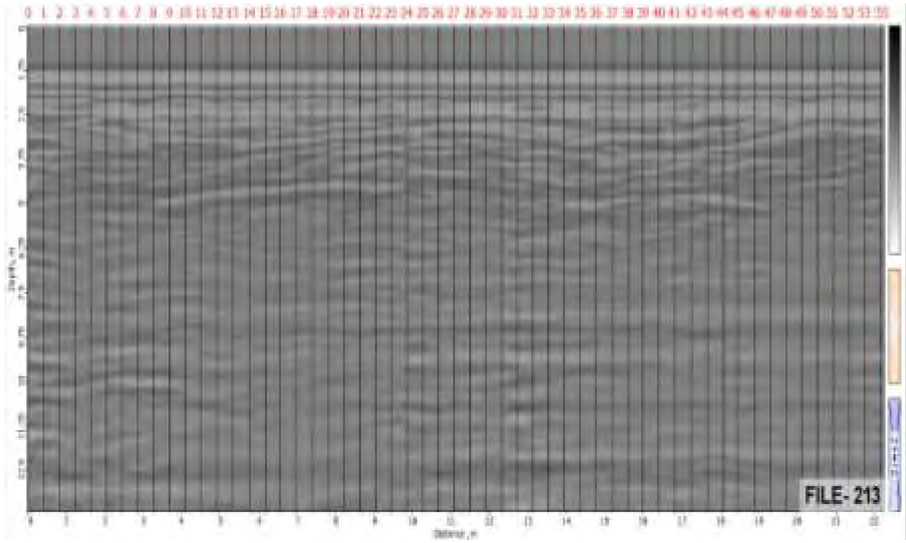
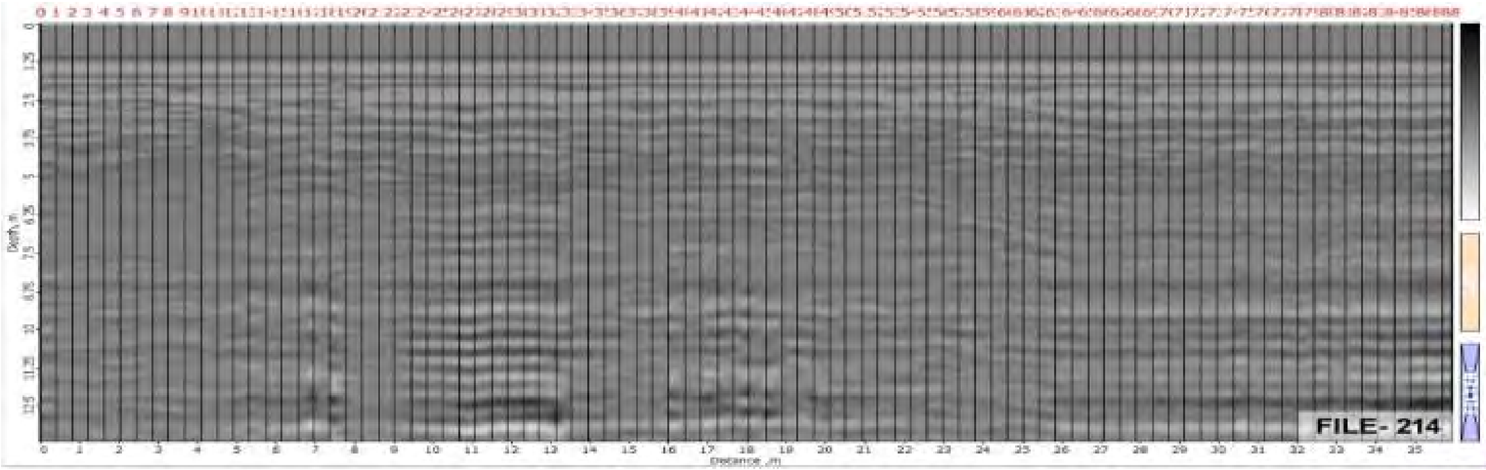

FILE- 210

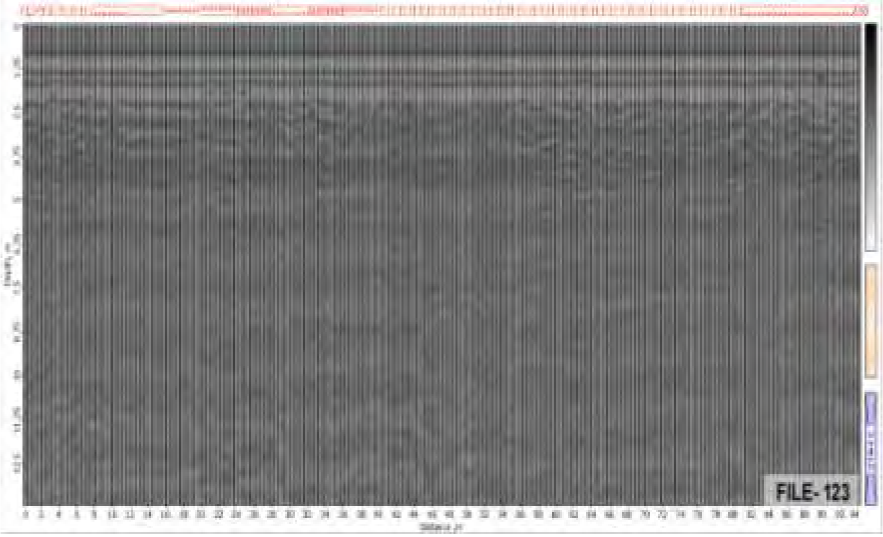

FILE- 211

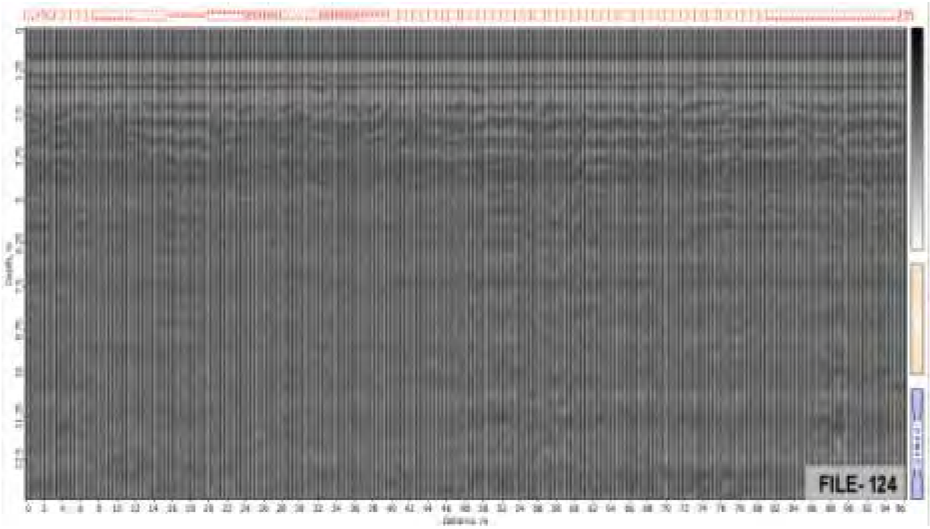

FILE- 212

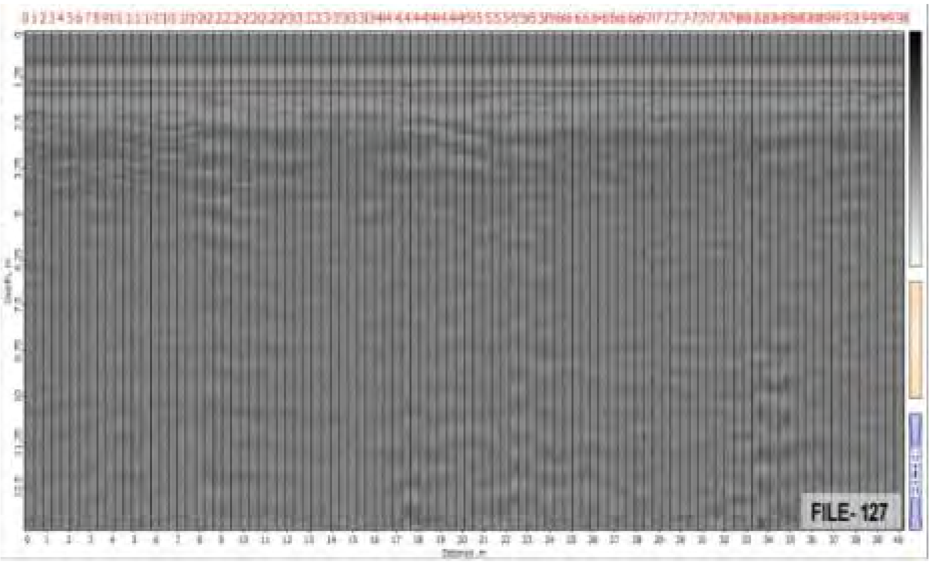

FILE- 213

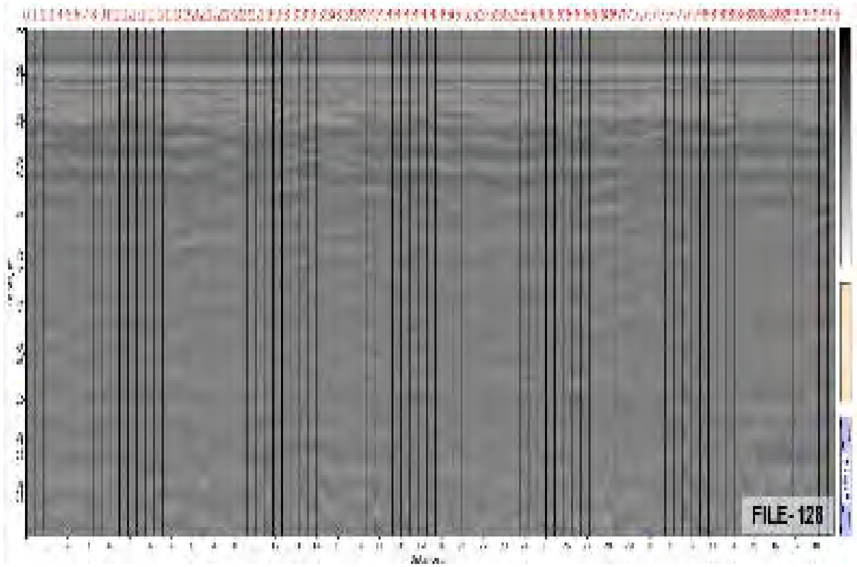

FILE- 214
Depth ,m
Distance ,m

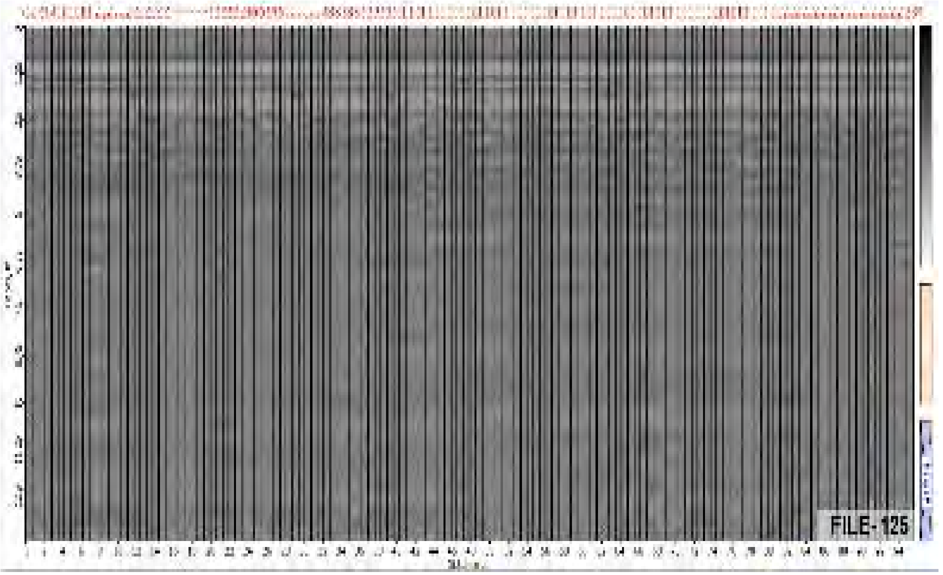
IMAGES OF GPR PROFILE SCANNED ALONG ERT-3

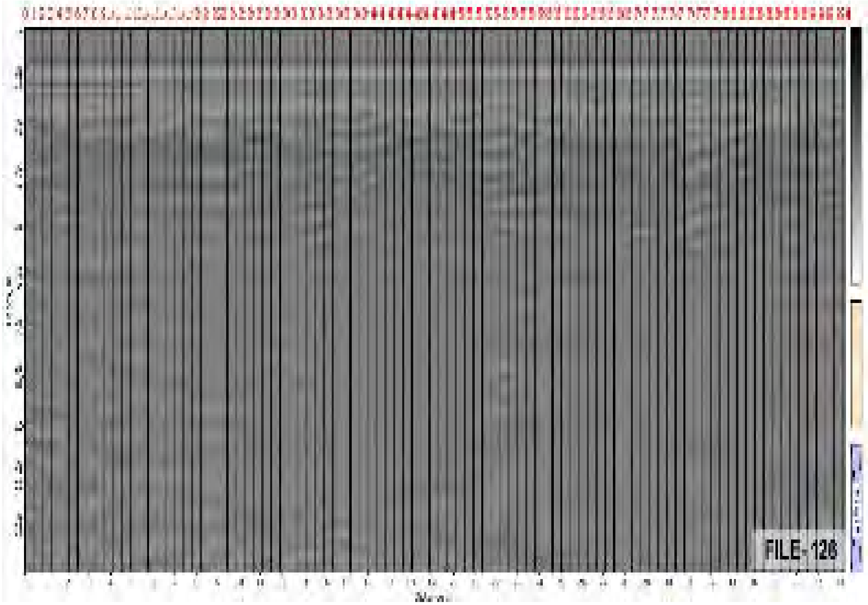


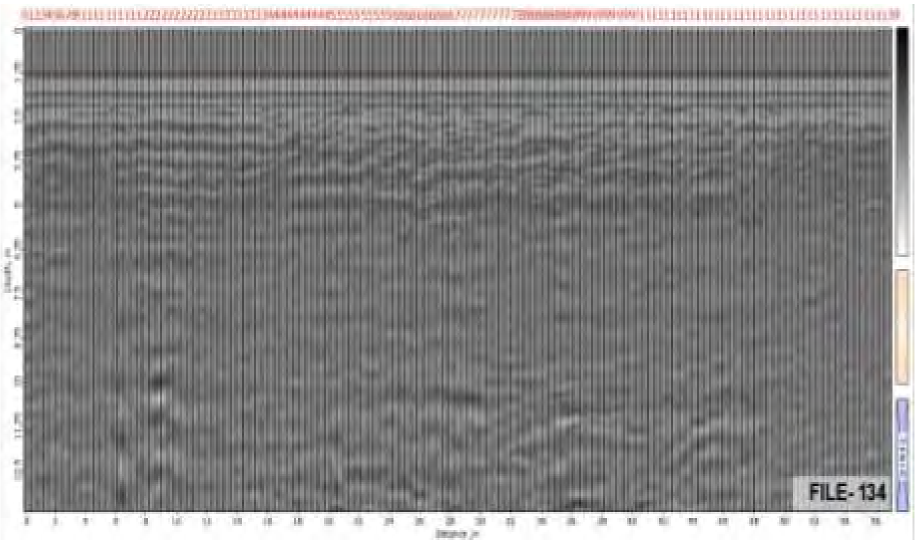


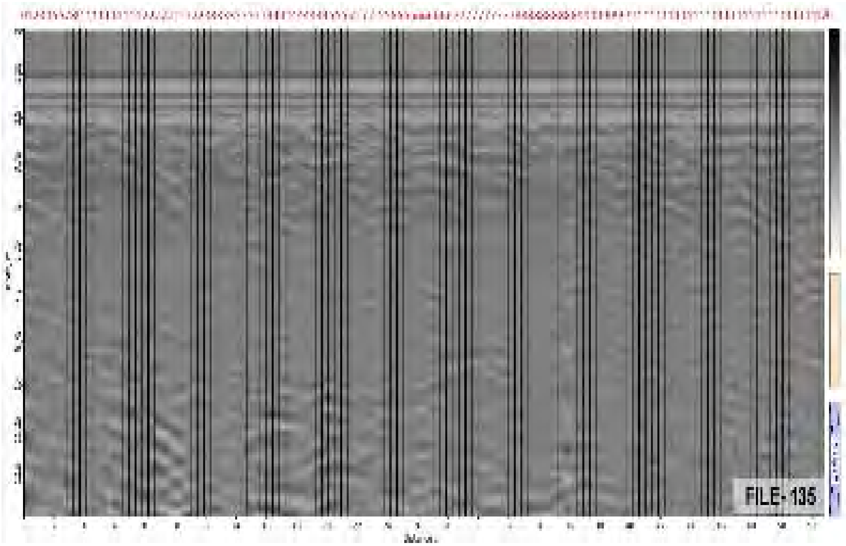




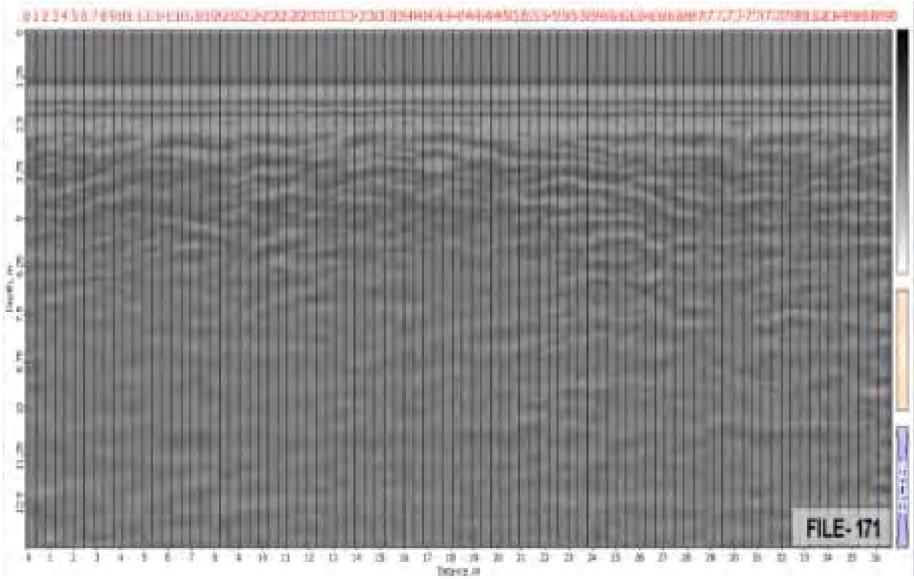

FILE- 125

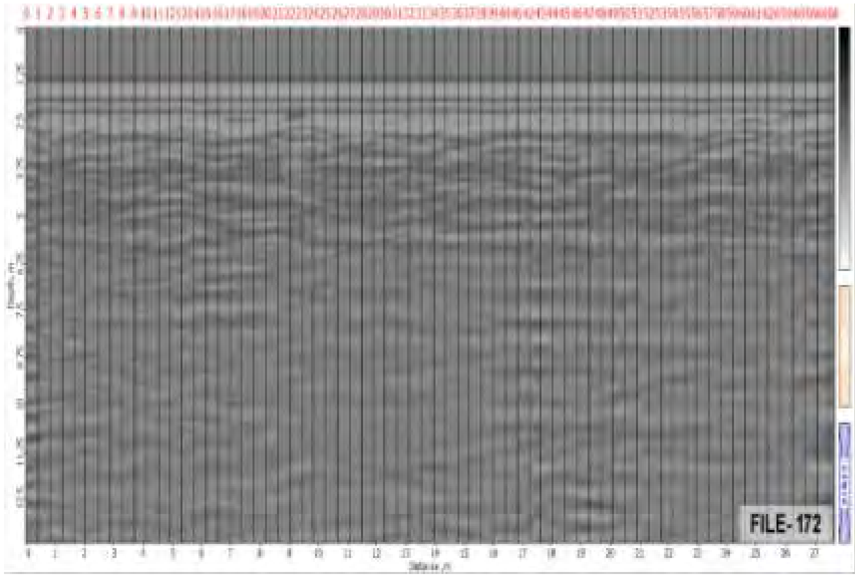

FILE- 126

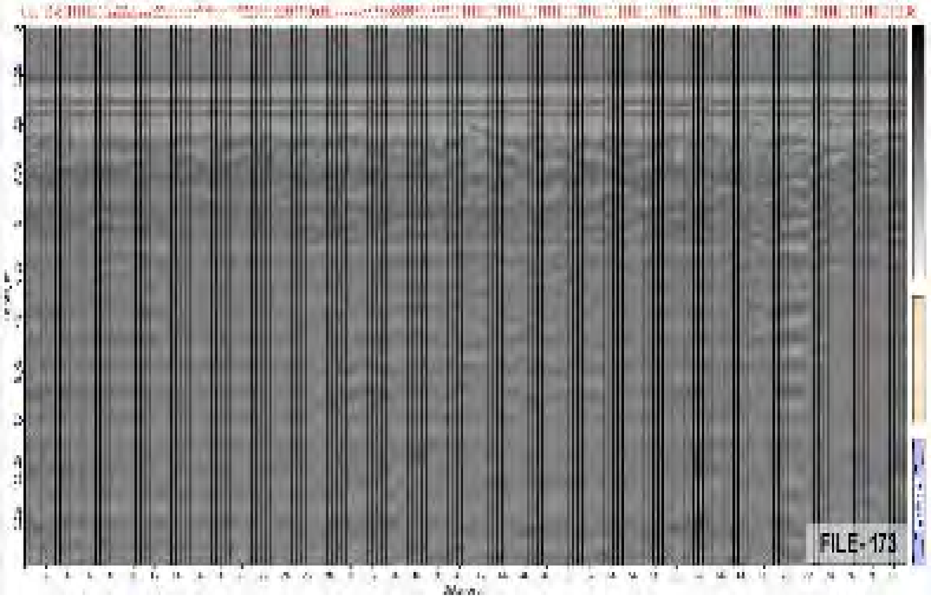

FILE- 134

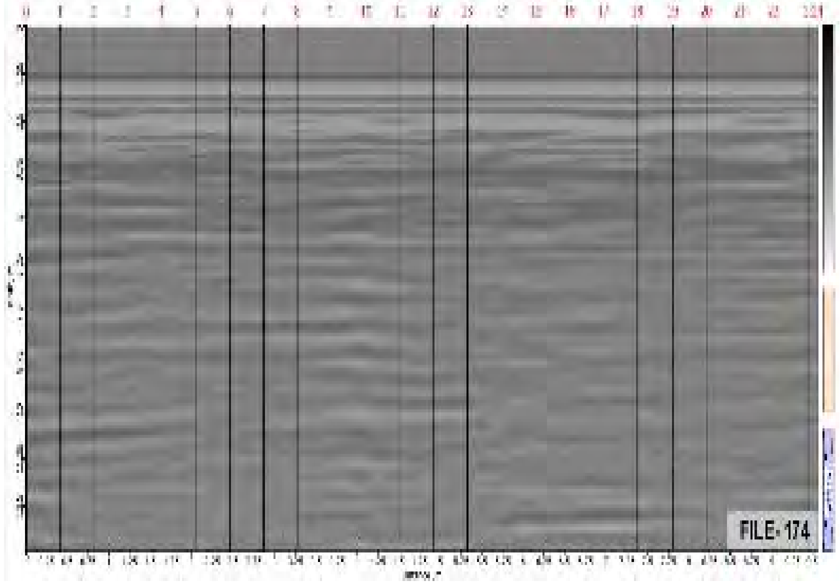

FILE- 135

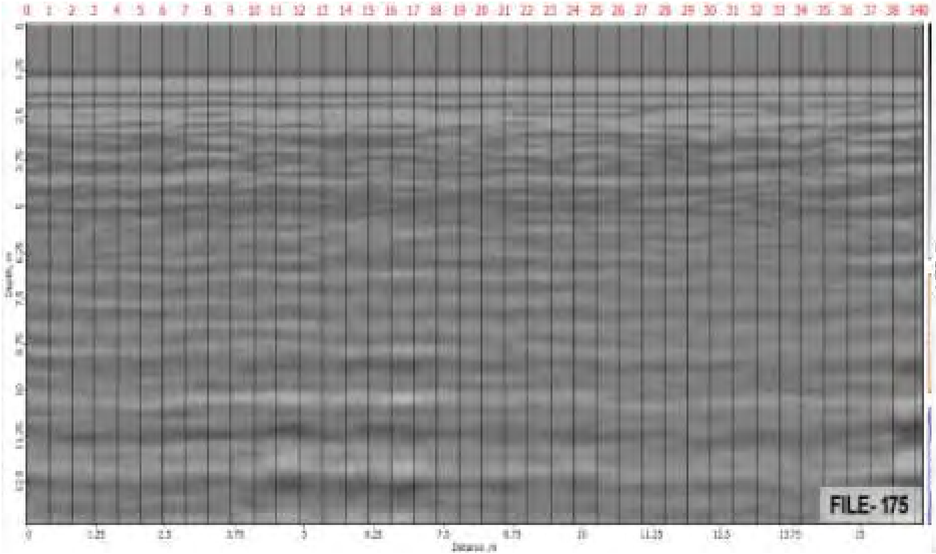
IMAGES OF GPR PROFILE SCANNED ALONG ERT-4

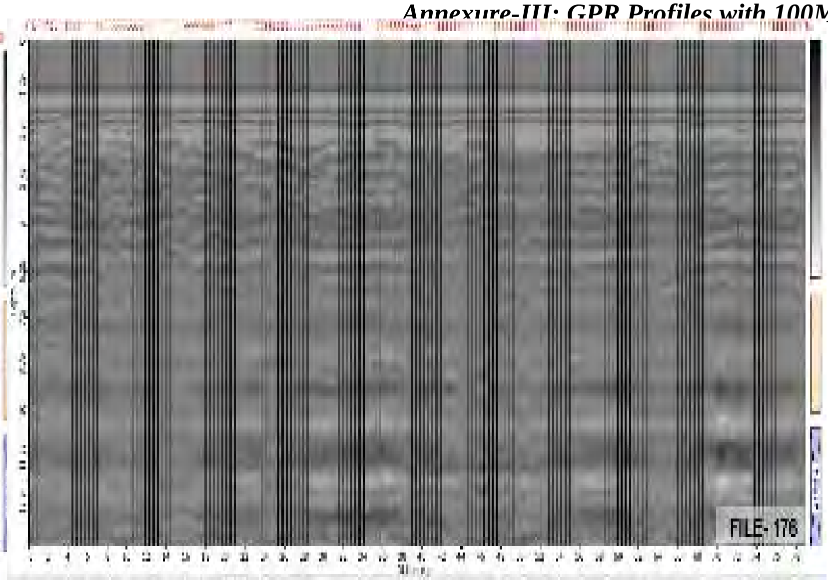


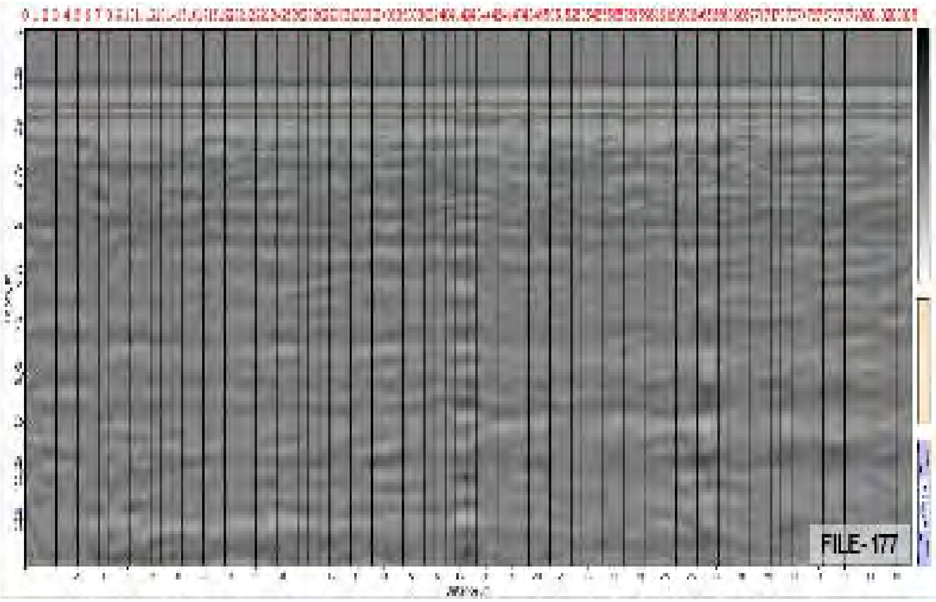


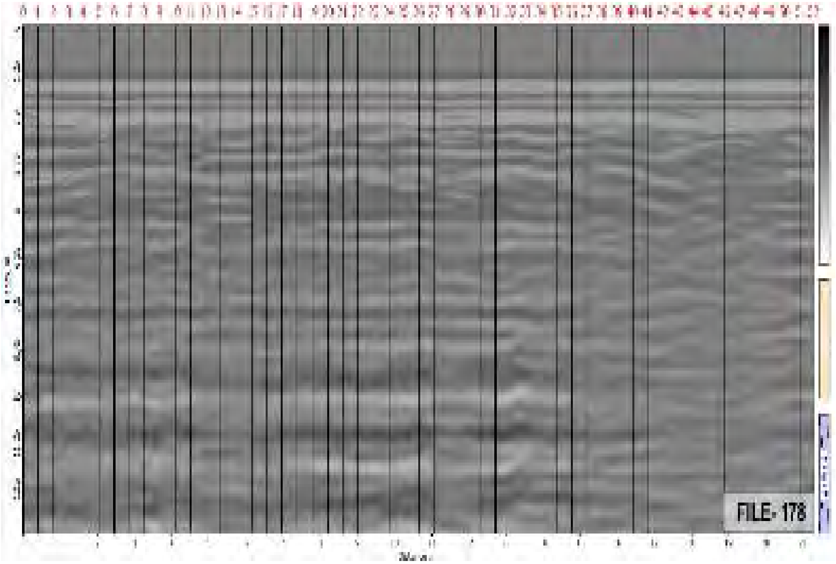


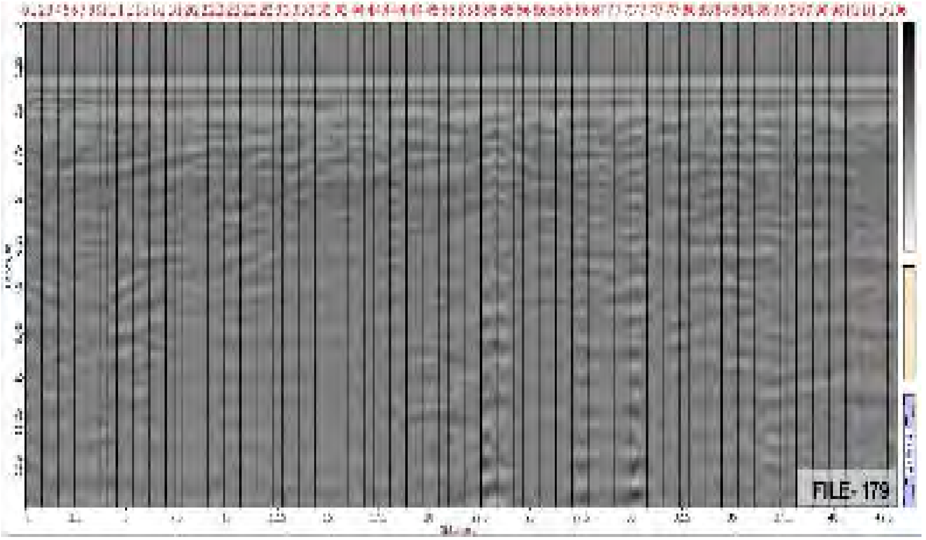


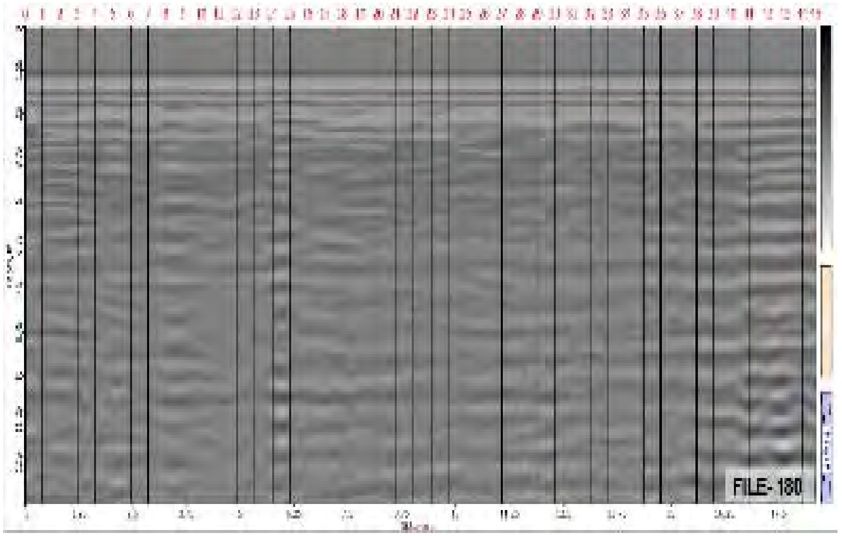

FILE- 175

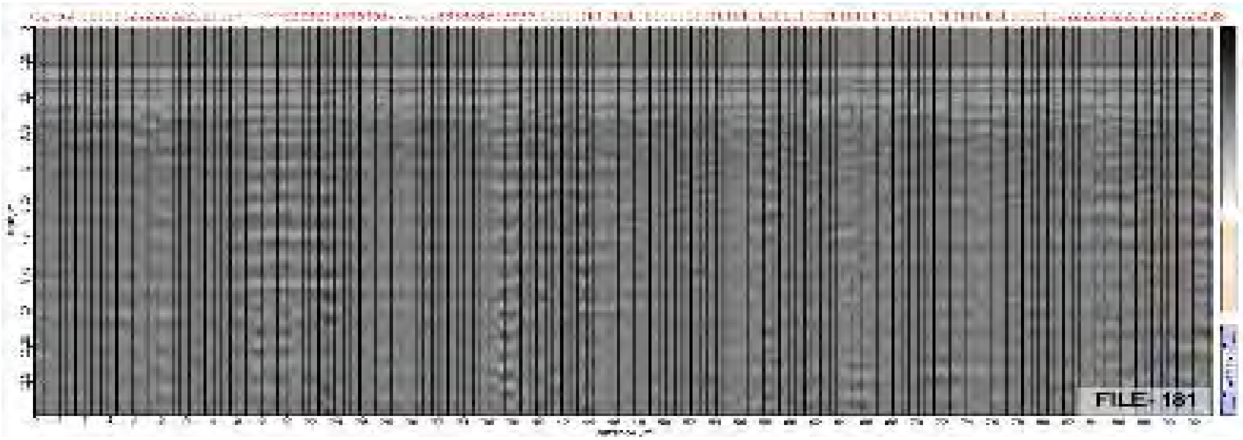

FILE- 176


FILE- 177

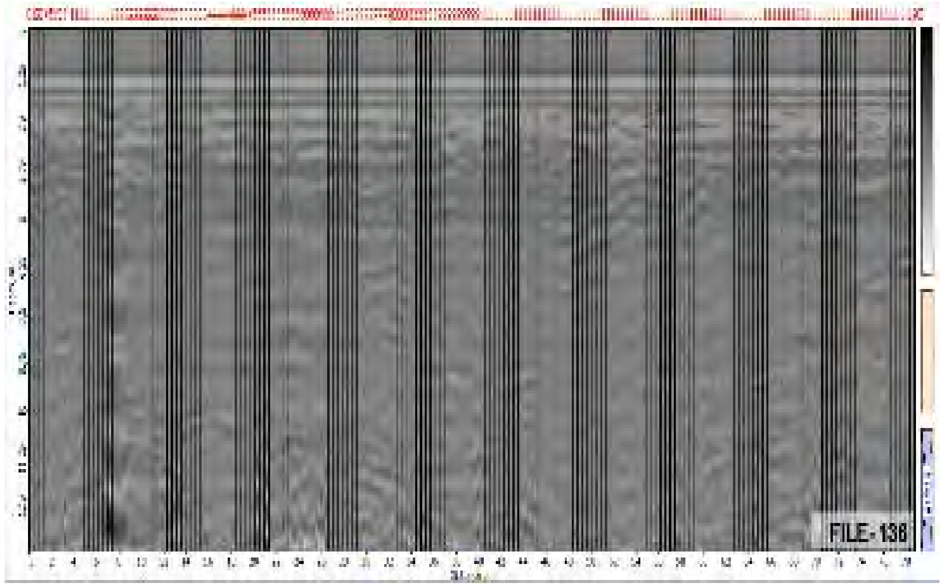

FILE- 178

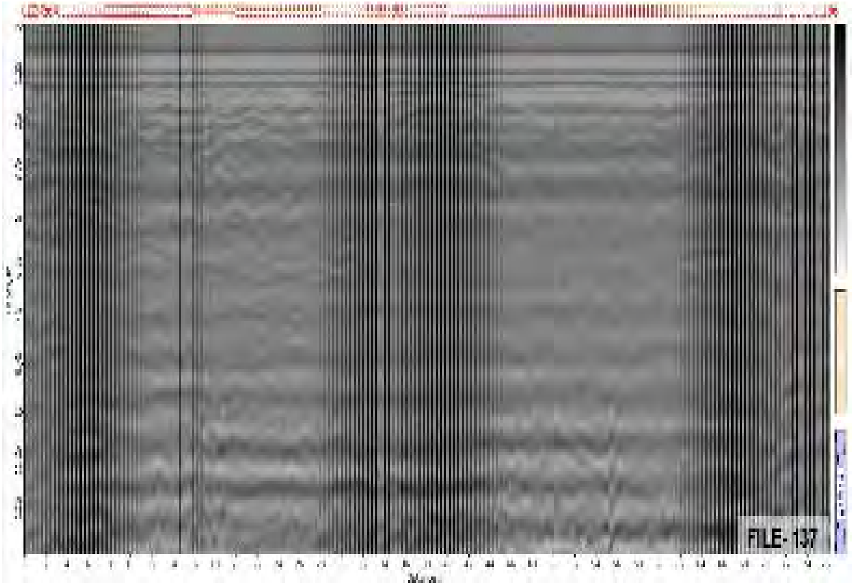

FILE- 179

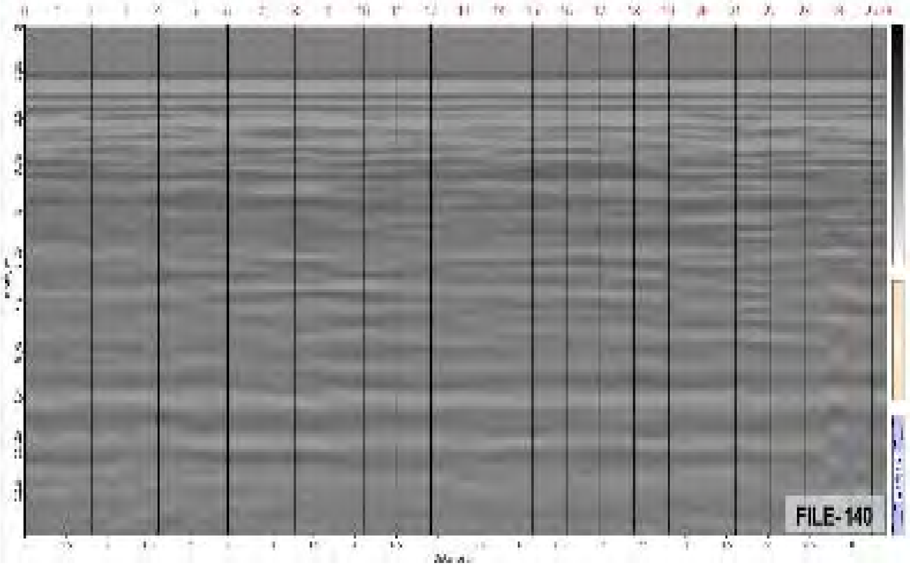

FILE- 180

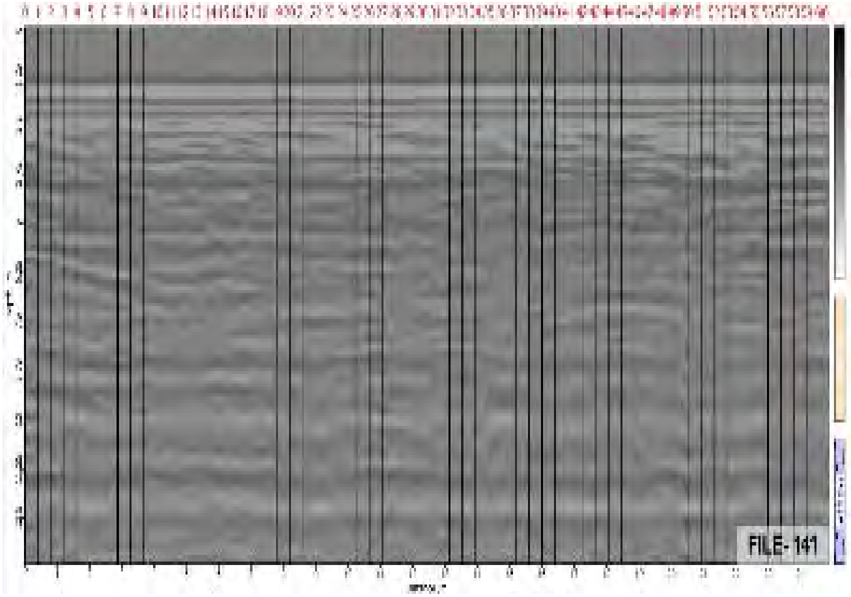

FILE- 181

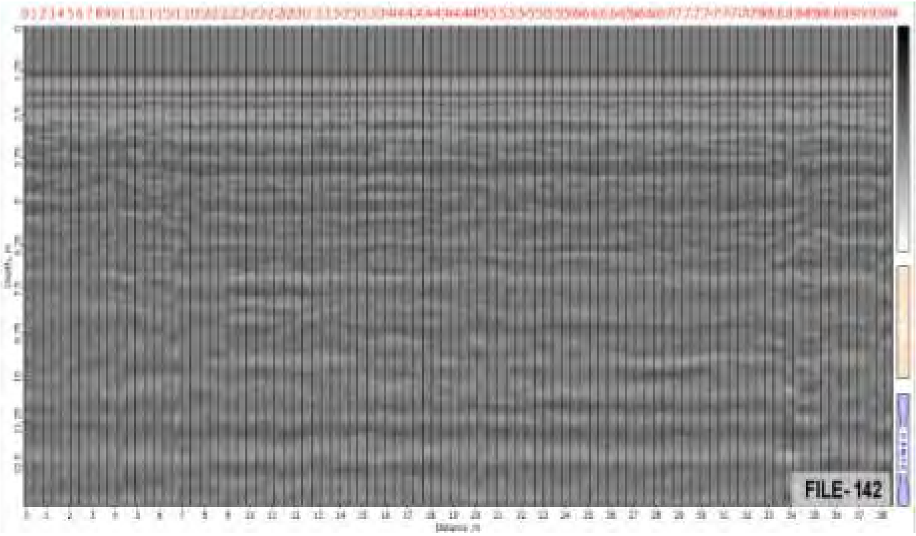
IMAGES OF GPR PROFILE SCANNED ALONG ERT-5

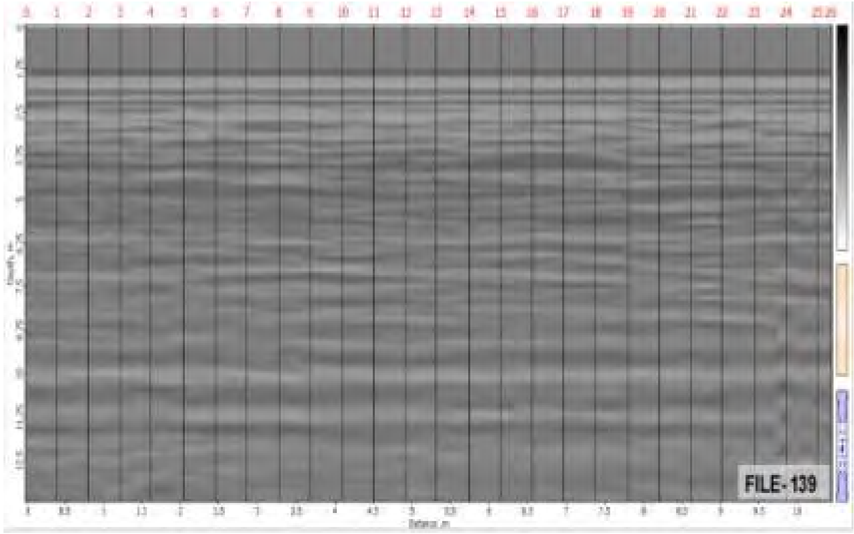


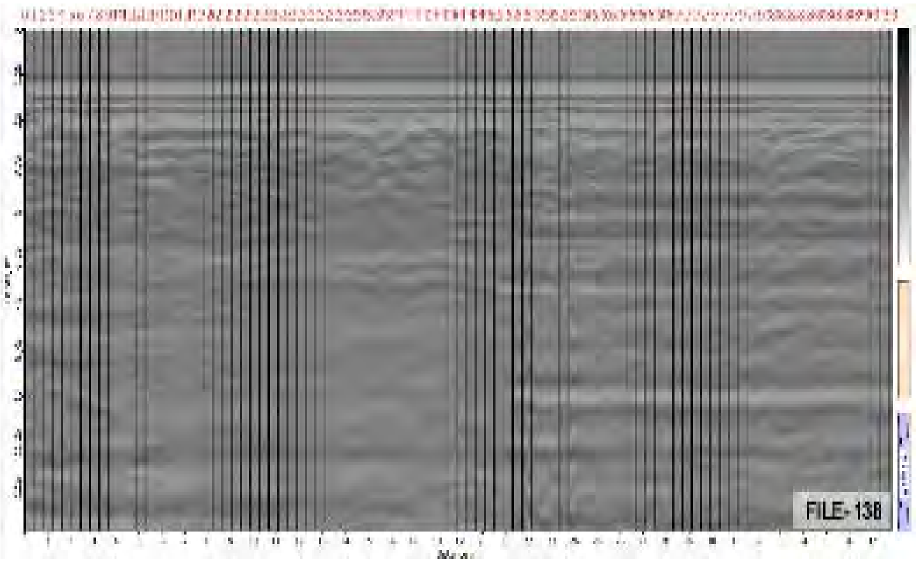


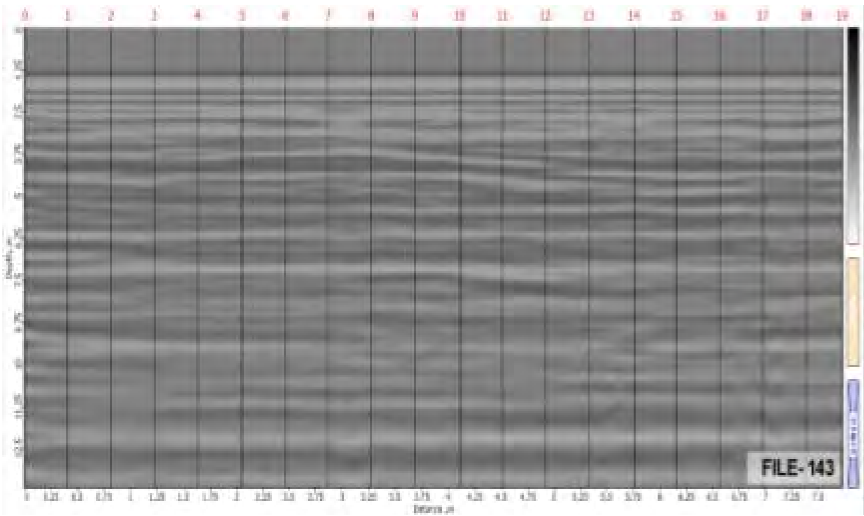




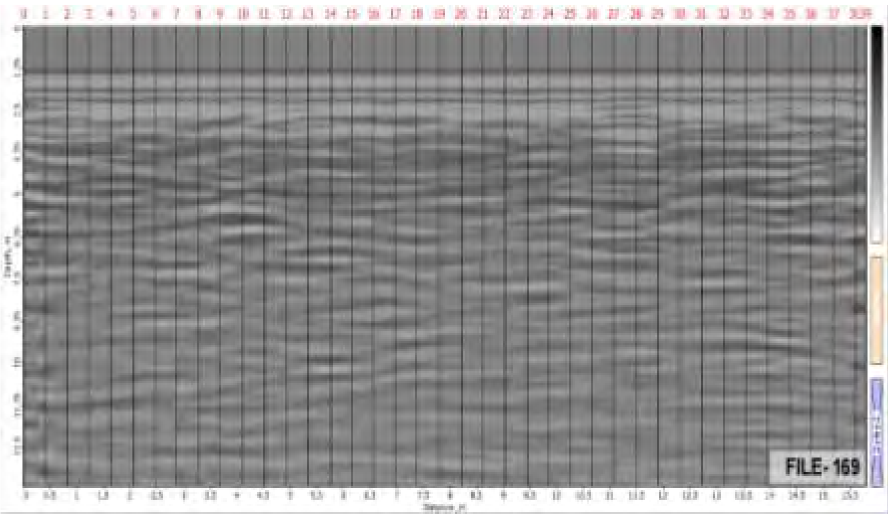

FILE- 142

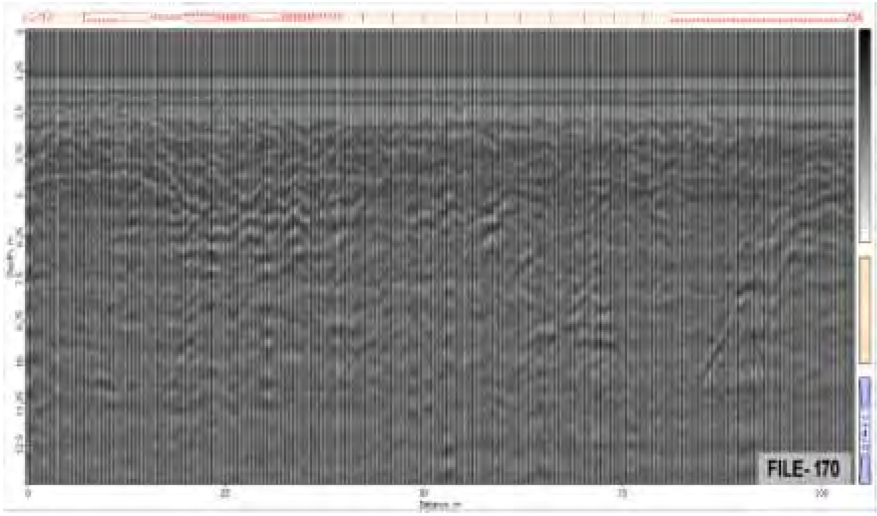

FILE- 139


FILE- 138

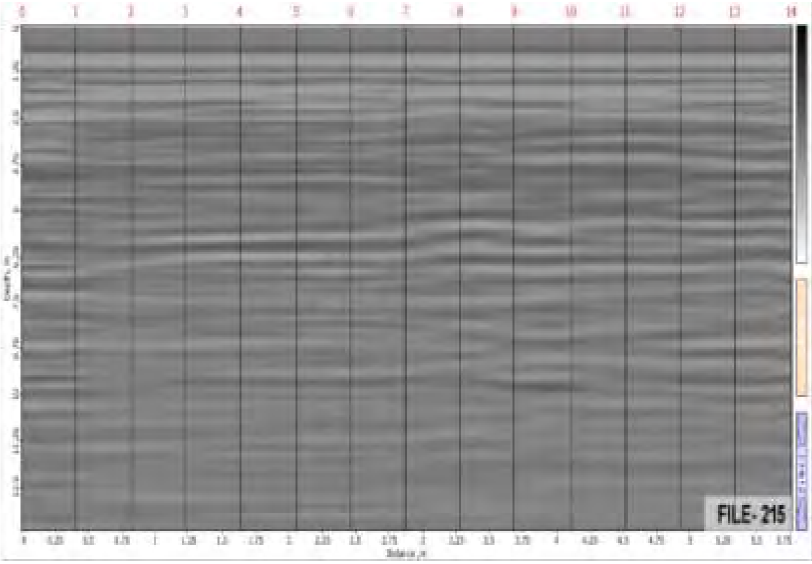

FILE- 143

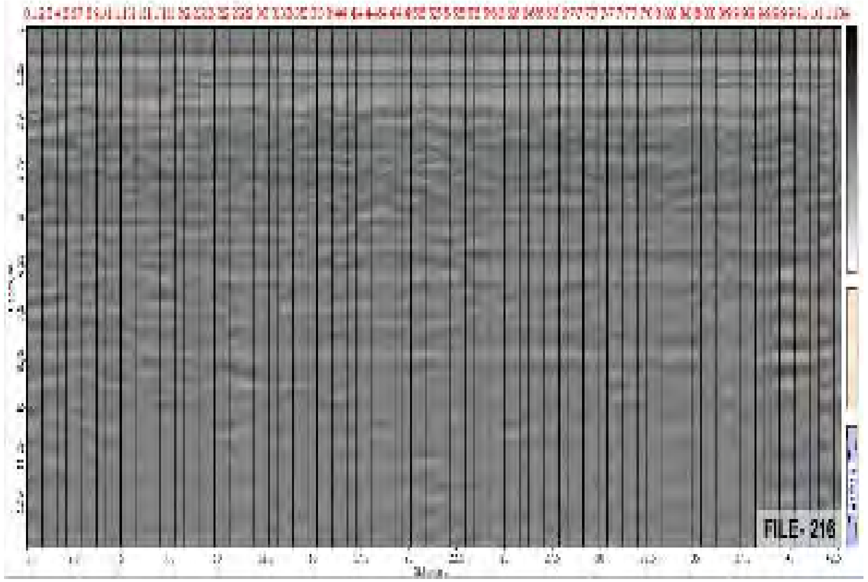
IMAGES OF GPR PROFILE SCANNED ALONG ERT-6

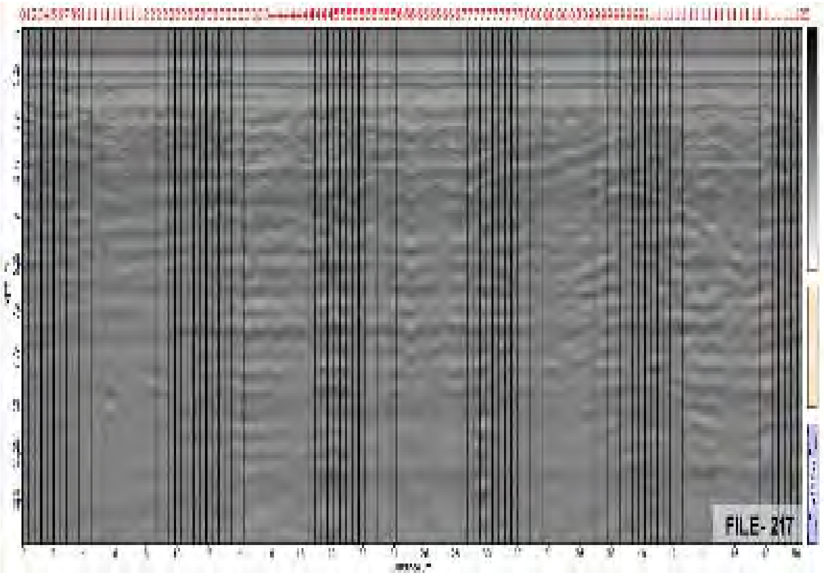


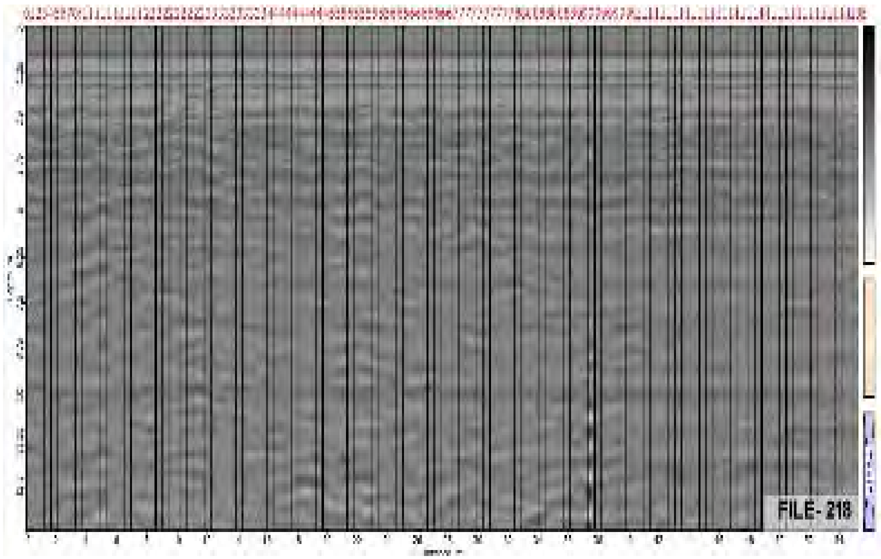


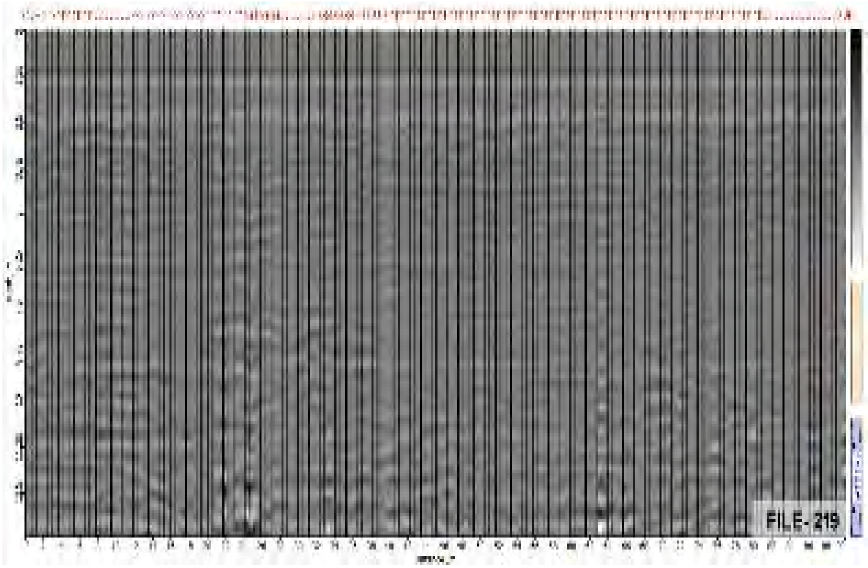
IMAGES OF GPR PROFILE SCANNED ALONG ERT-7

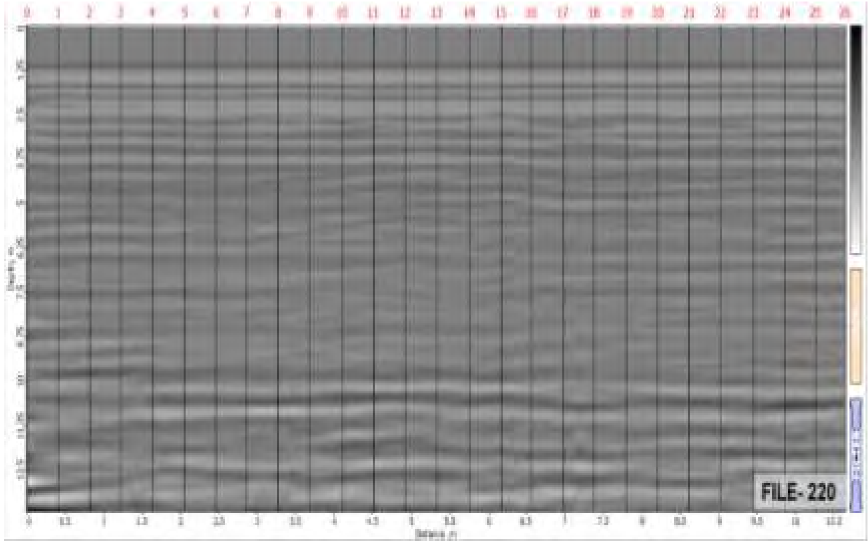


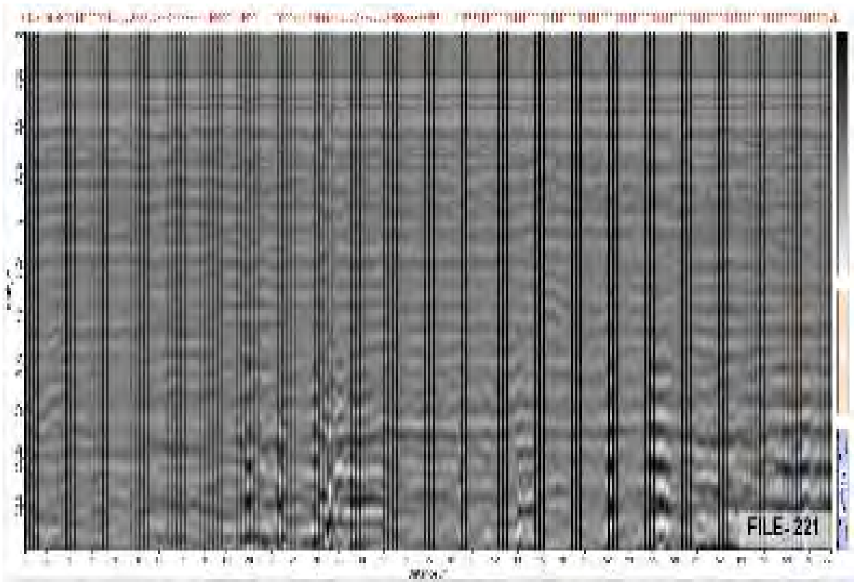


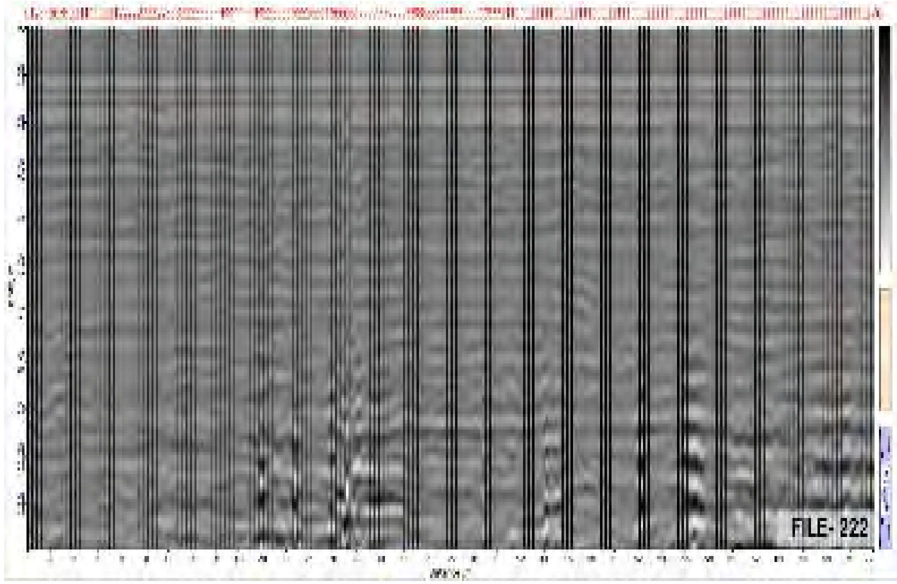




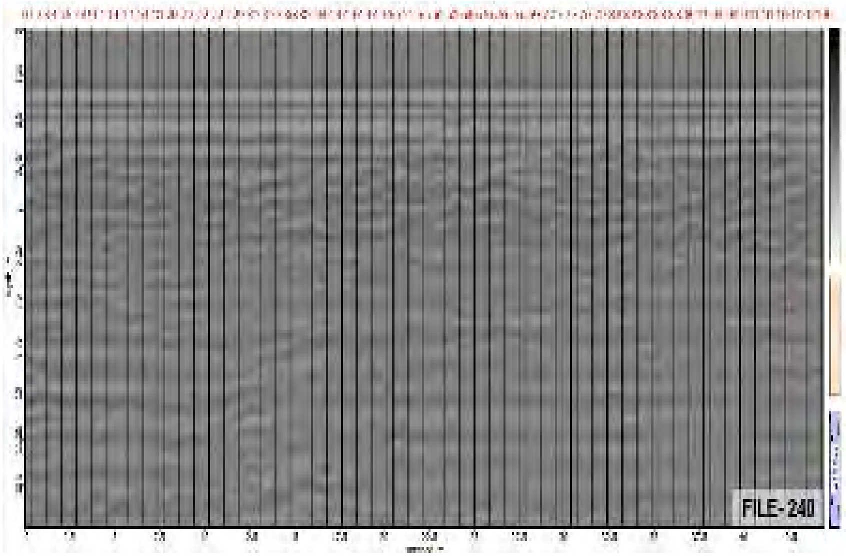

FILE- 219

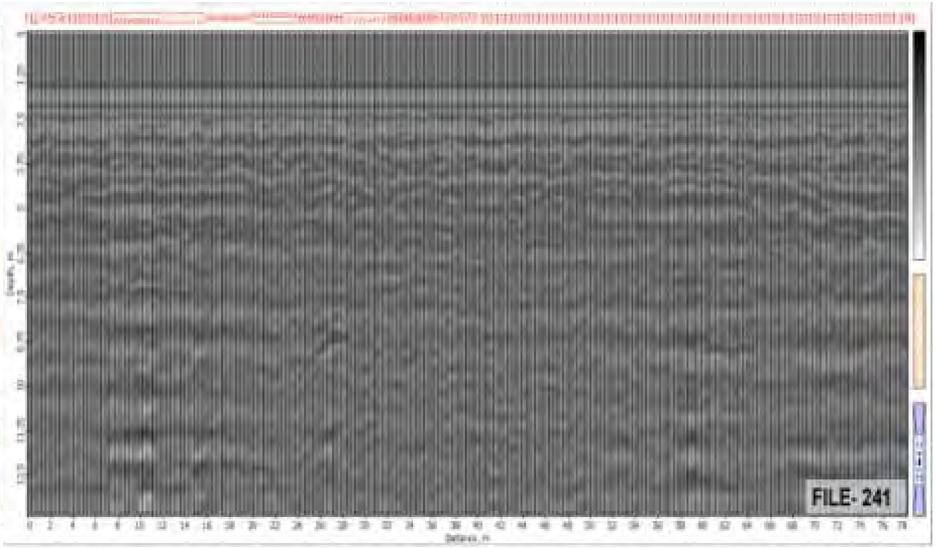

FILE- 220

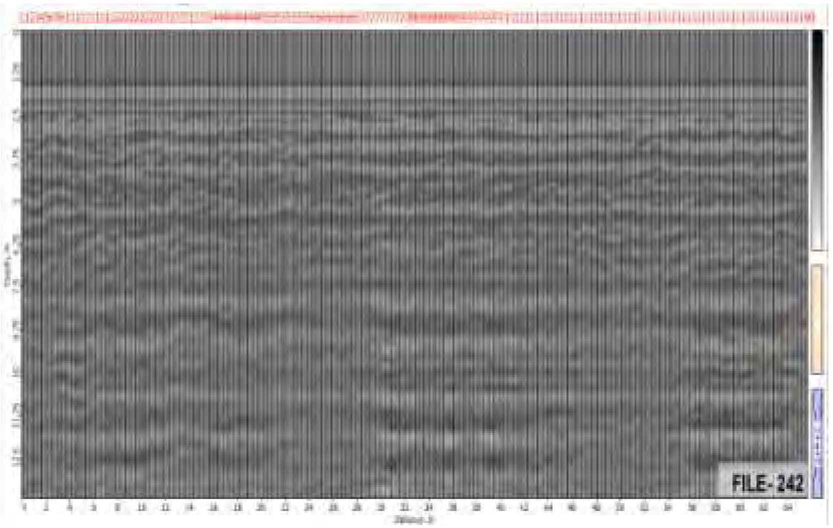

FILE- 221

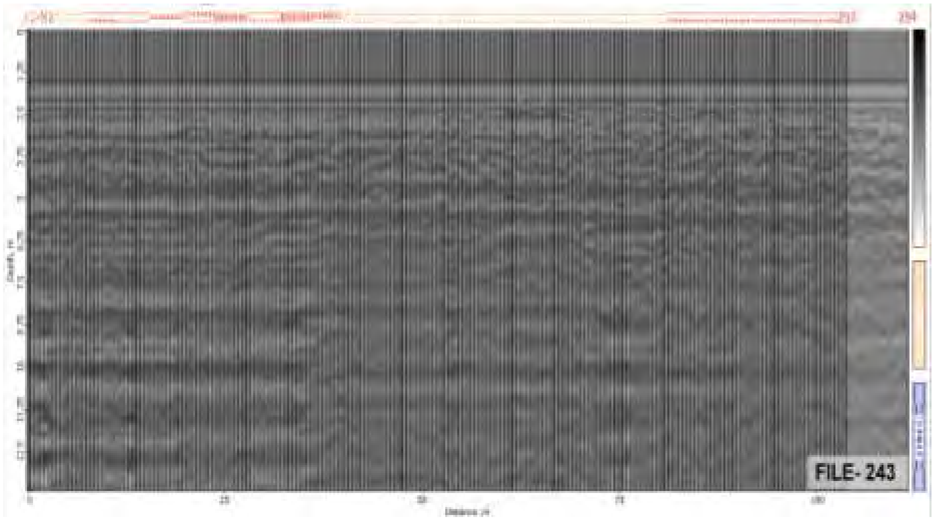

FILE- 222

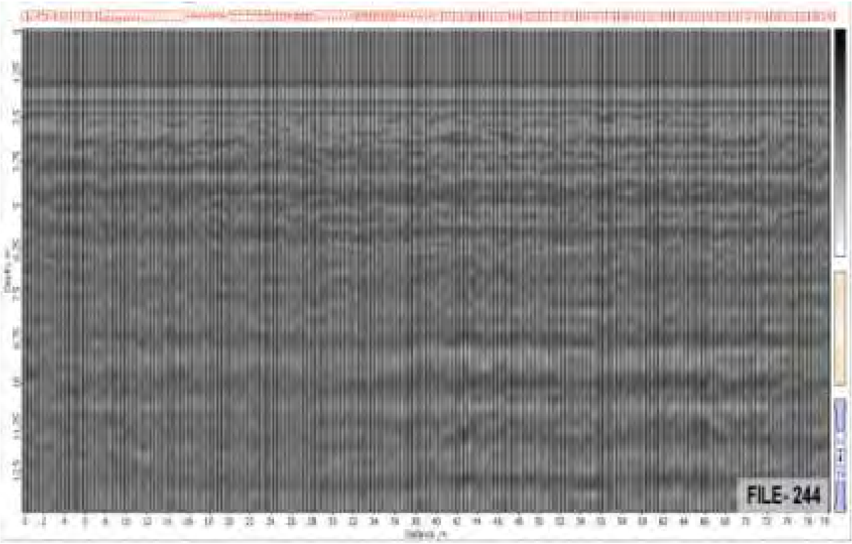
IMAGES OF GPR PROFILE SCANNED ALONG ERT-8

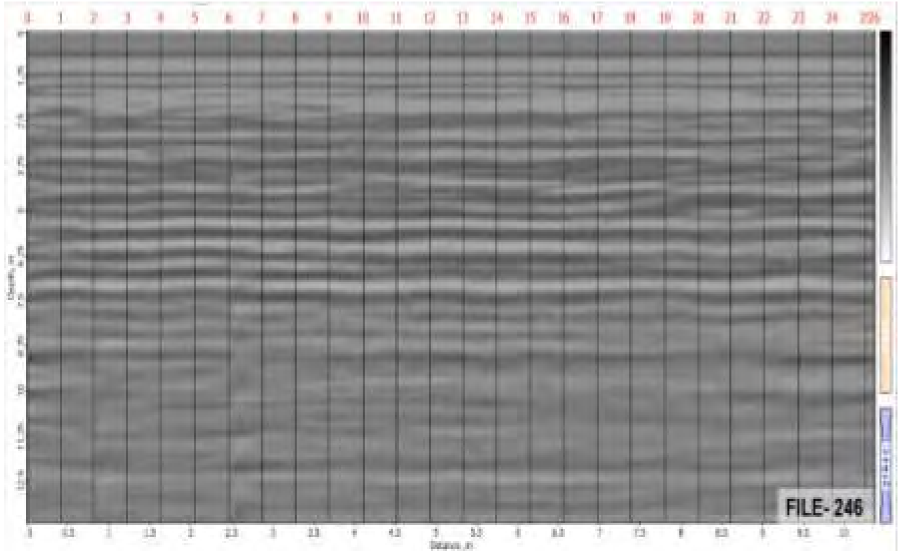




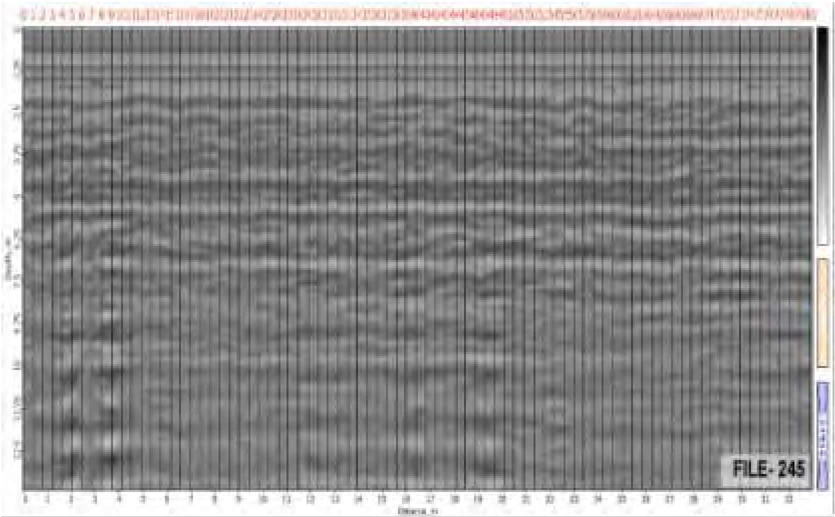


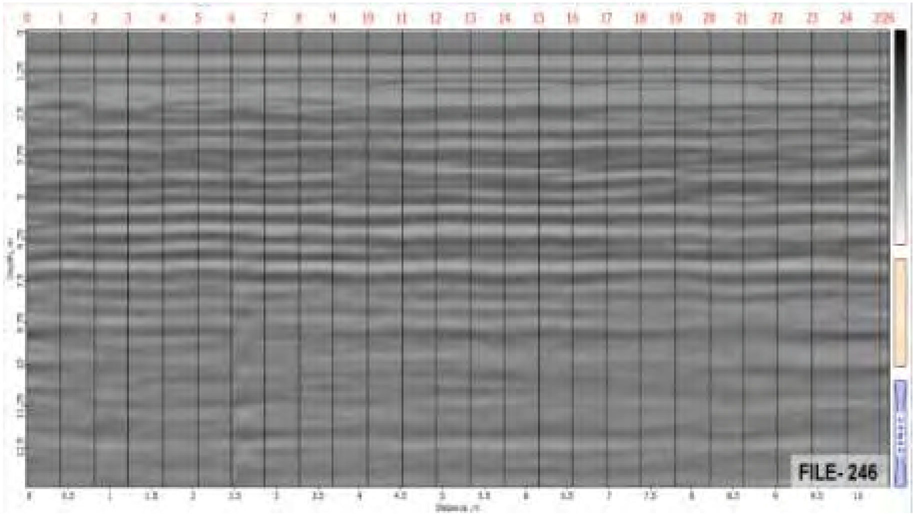


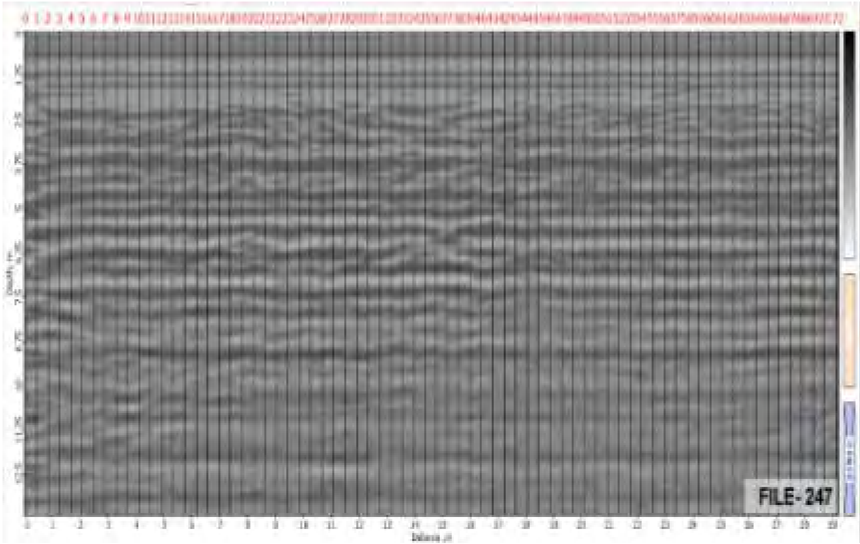

FILE- 244

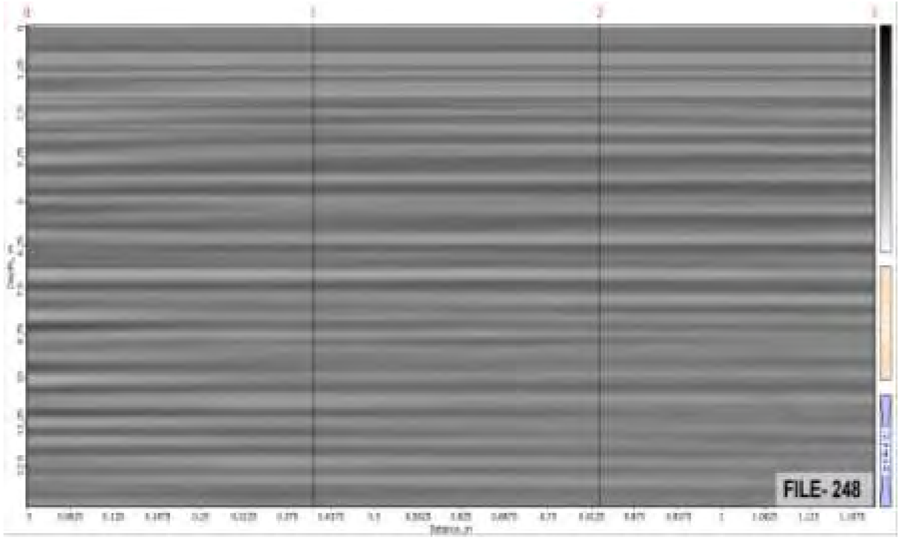

FILE- 246

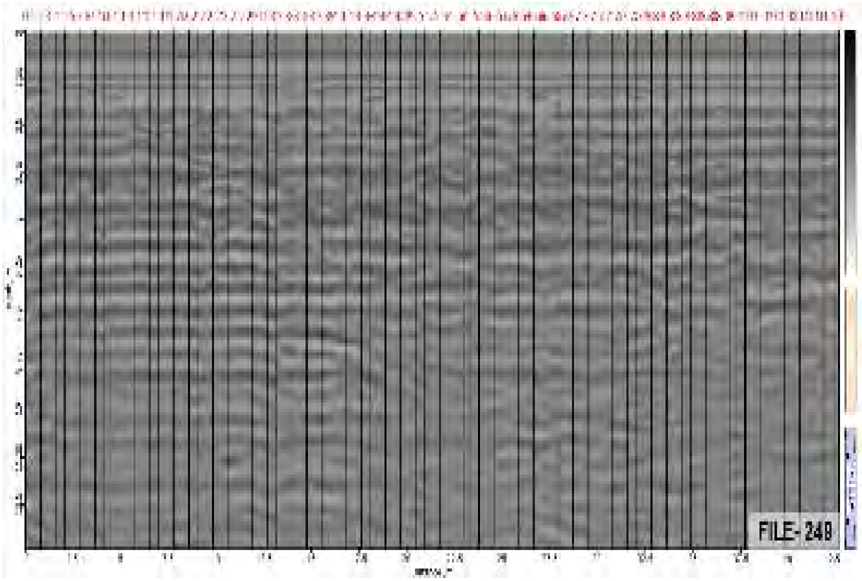
IMAGES OF GPR PROFILE SCANNED ALONG ERT-9

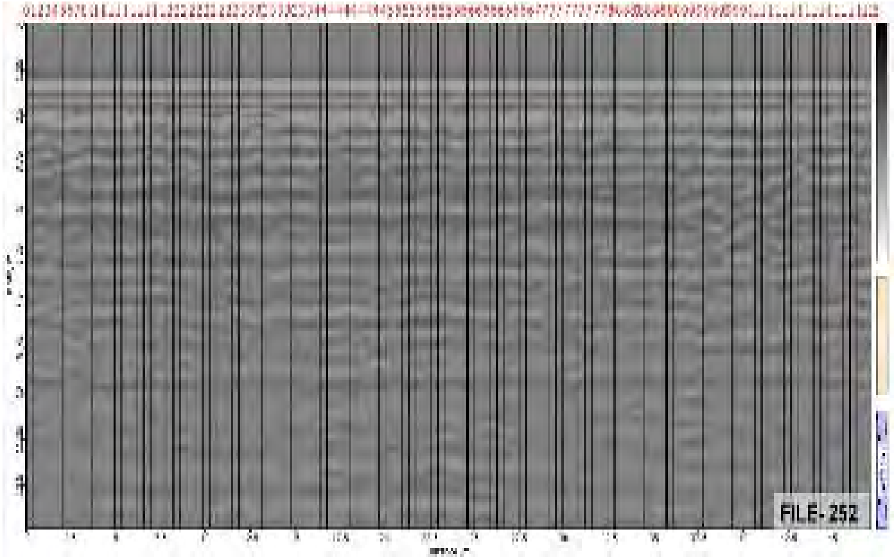


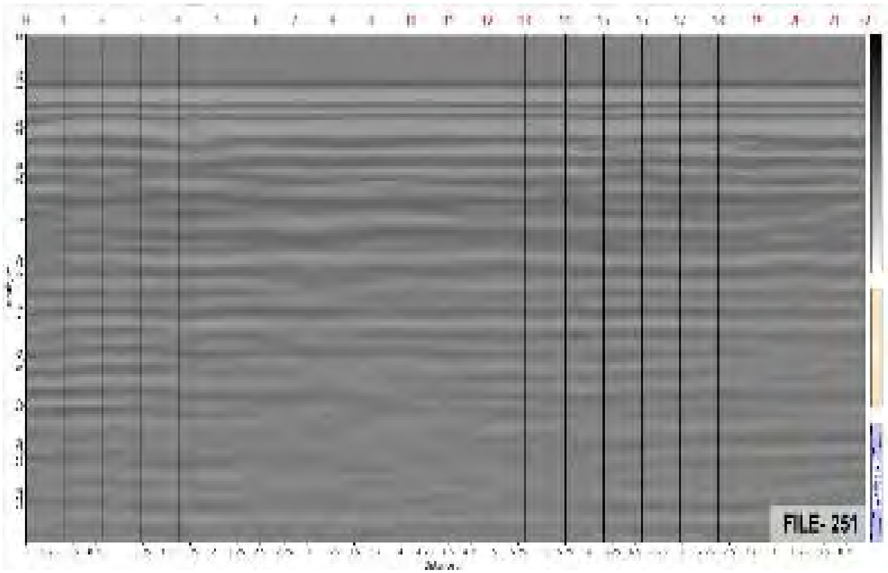


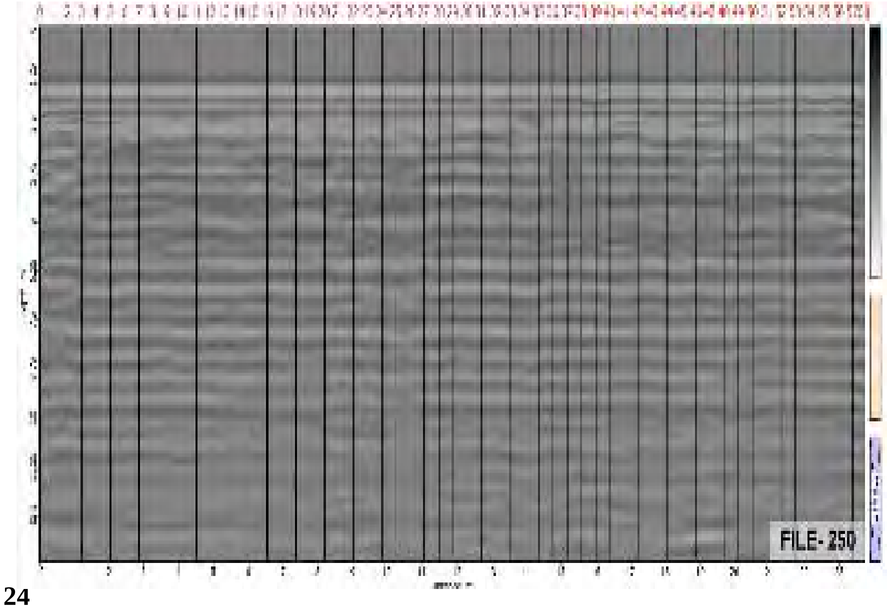


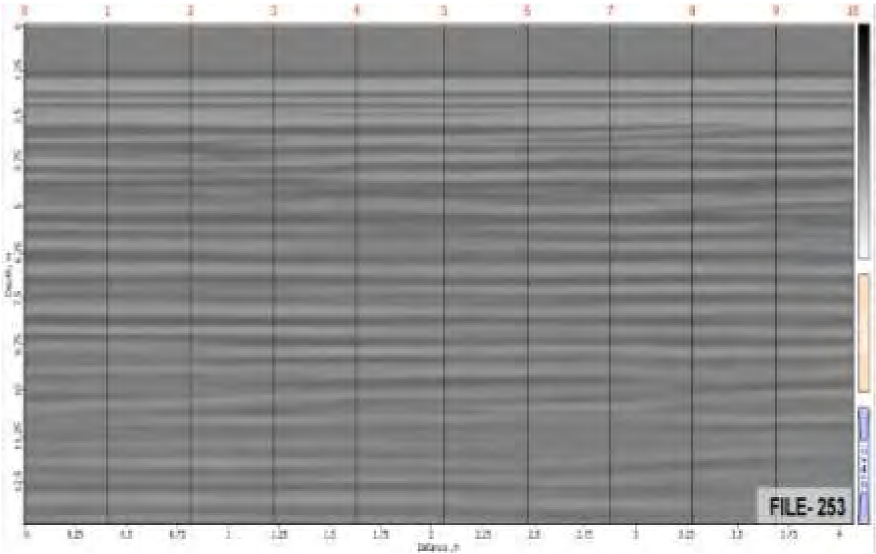


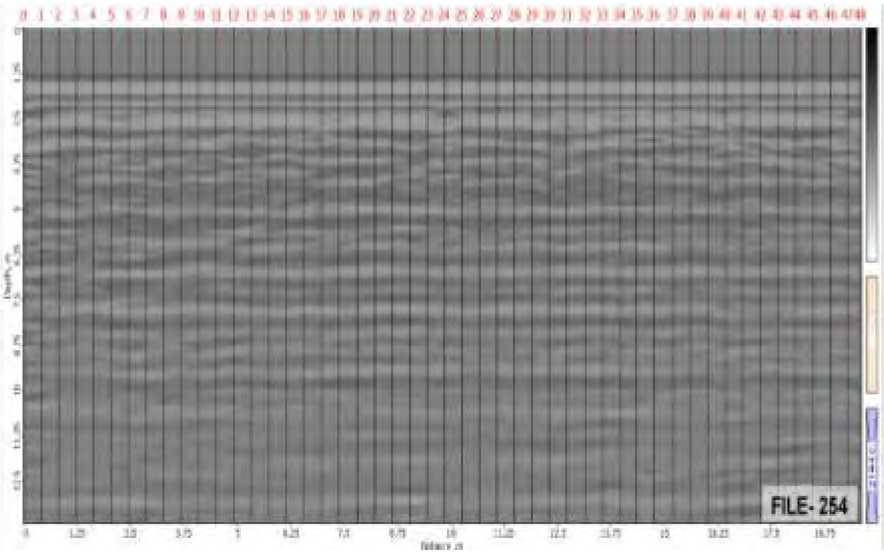

FILE- 248


FILE- 252

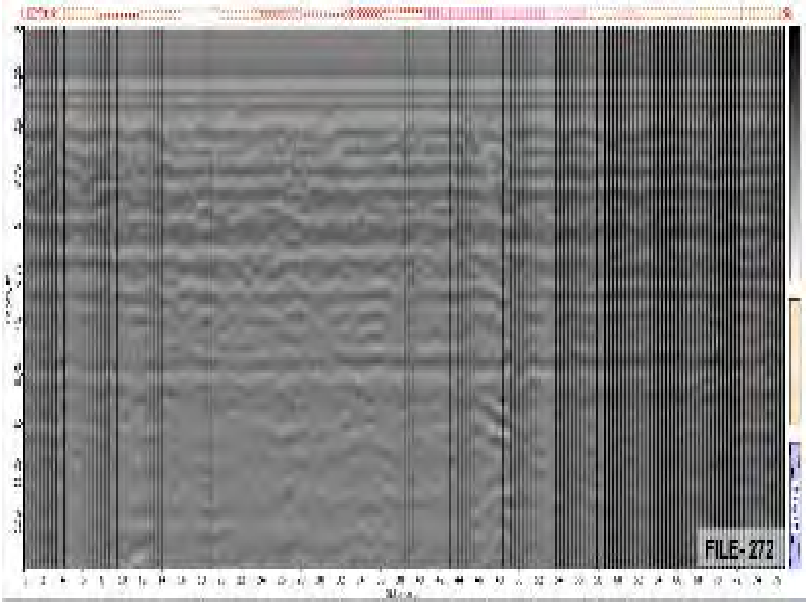

FILE- 251

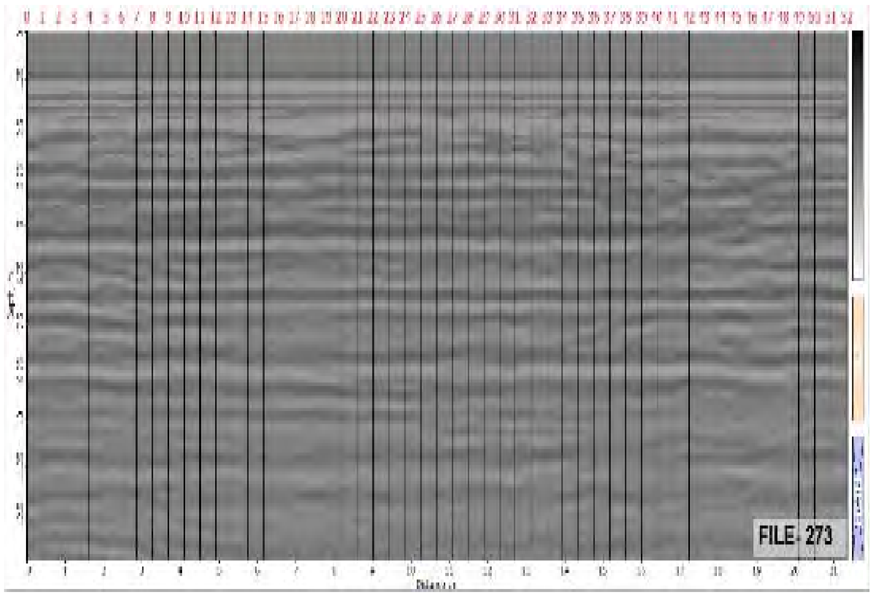

FILE- 250

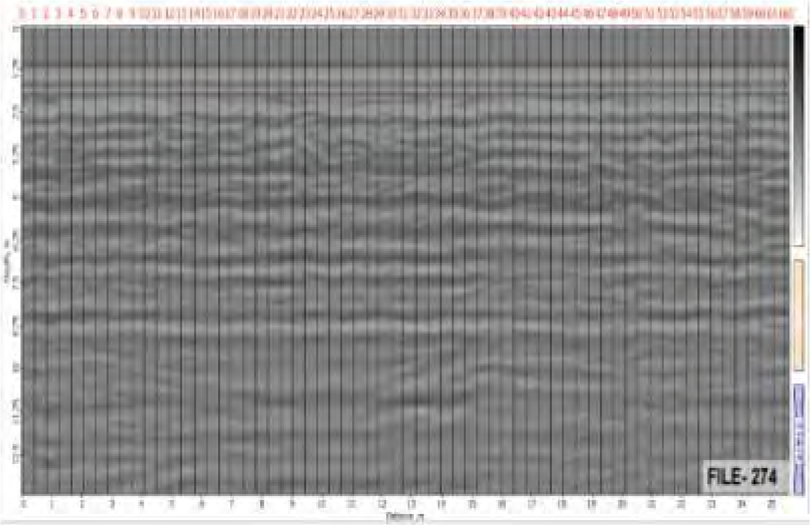

FILE- 253

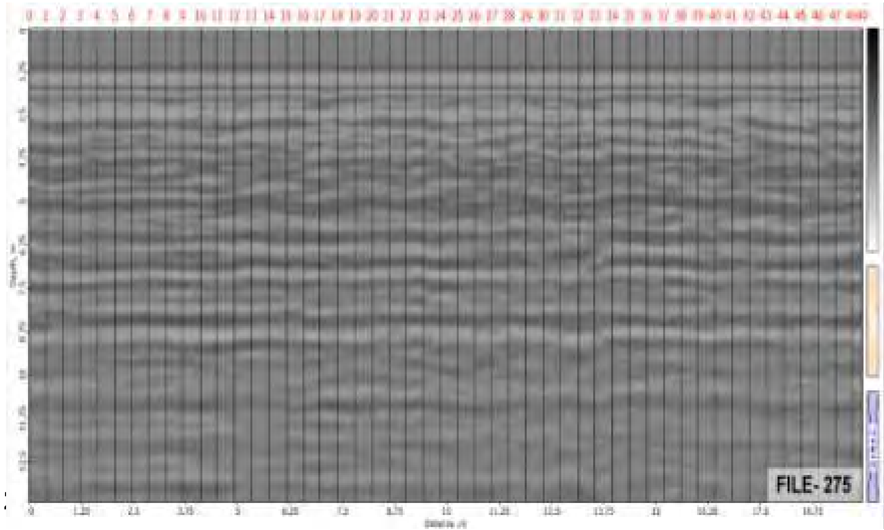

FILE- 254

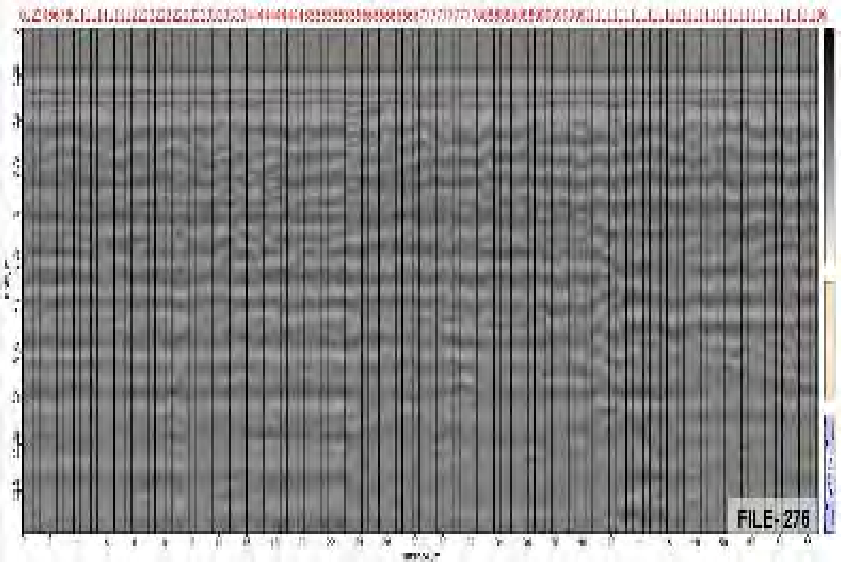
IMAGES OF GPR PROFILE SCANNED ALONG ERT-10

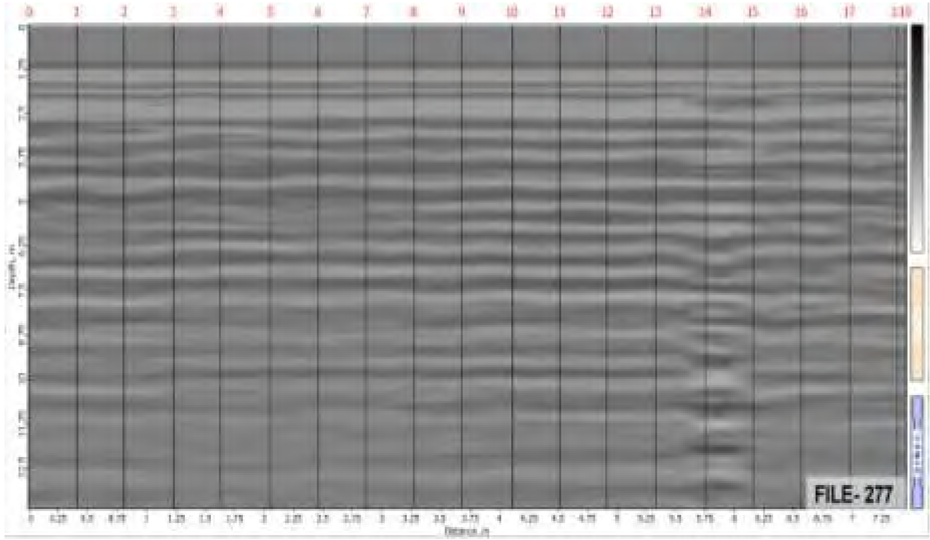


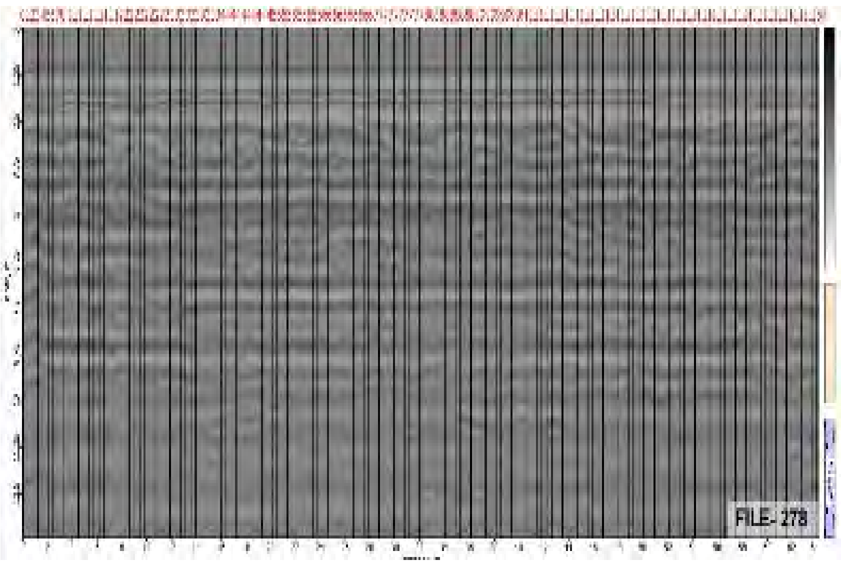


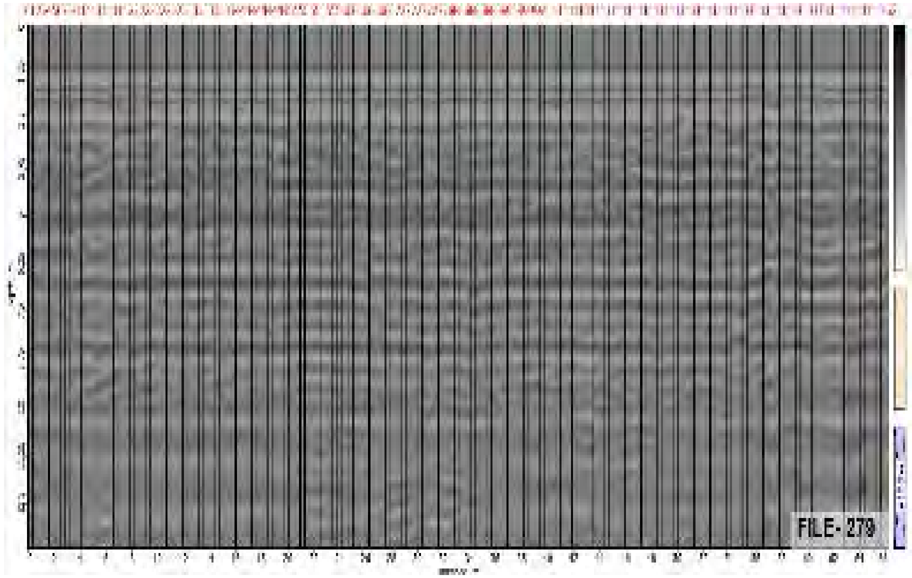


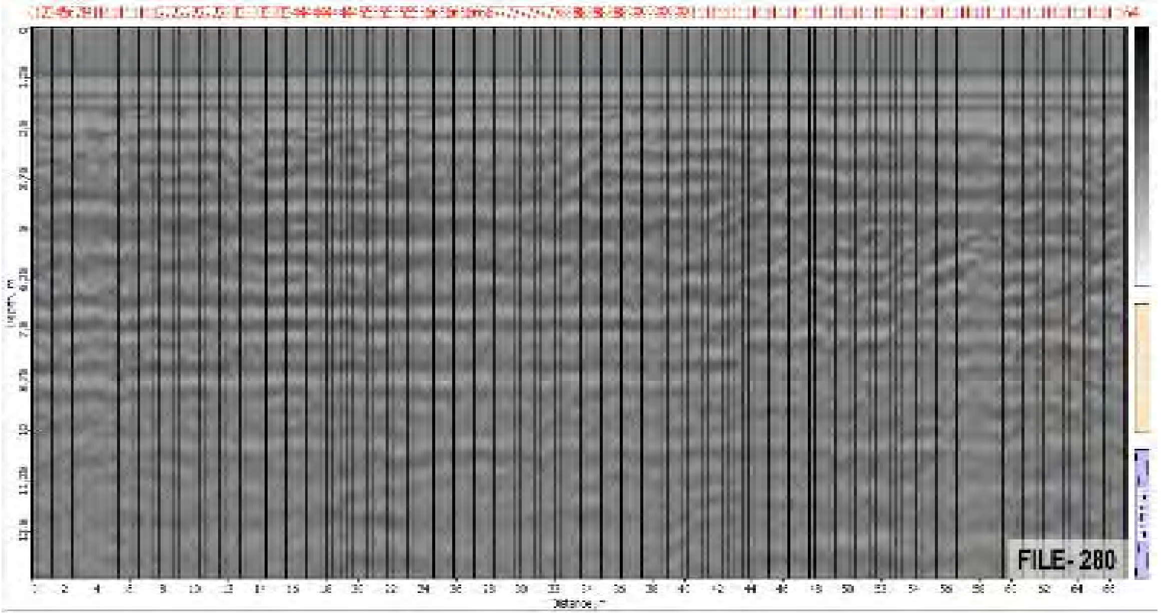



FILE- 276


FILE- 277


FILE- 278

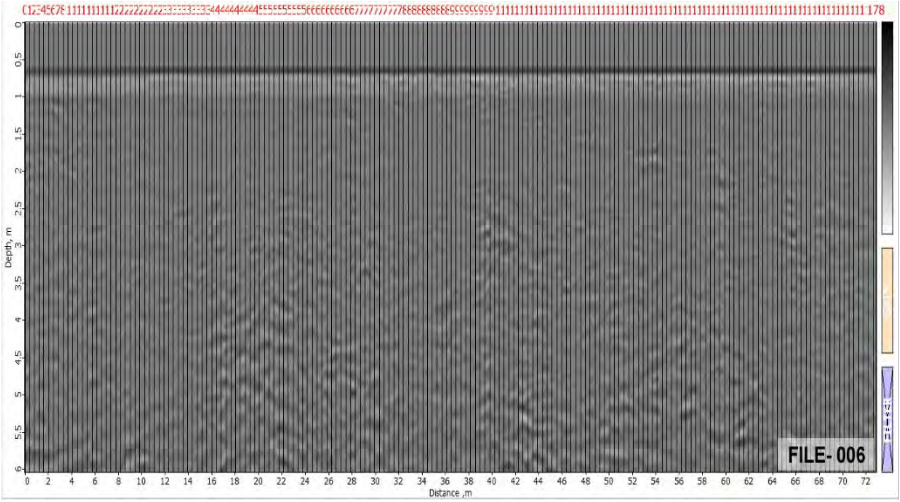

FILE- 279

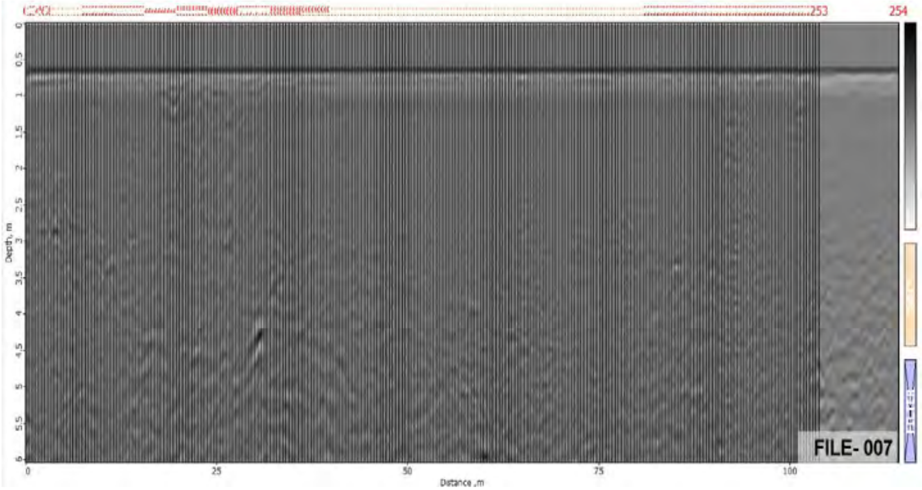

FILE- 280
Distance, m

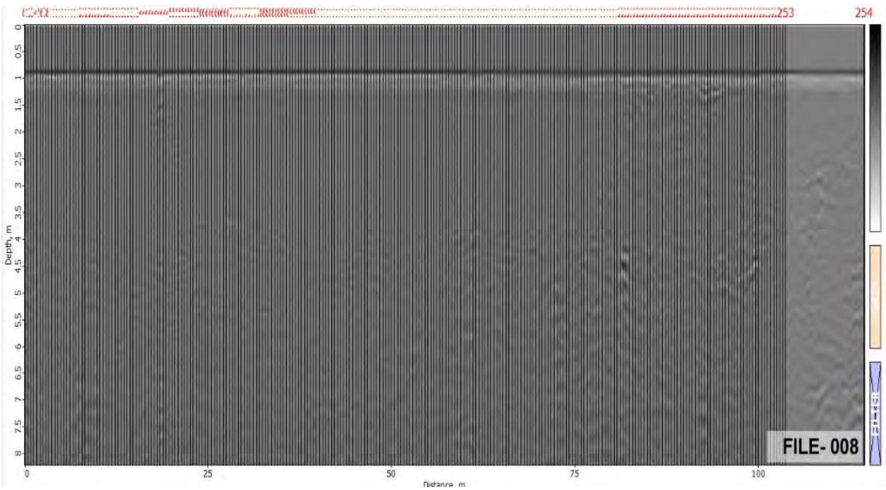
Annexure-IV

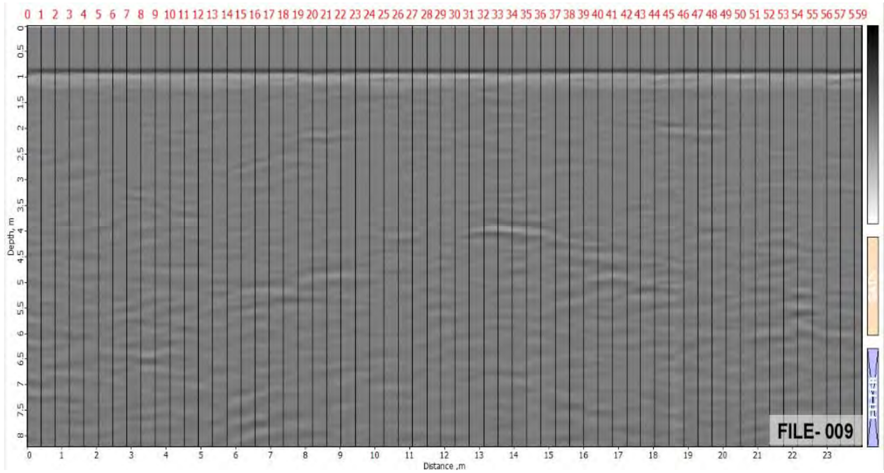
GPR PROFILES WITH 200 & 270 MHz ANTENNA (SAVED FROM PRISM-2.59 SOFTWARE)

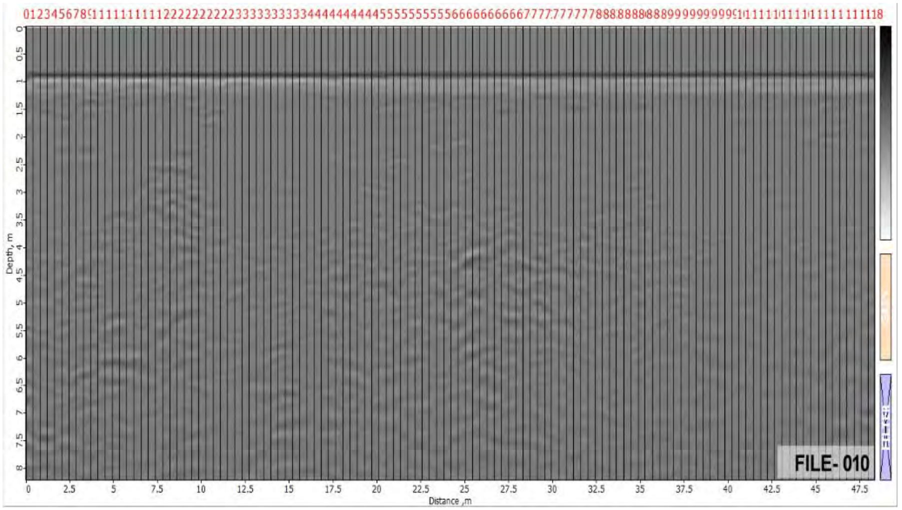
IMAGES OF GPR PROFILE SCANNED ALONG ERT-1

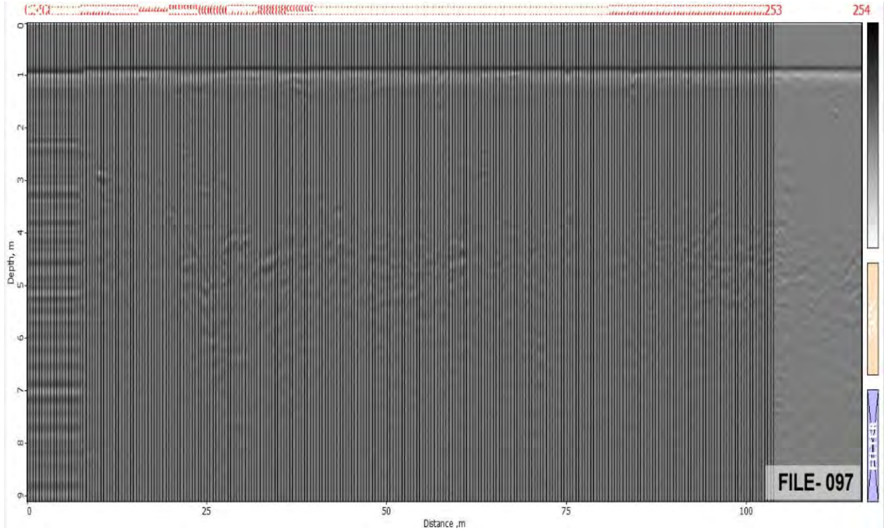


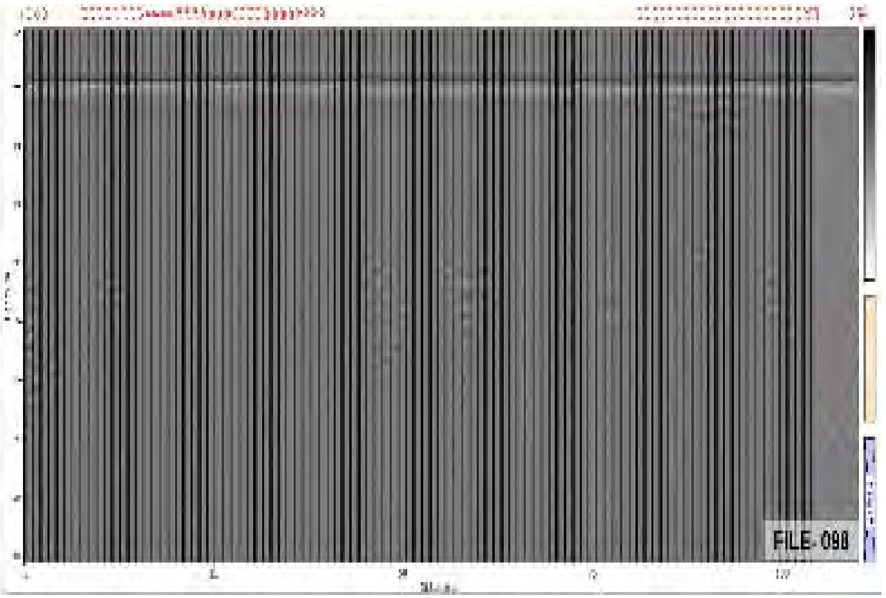


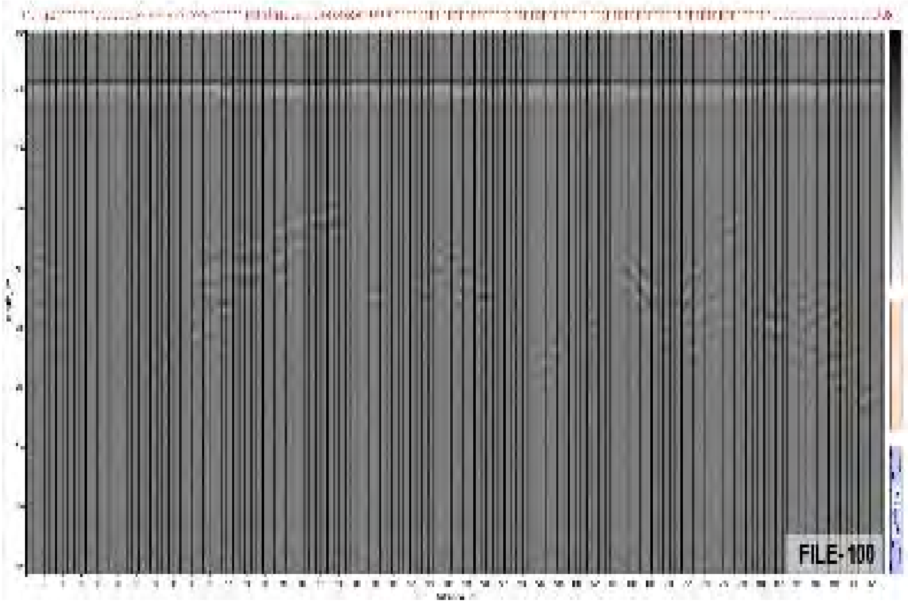


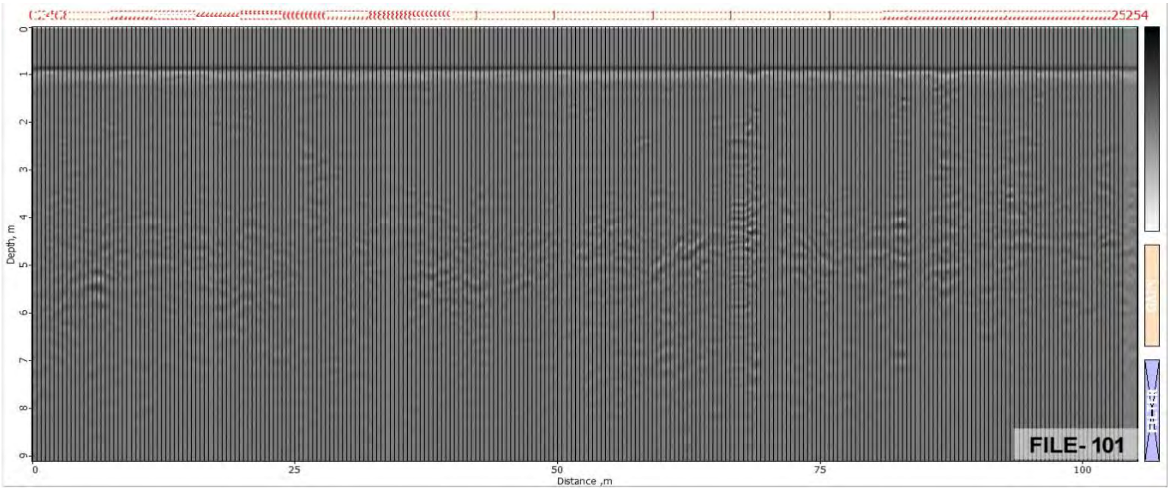



FILE- 010
Depth, m
Distance ,m


FILE- 097
Depth, m
Distance ,m

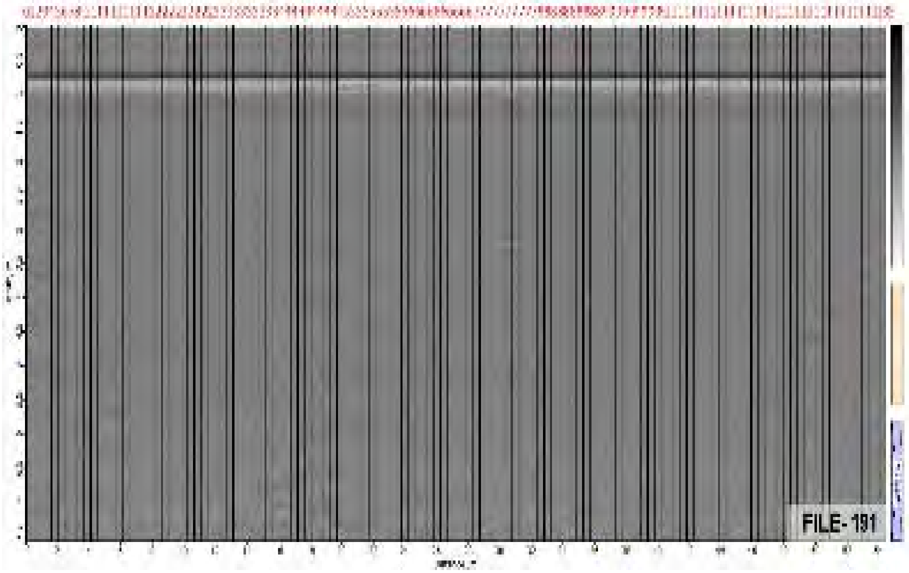

FILE- 098

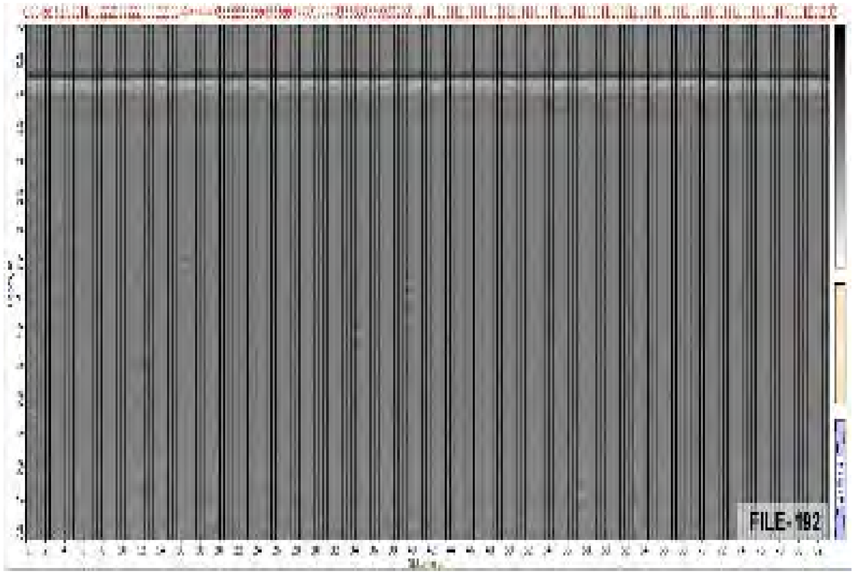

FILE- 100

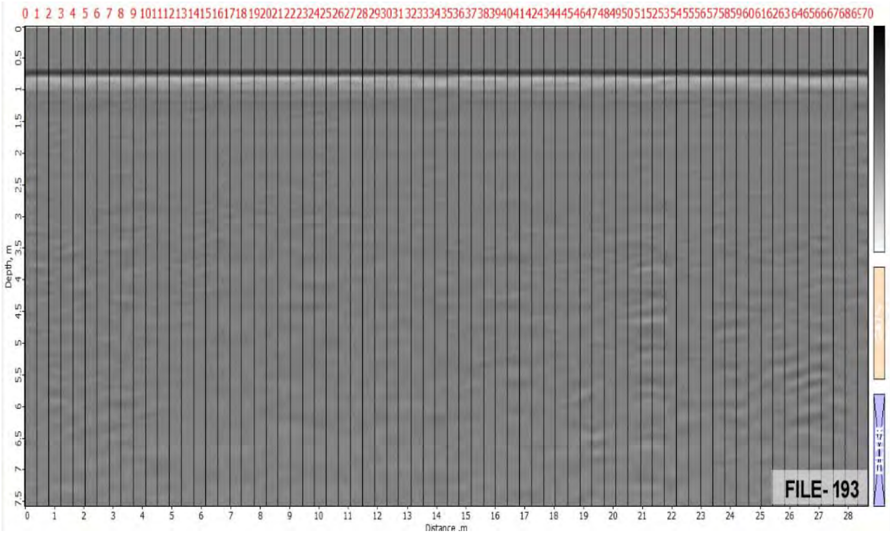


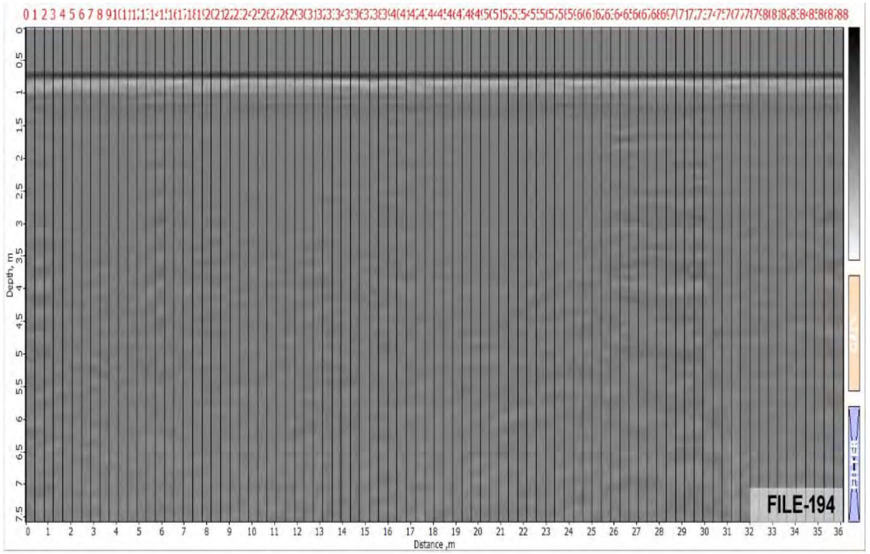
Depth, m
0
1
2
3
4
5
6
7
8
9
0
25
50
75
100
Distance ,m
FILE- 101
25254

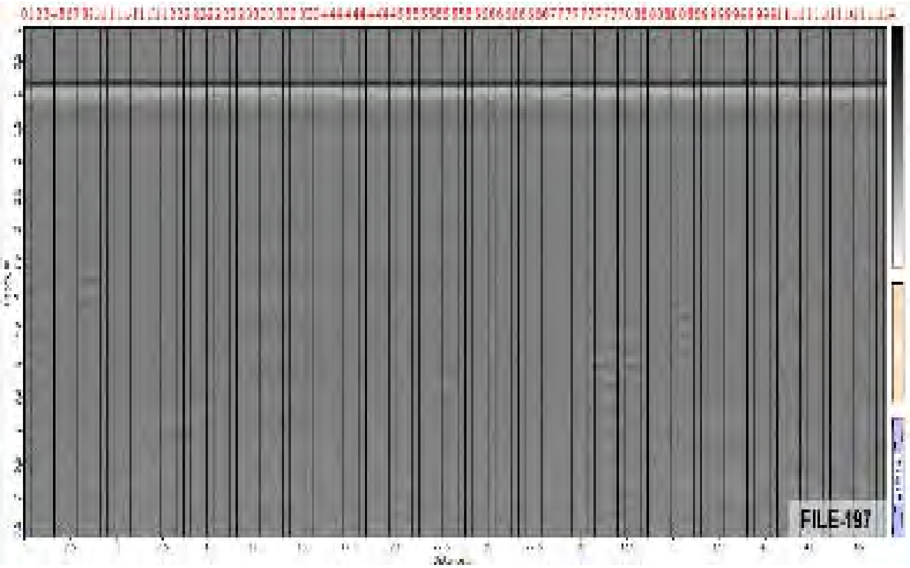
IMAGES OF GPR PROFILE SCANNED ALONG ERT-2

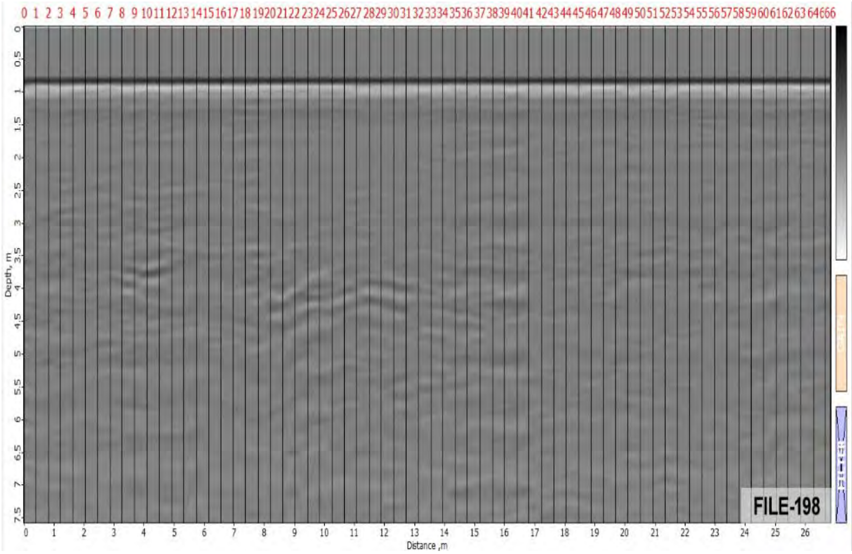


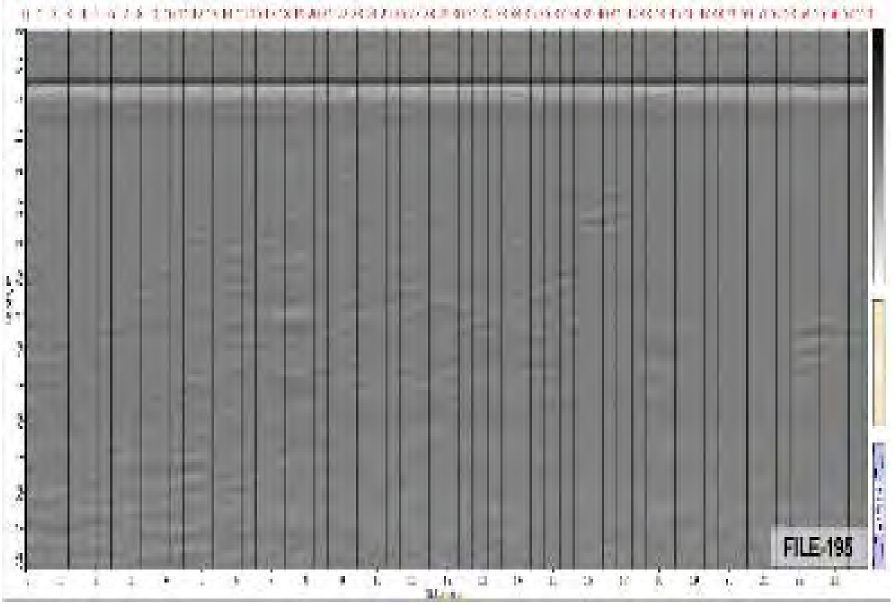


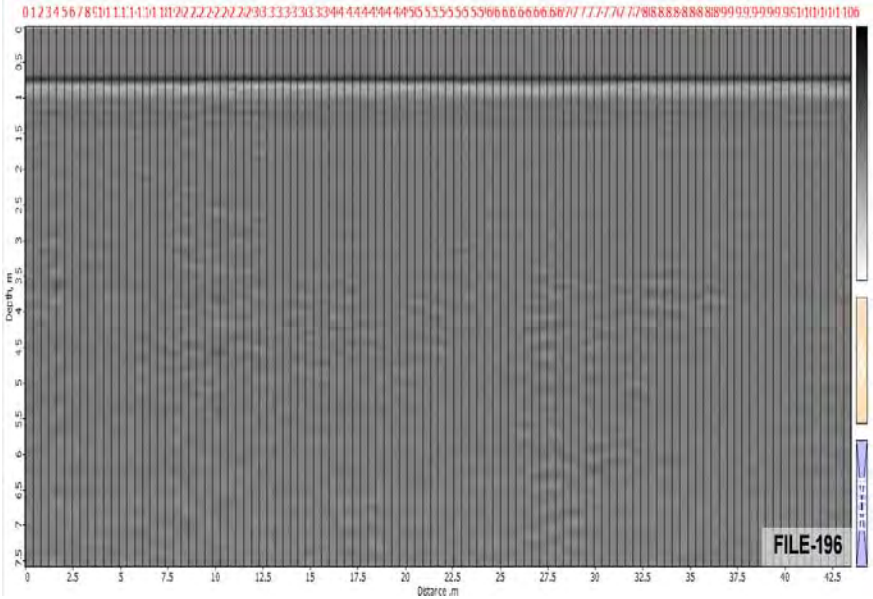


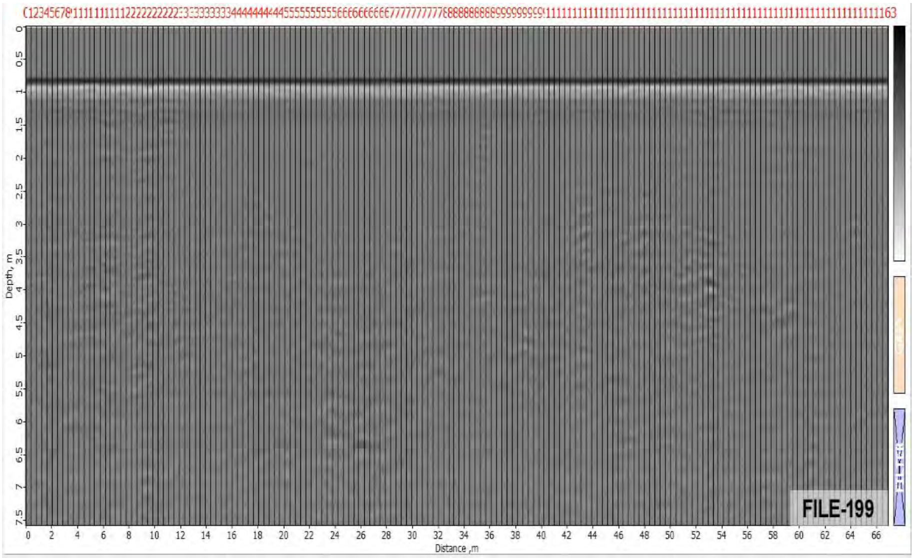


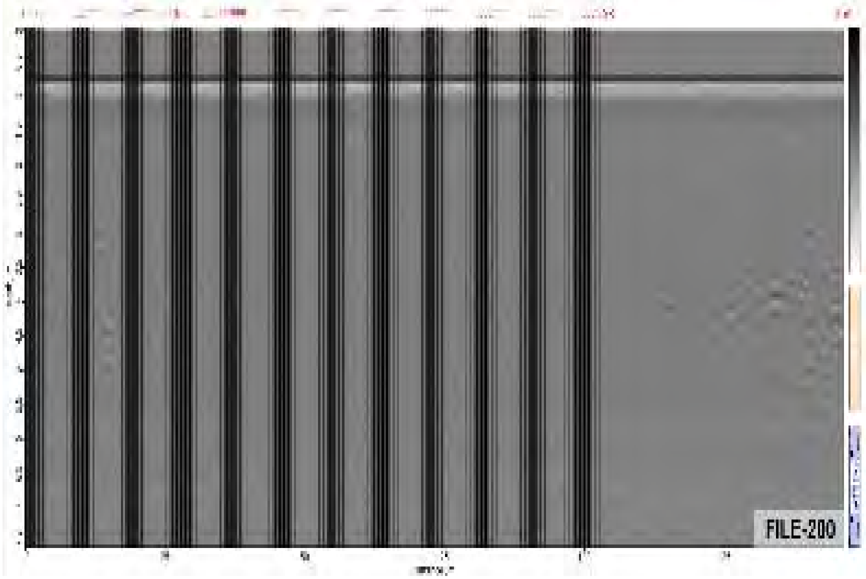

FILE-197

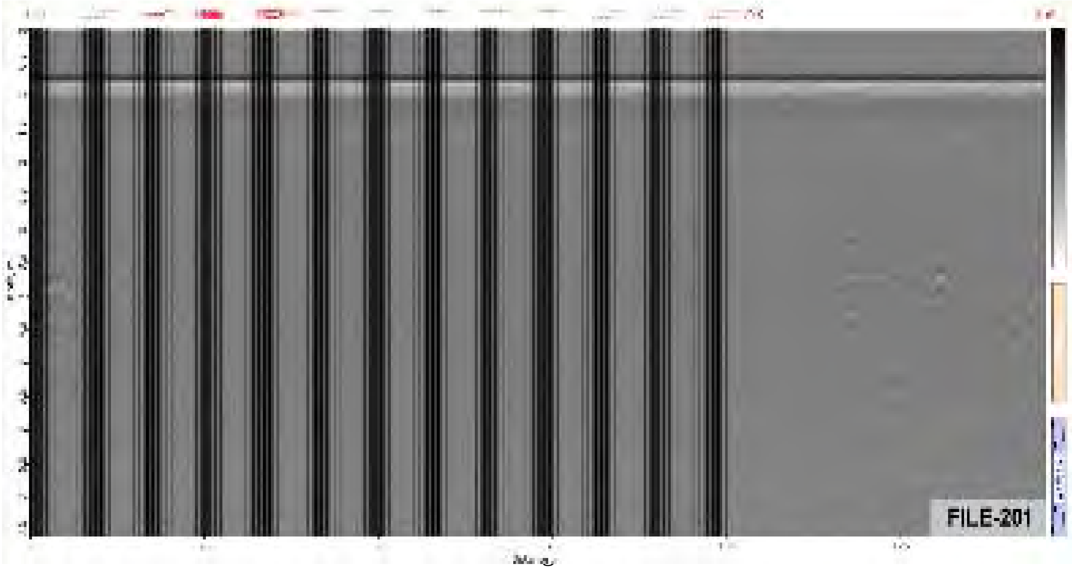

Depth, m
Distance ,m
FILE-198


FILE-195

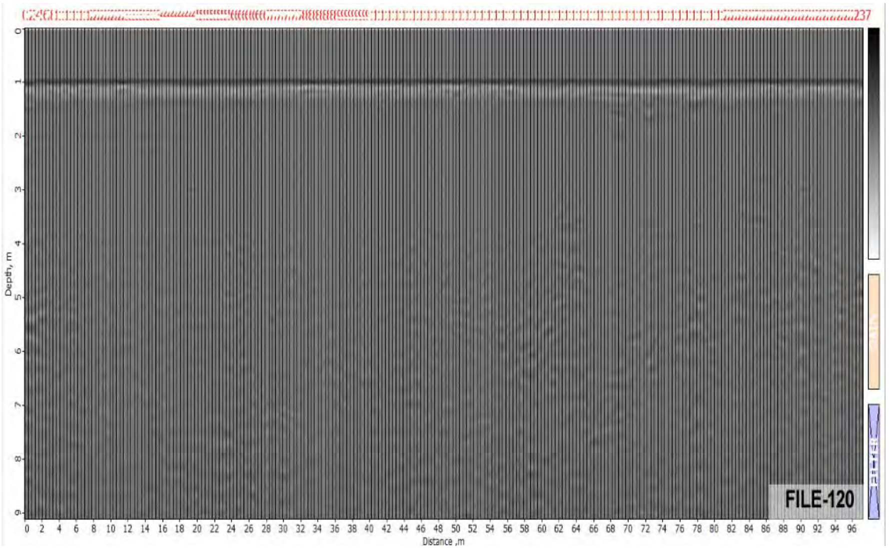

Depth, m
Distance ,m
FILE-196

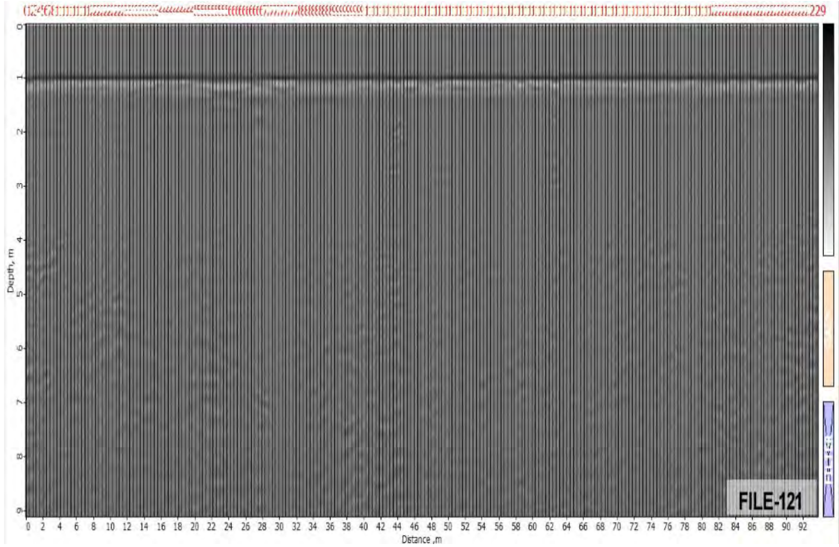

Depth, m
Distance ,m
FILE-199

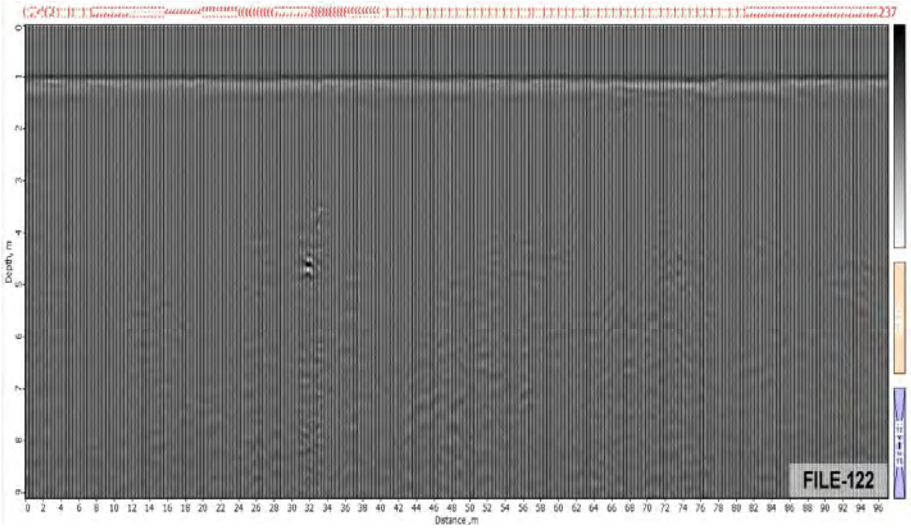

FILE-200

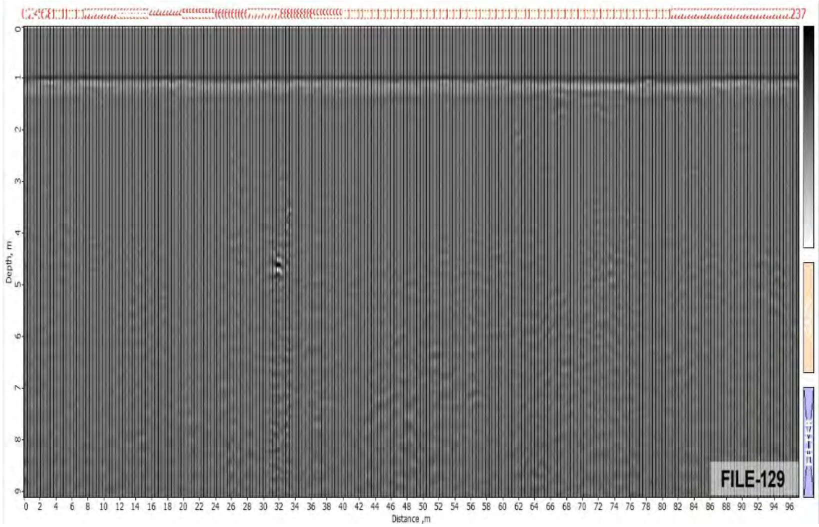

FILE-201

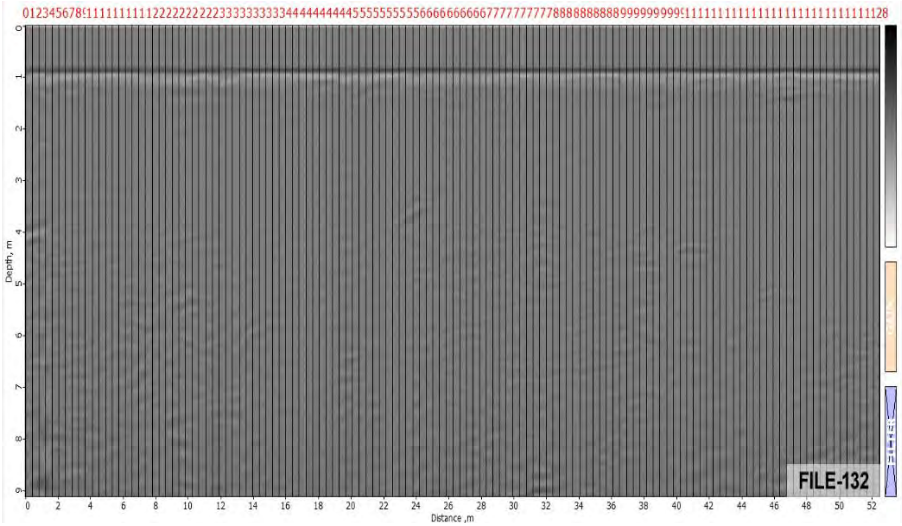
IMAGES OF GPR PROFILE SCANNED ALONG ERT- 3

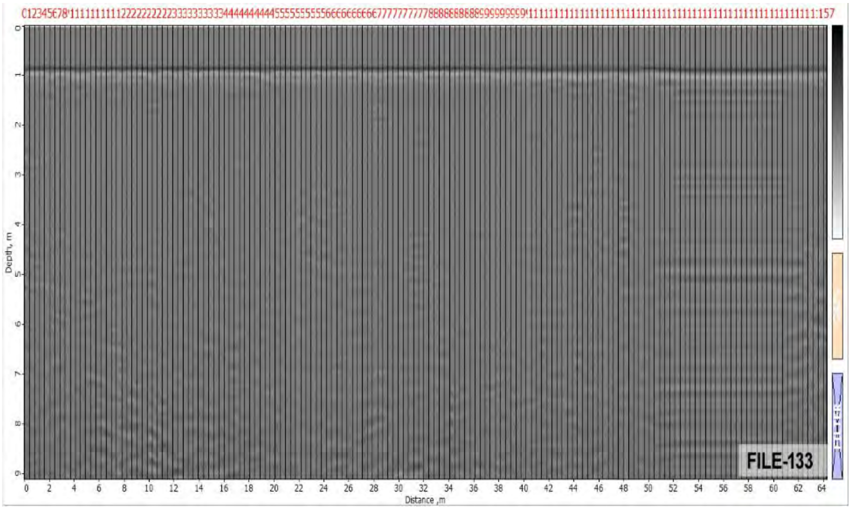


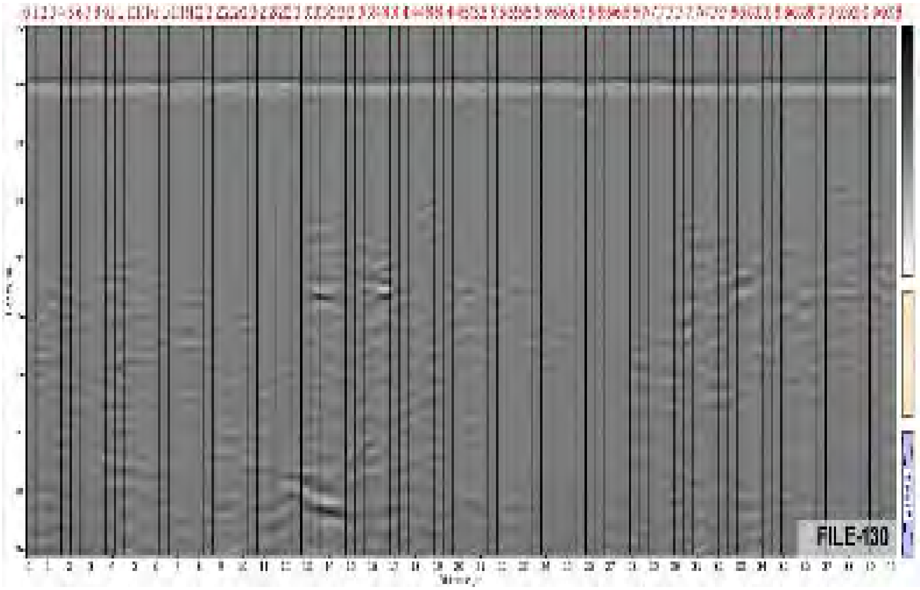


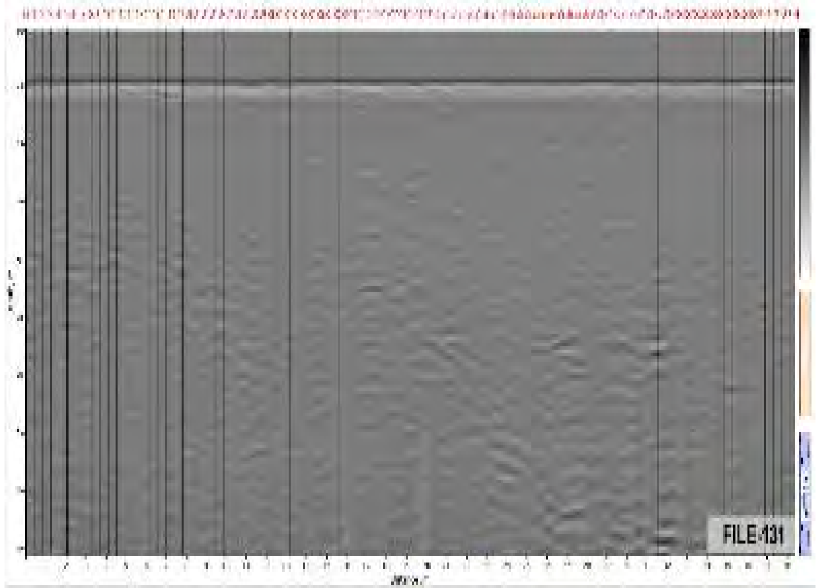




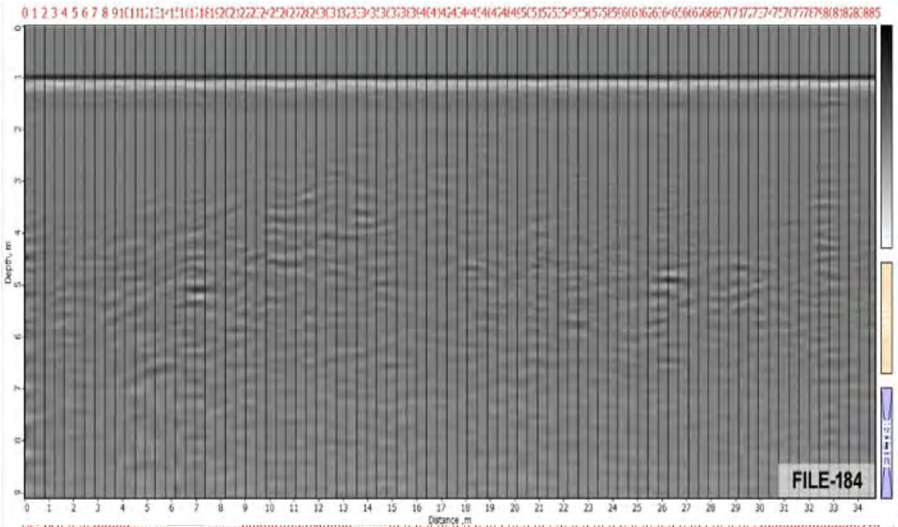

FILE-132
Depth, m
Distance ,m

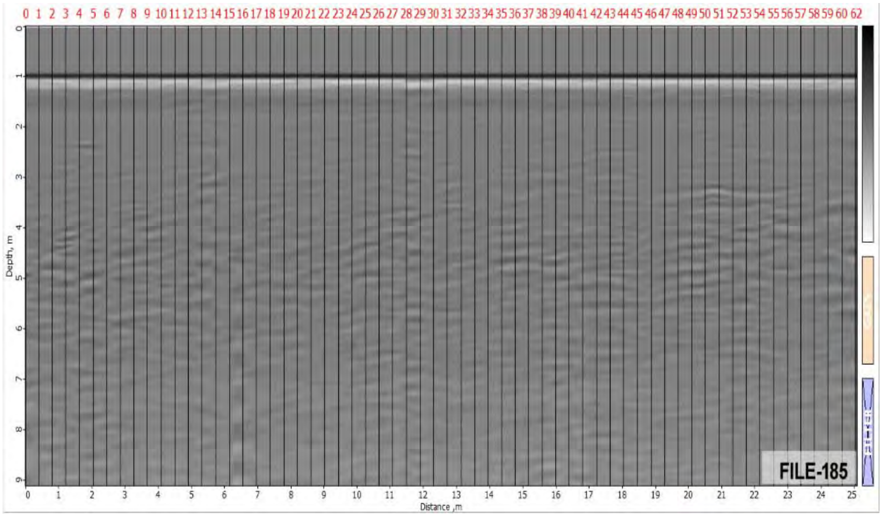

FILE-133
Depth, m
Distance ,m

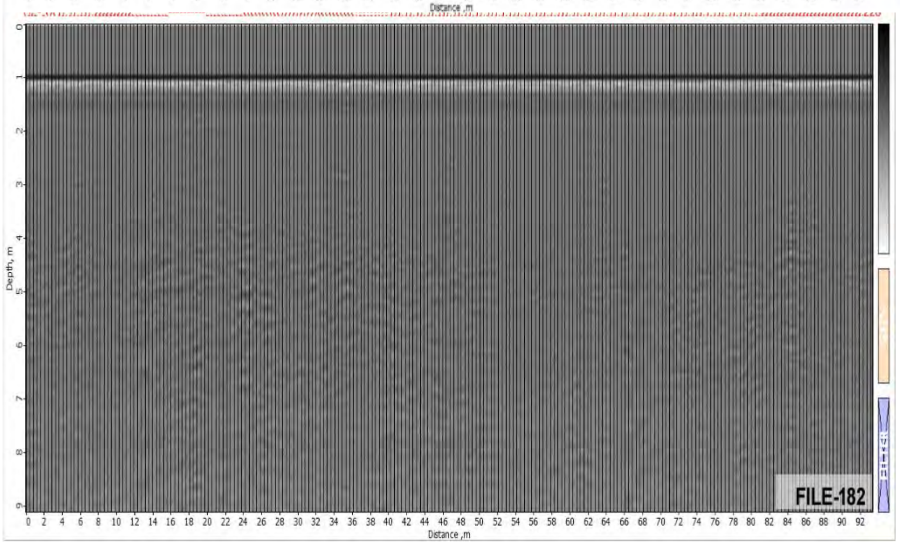

FILE-130

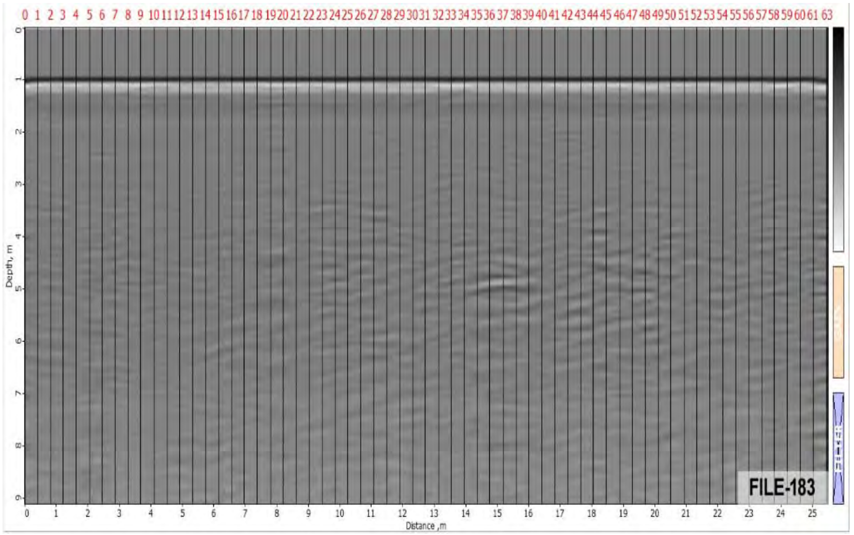

FILE-131

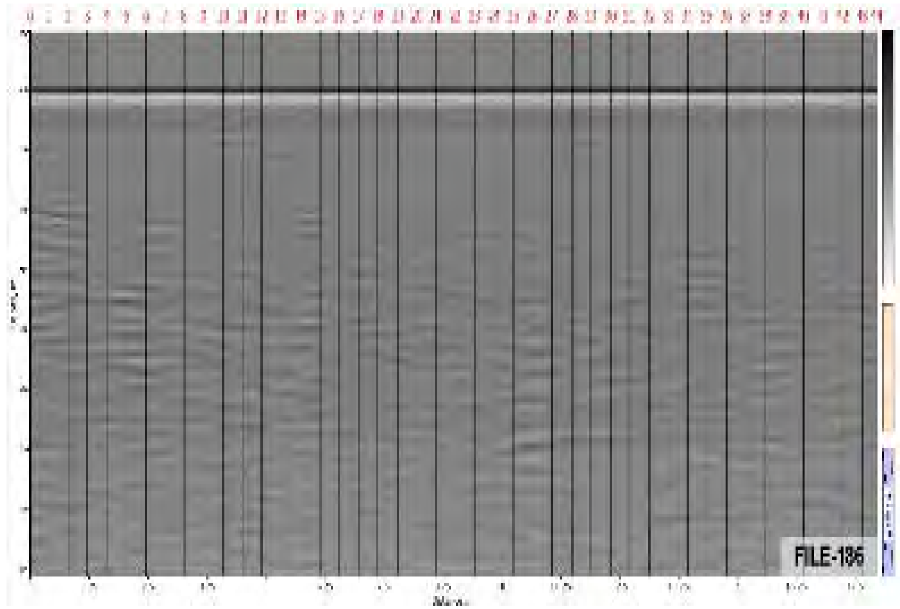
IMAGES OF GPR PROFILE SCANNED ALONG ERT- 4

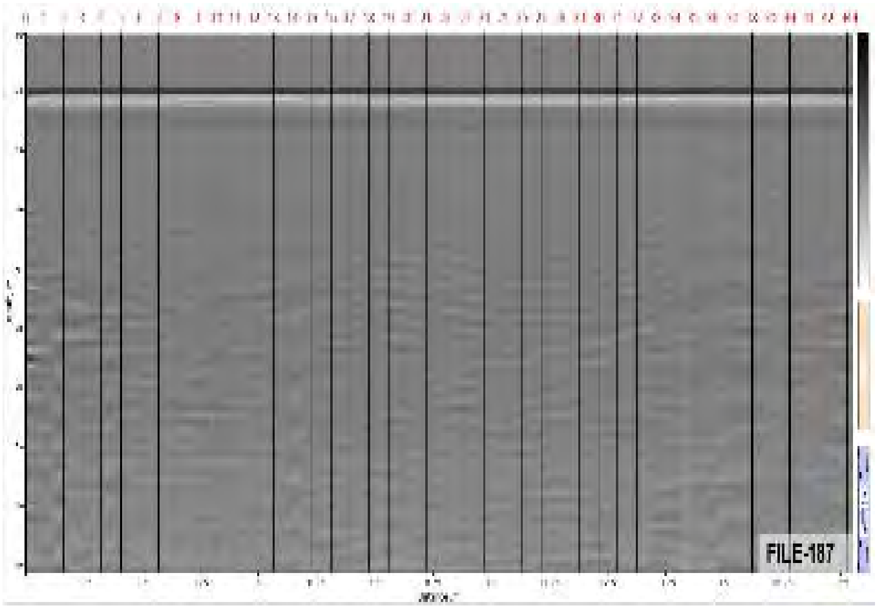


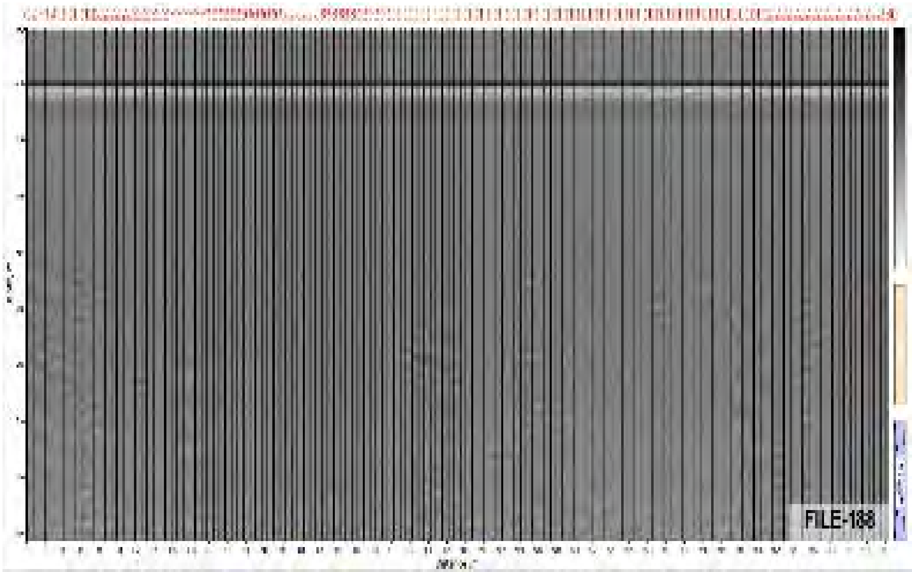


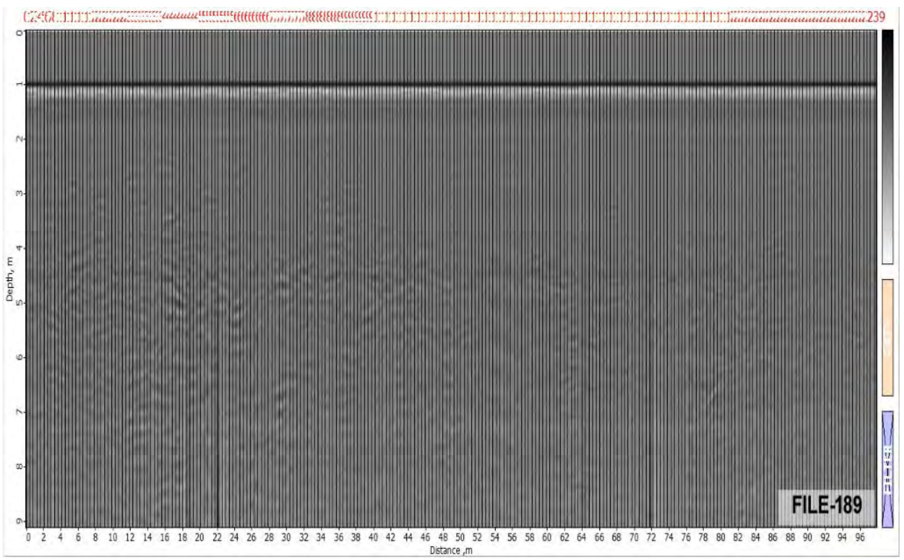


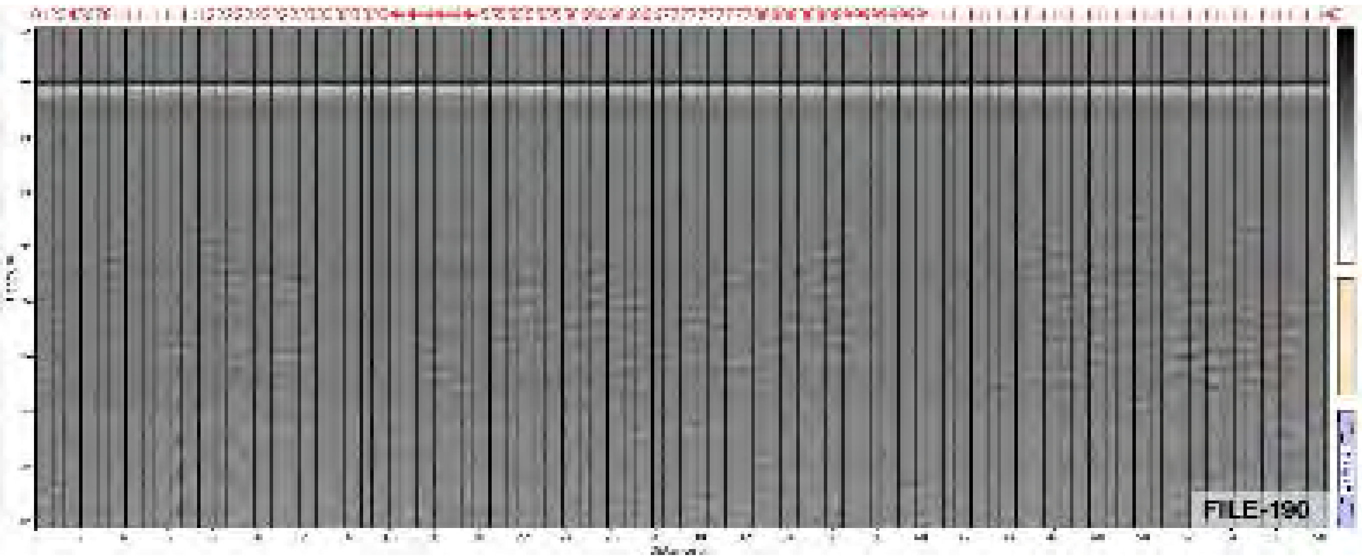



FILE-186

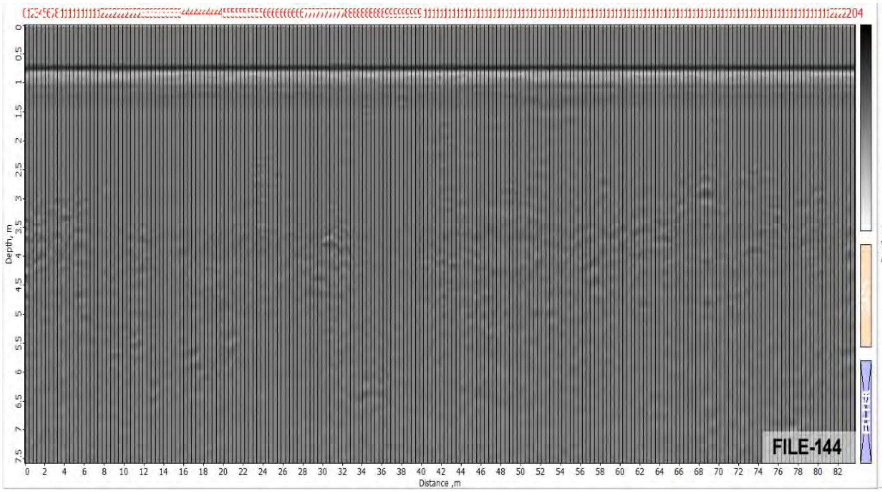

FILE-187

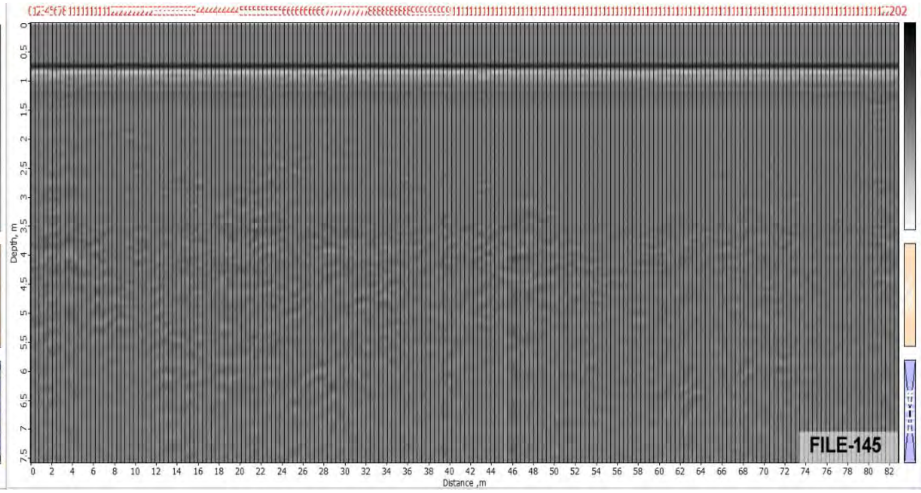

FILE-188

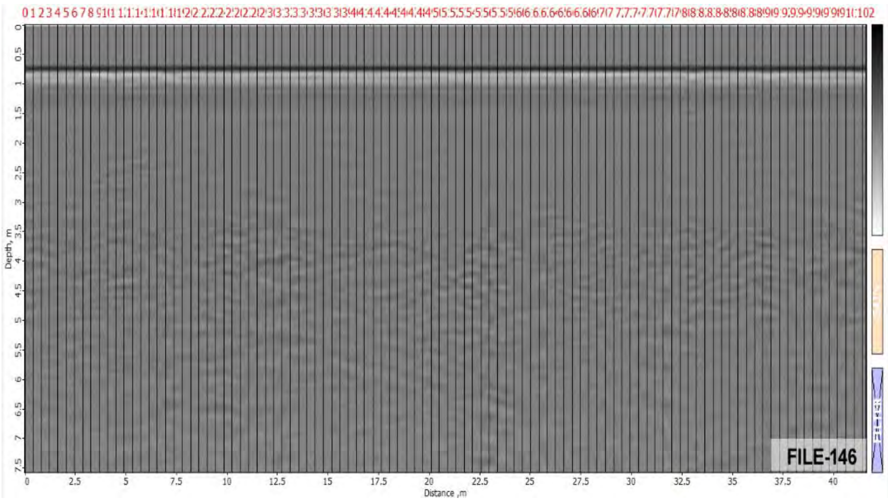

Depth, m
Distance ,m
FILE-189

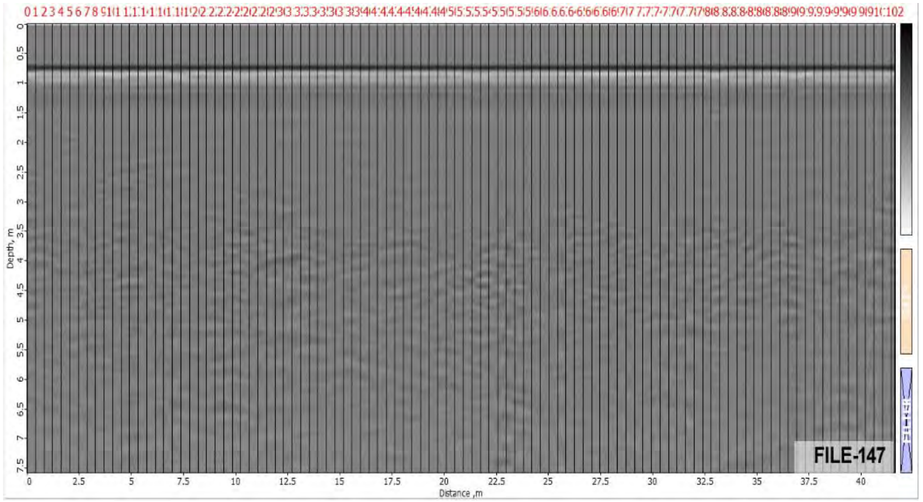

FILE-190

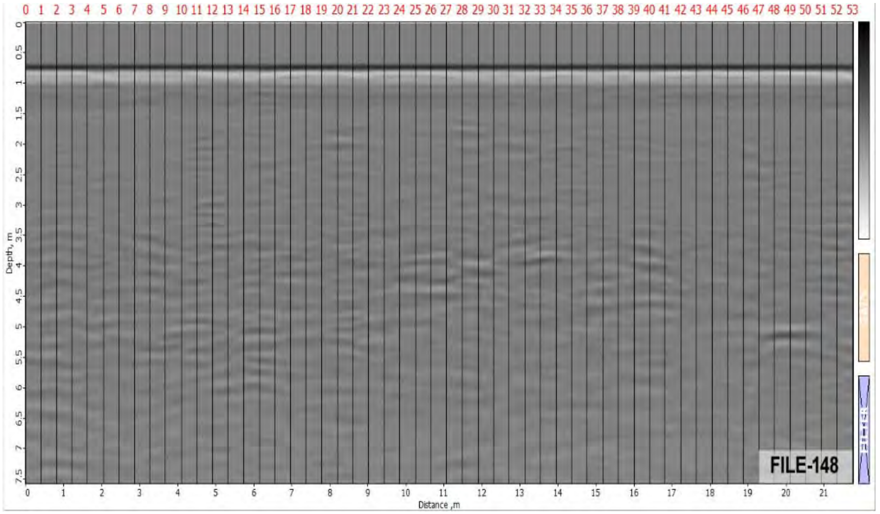
IMAGES OF GPR PROFILE SCANNED ALONG ERT- 5

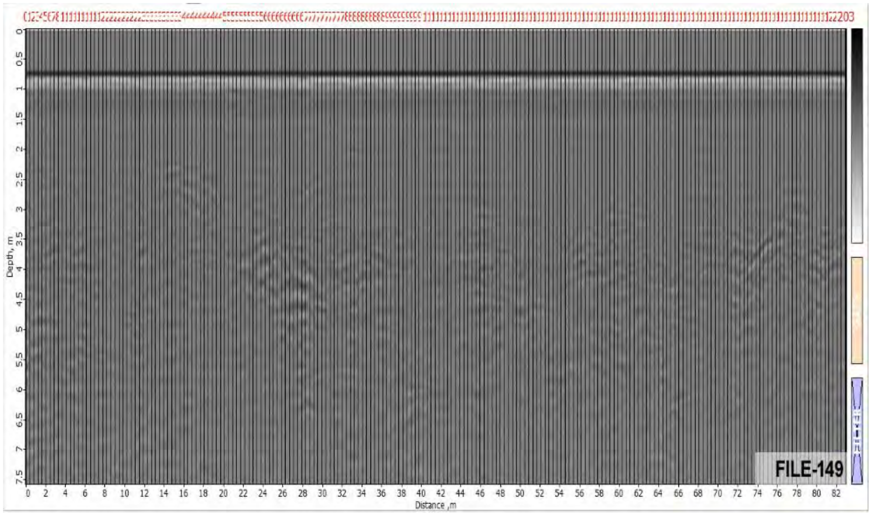




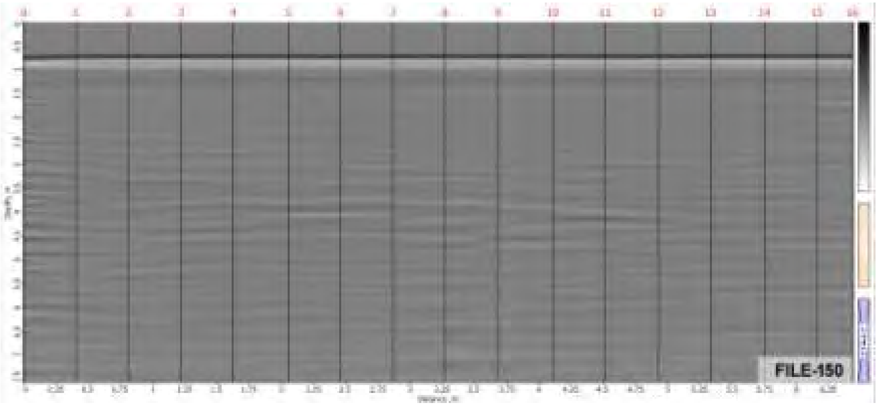


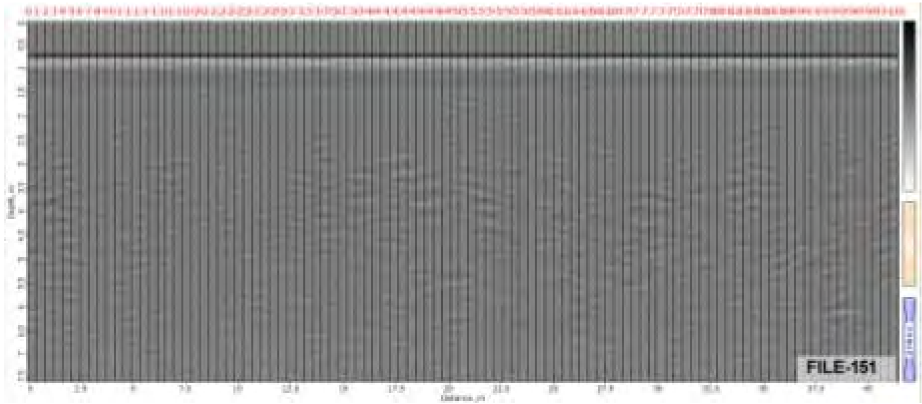


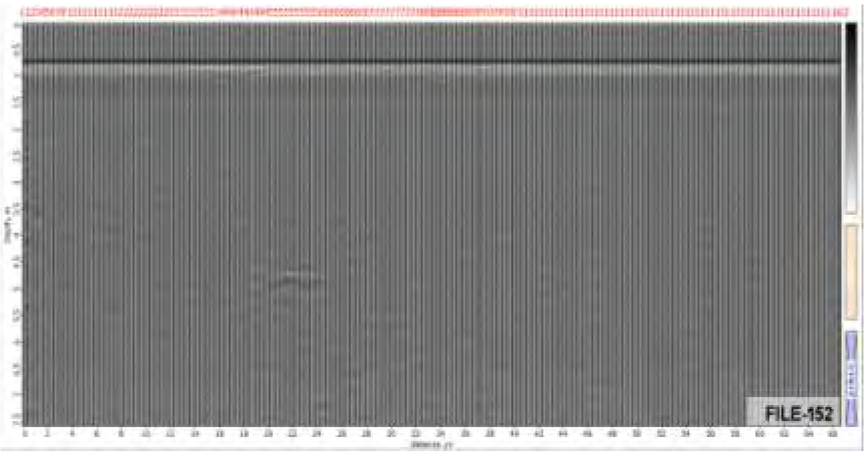

FILE-148
Depth, m
Distance ,m

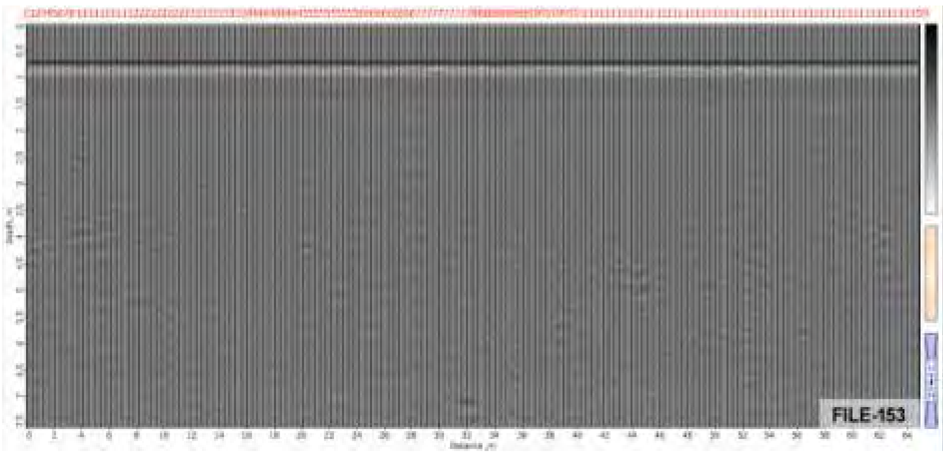

FILE-149
Depth, m
Distance ,m

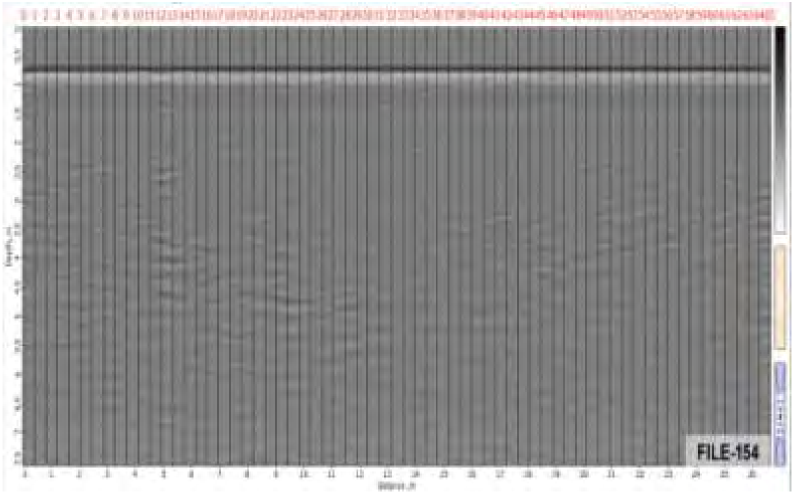
GPR PROFILES ALONG THE ERT LINE-6 APPENDIX-I

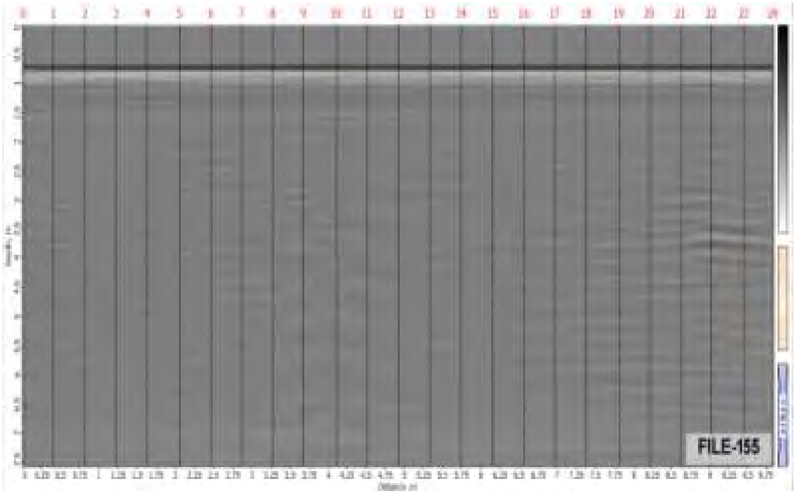


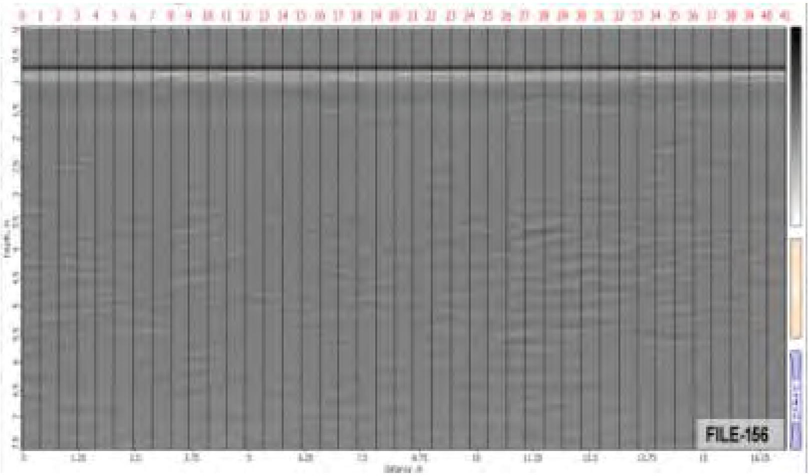


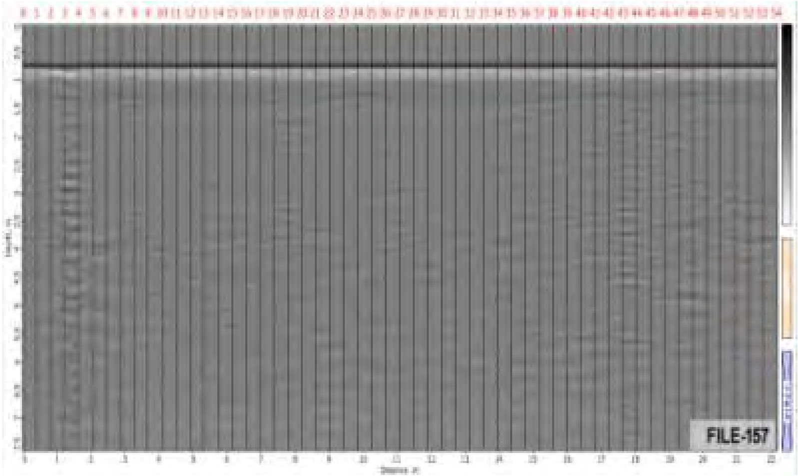


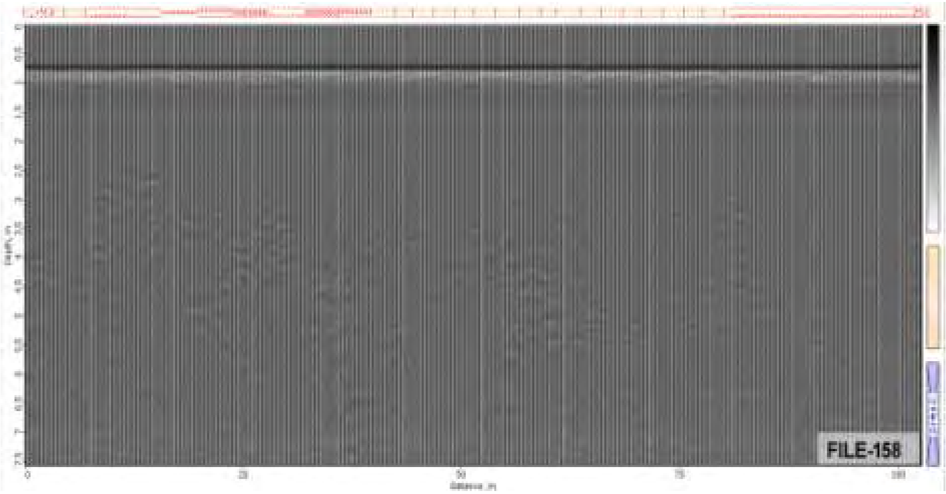



FILE-154

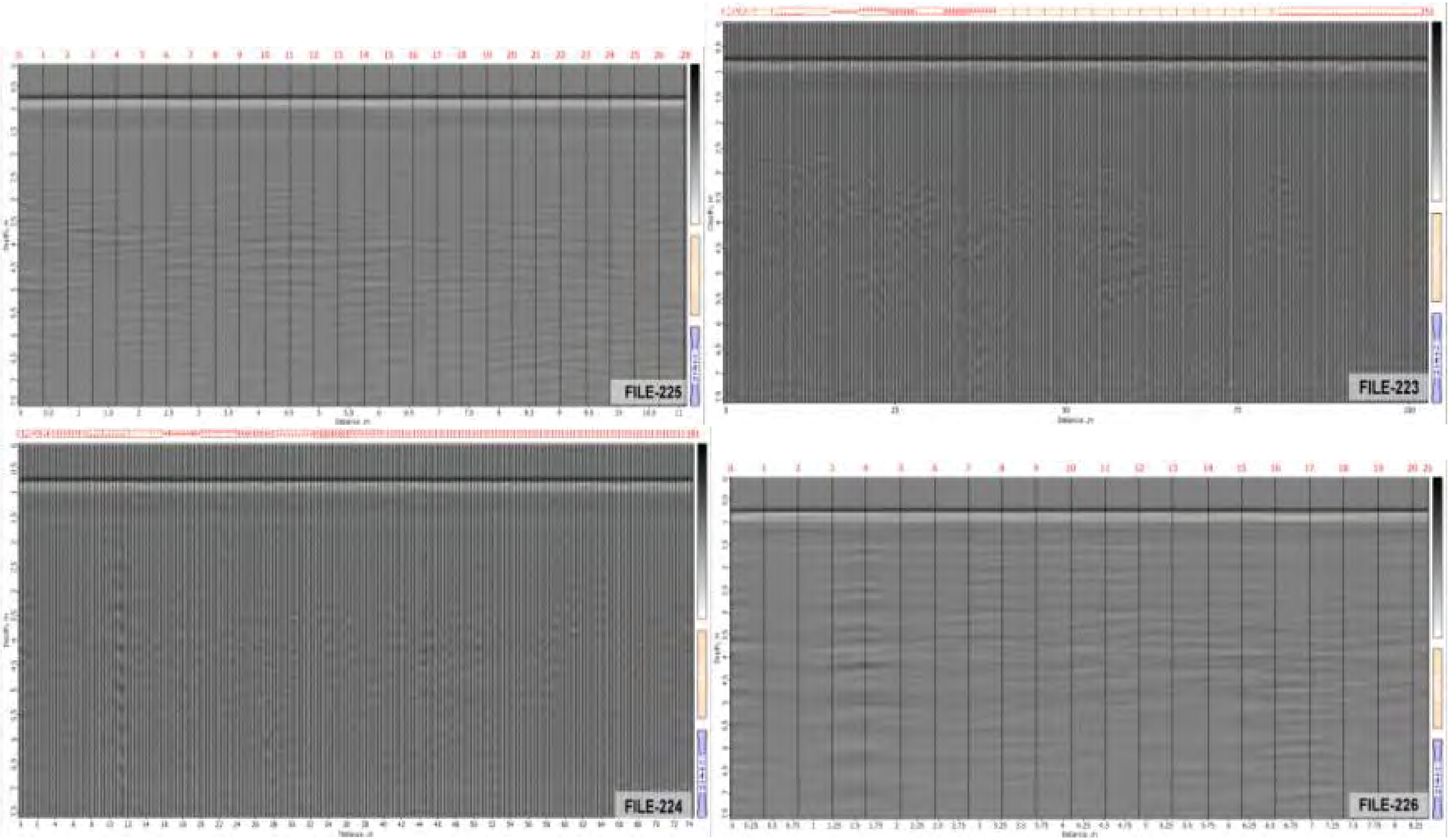

FILE-155

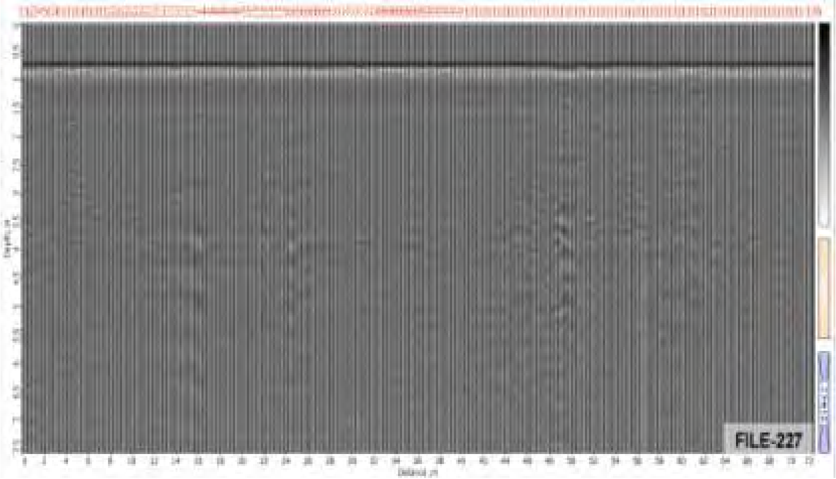

FILE-156

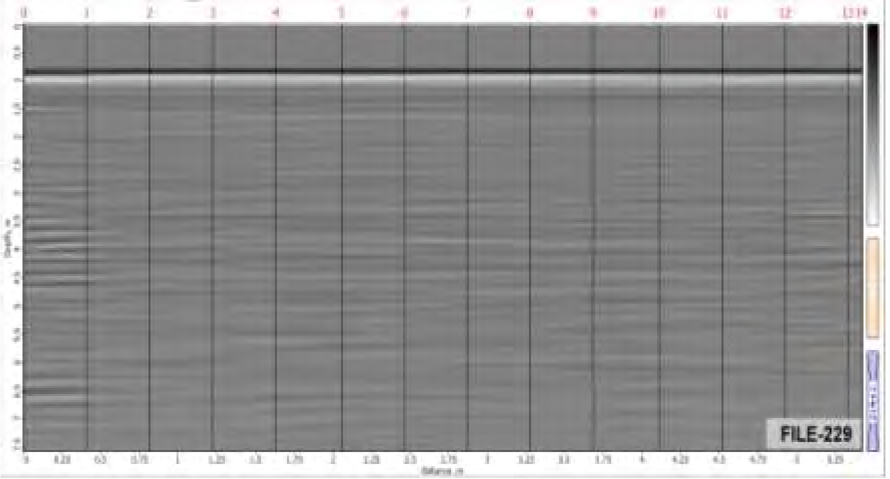

FILE-157

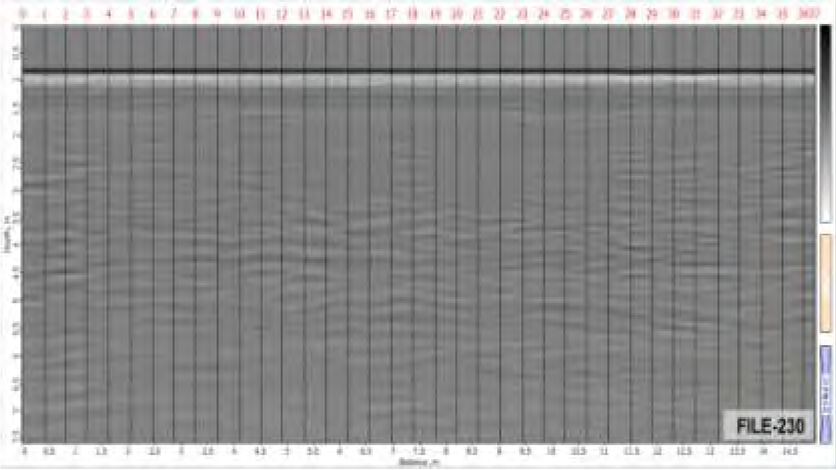

FILE-158

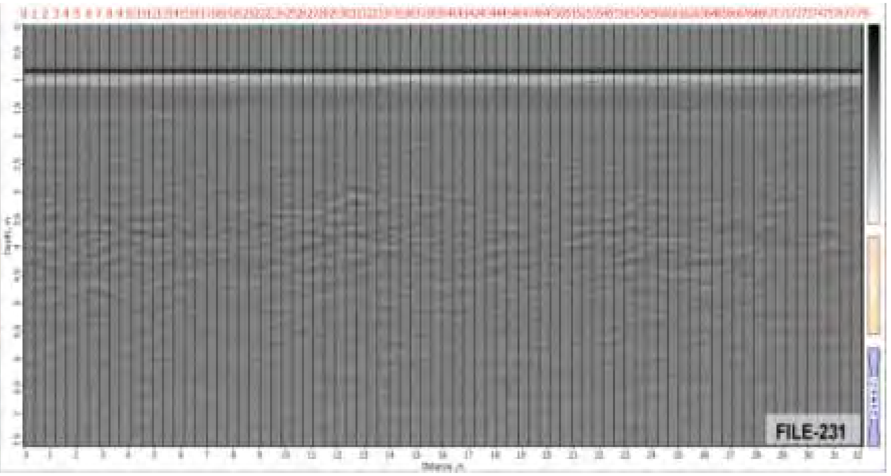
GPR PROFILES ALONG THE ERT LINE-7

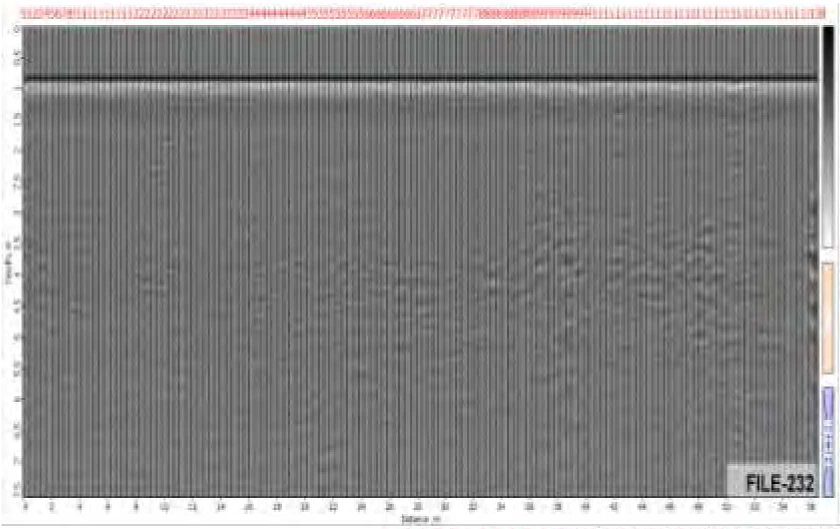


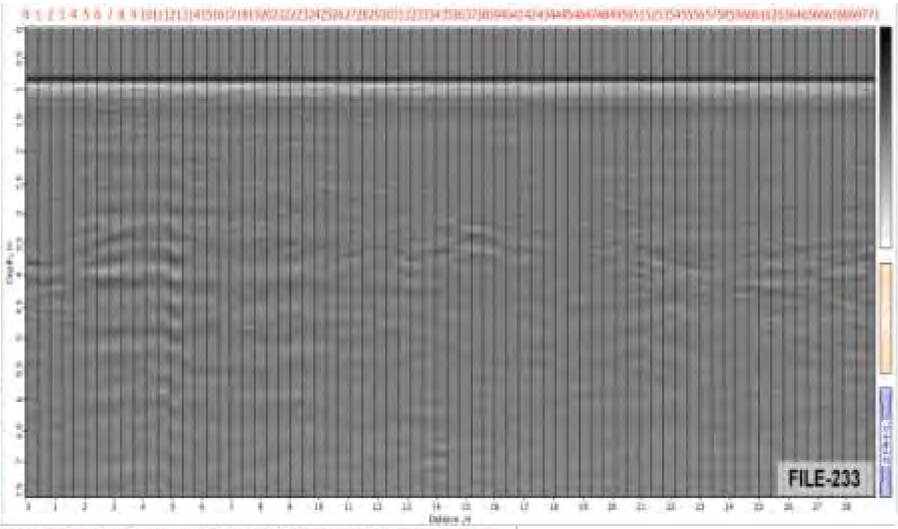

FILE-227

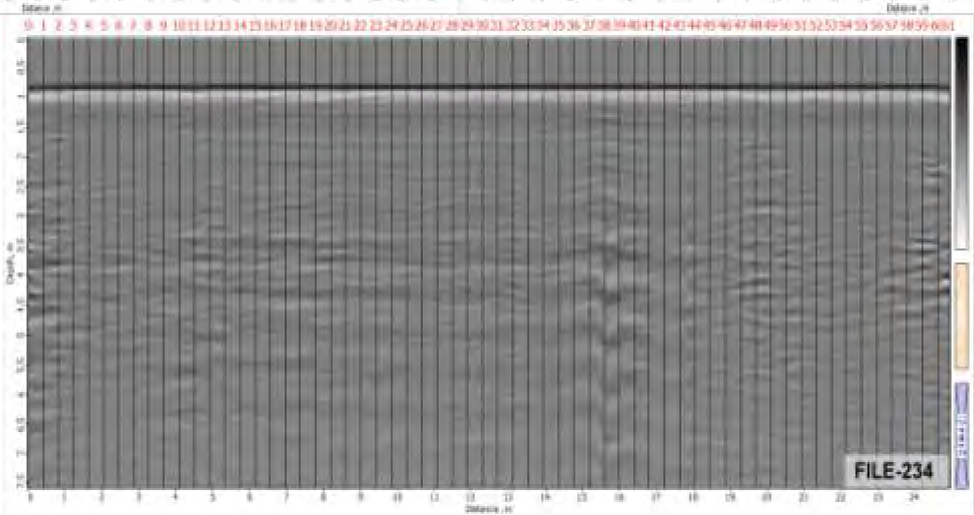

FILE-229


FILE-230

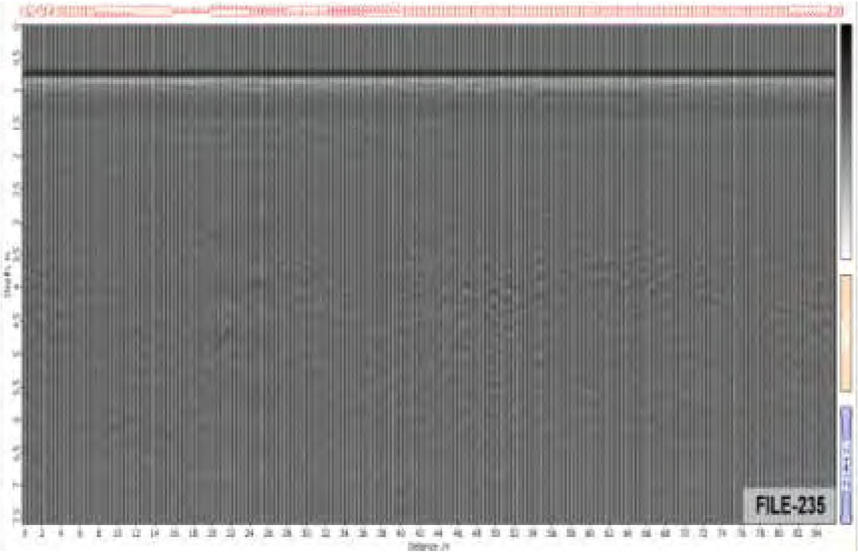

FILE-231

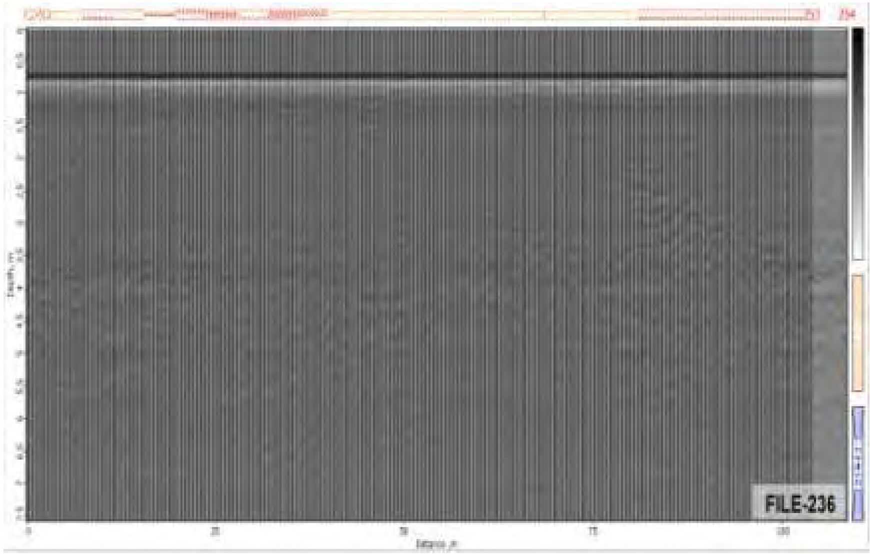

FILE-232

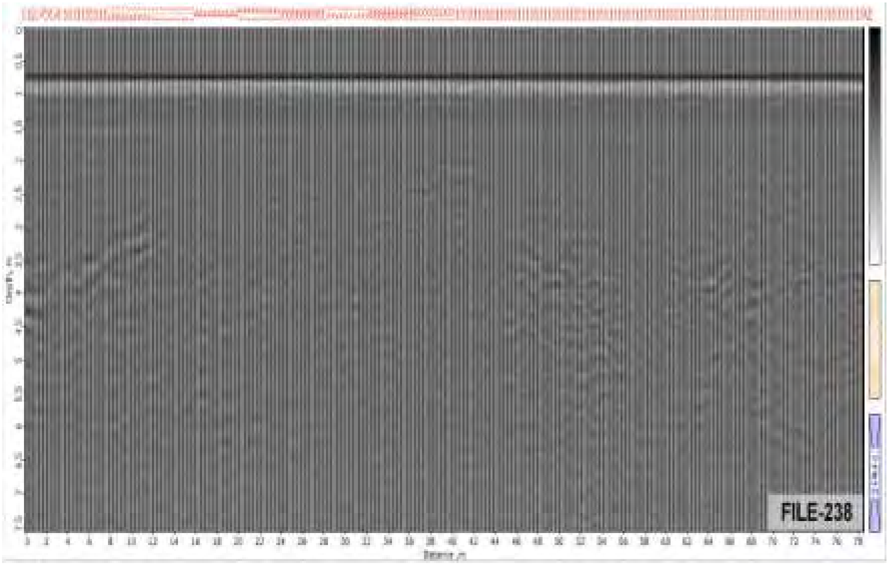

FILE-233

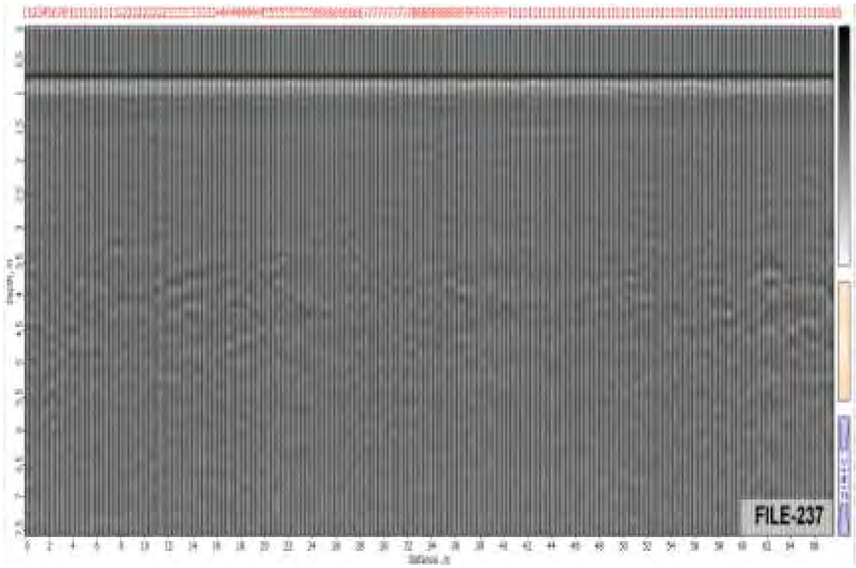

FILE-234

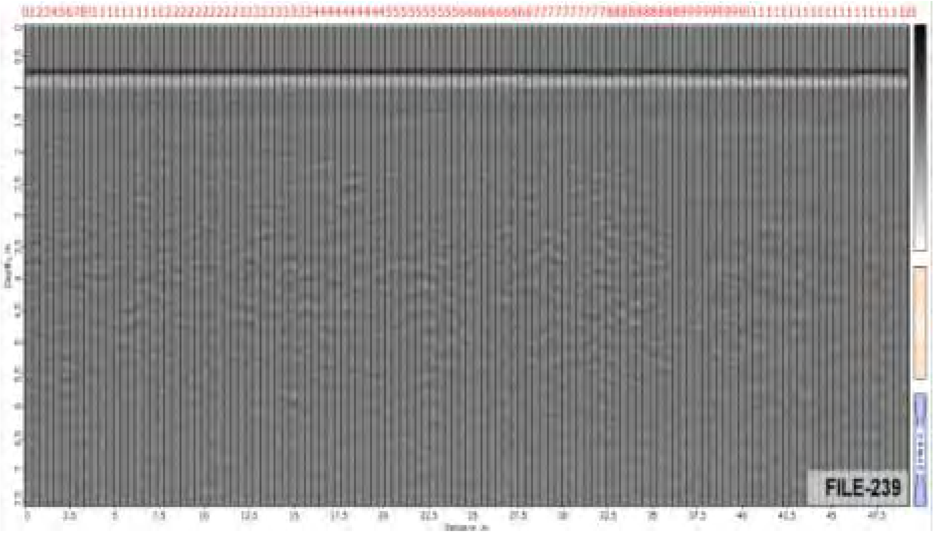
GPR PROFILES ALONG THE ERT LINE-8



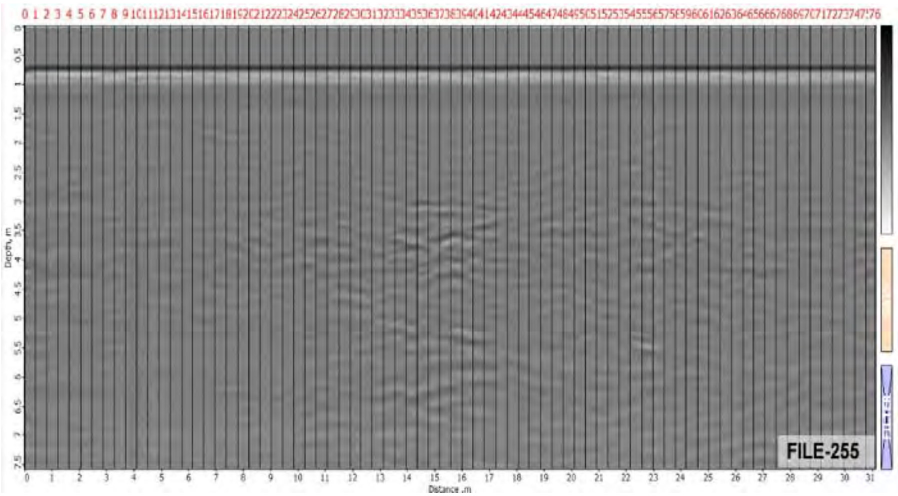


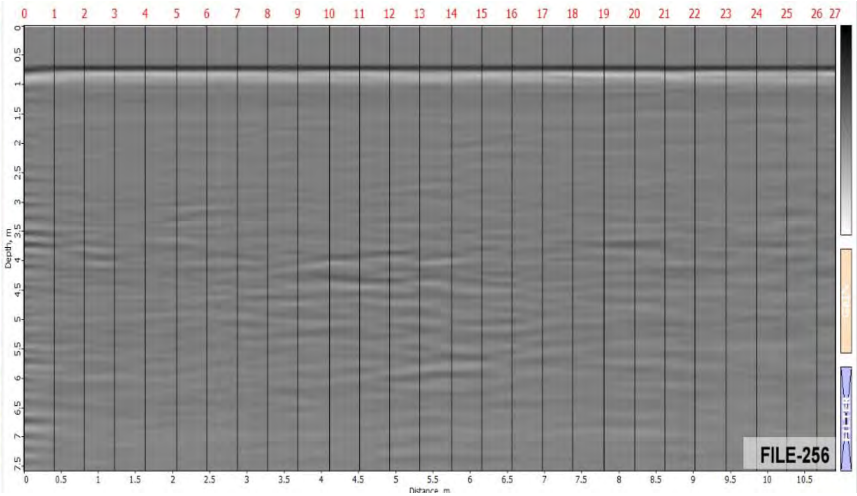


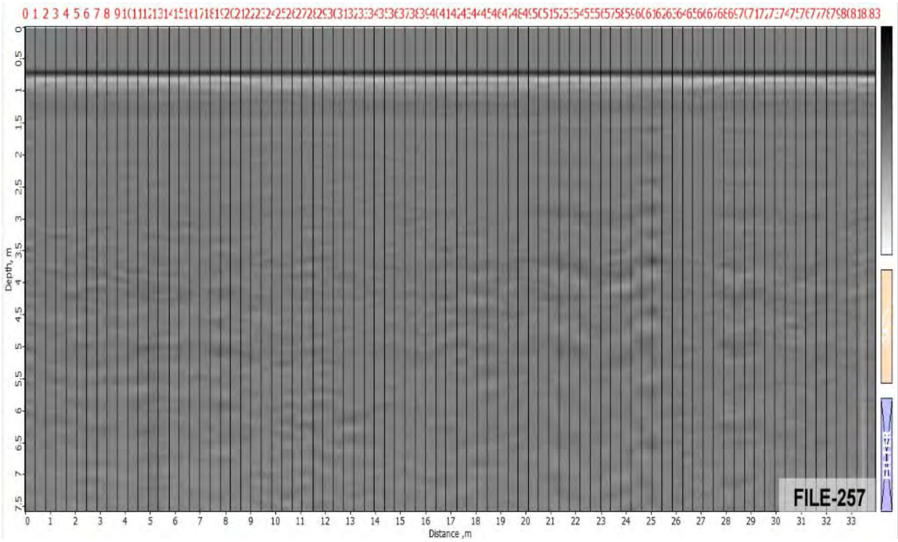


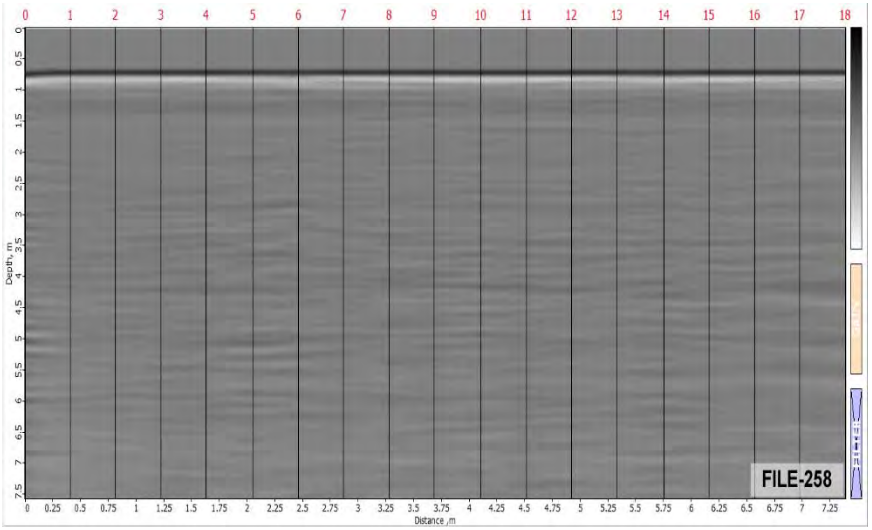

FILE-239

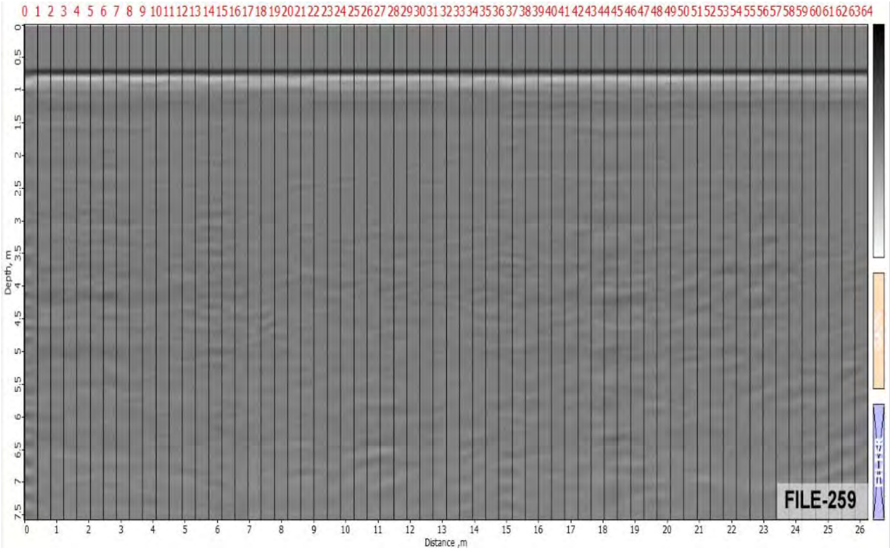
IMAGES OF GPR PROFILE SCANNED ALONG ERT-9

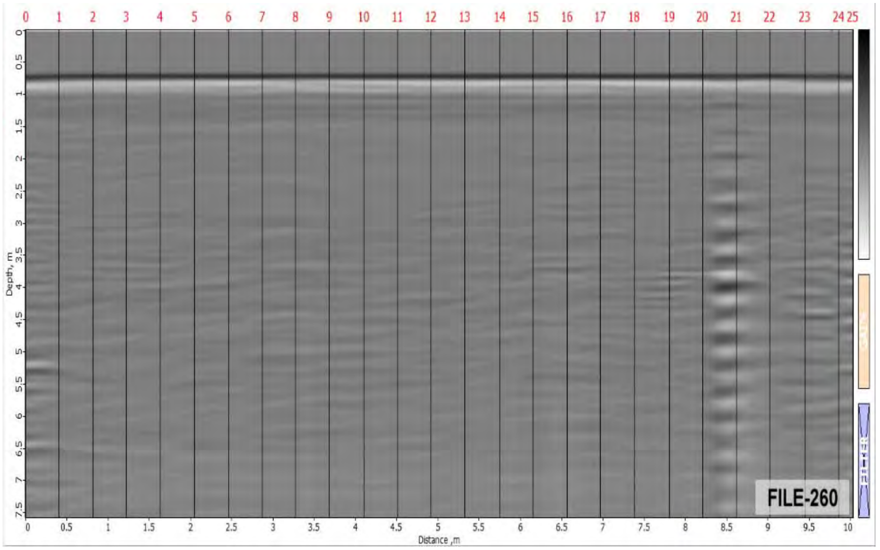


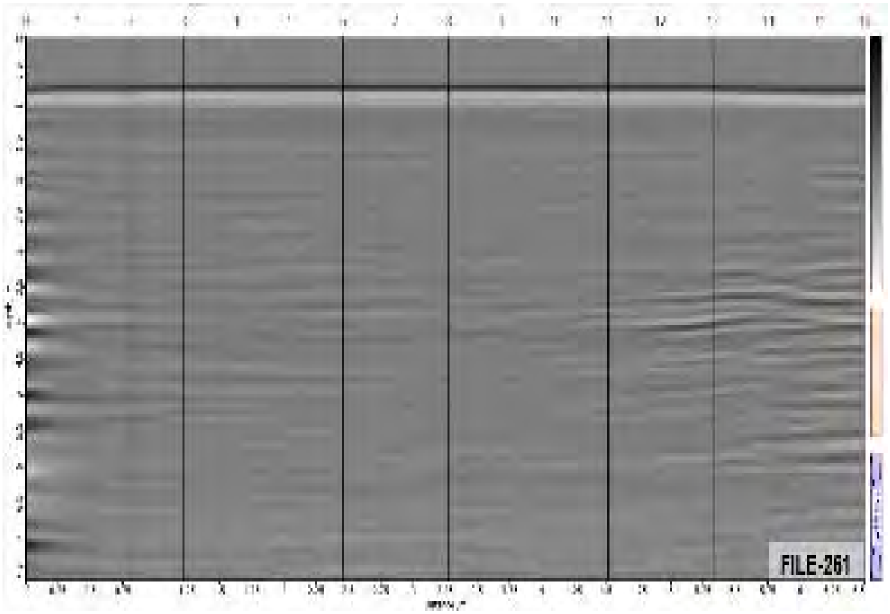


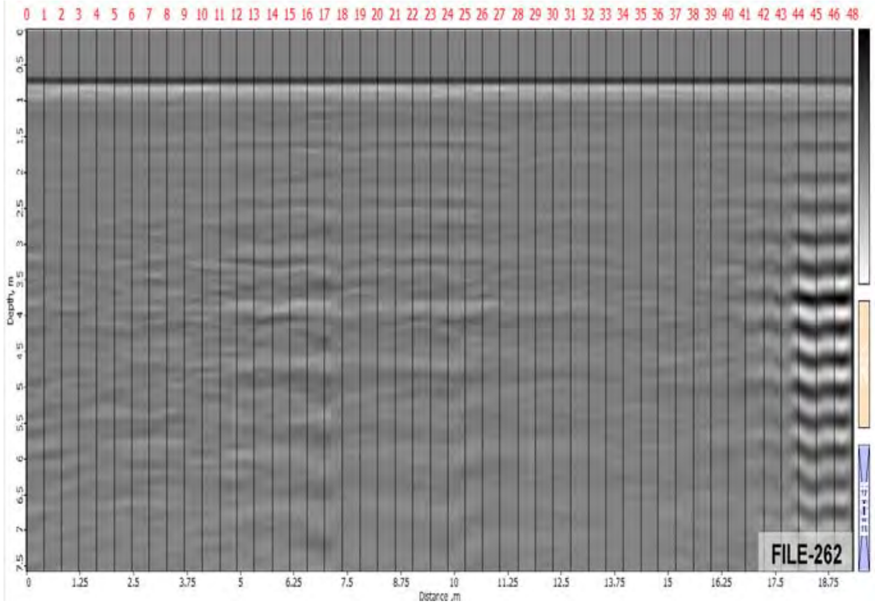


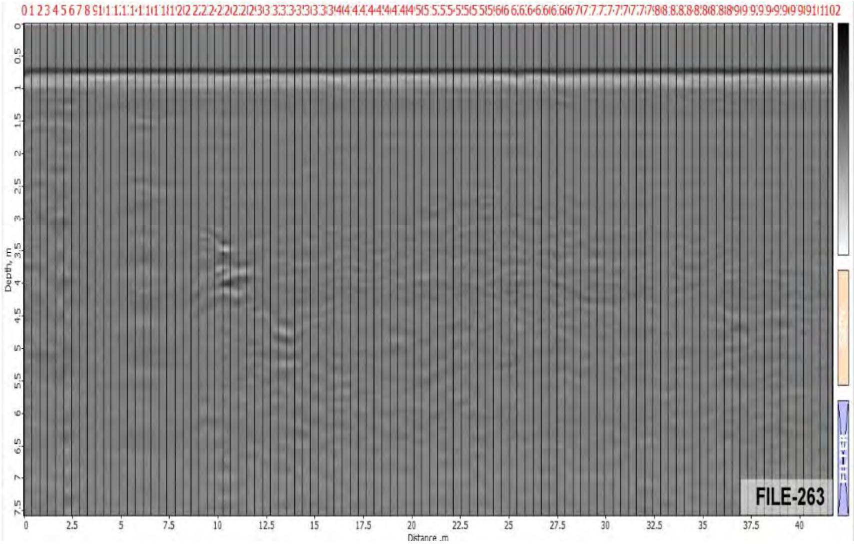


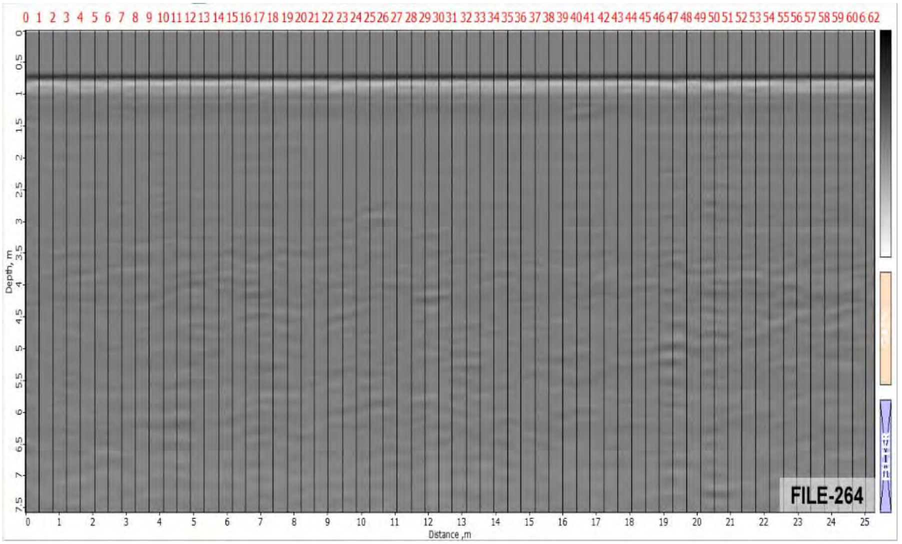

Depth, m
Distance ,m
FILE-259

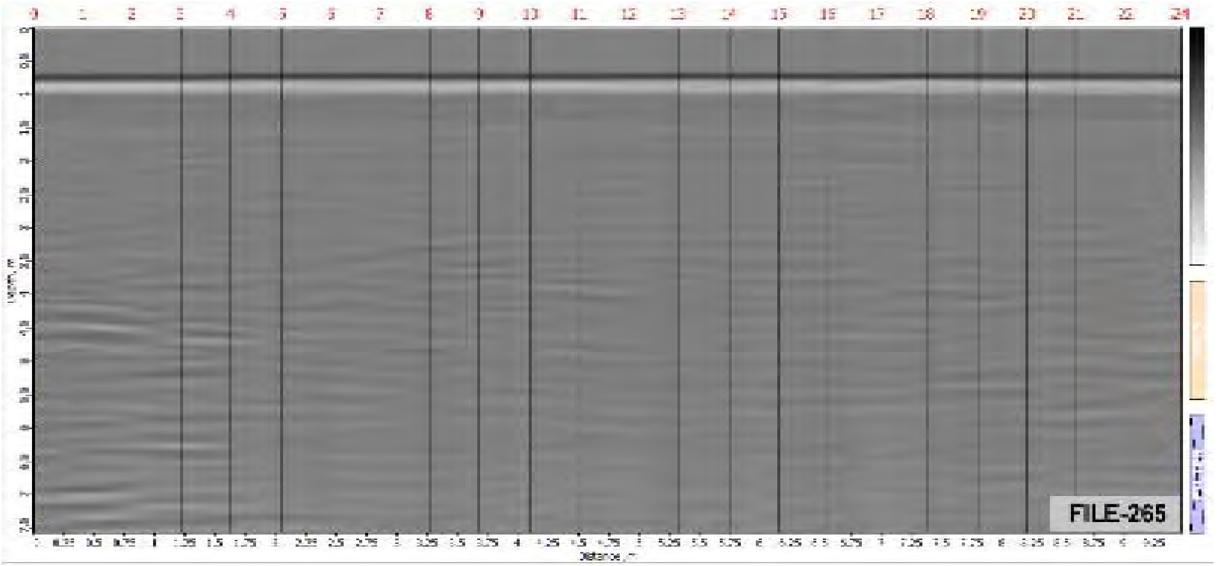

Depth, m
Distance ,m
FILE-260


FILE-261

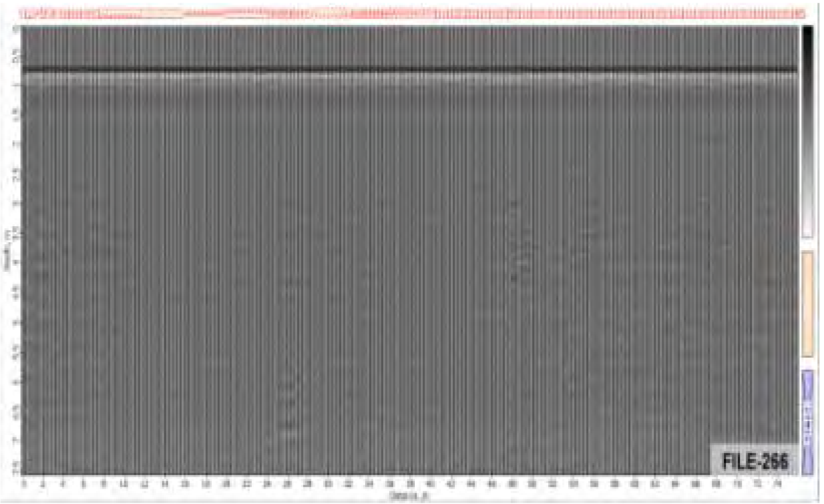

Depth, m
Distance ,m
FILE-262

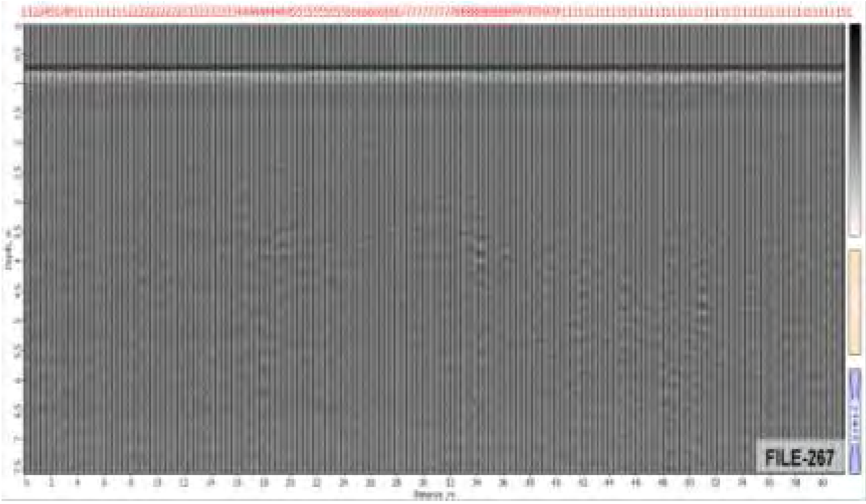

FILE-263
Depth, m
Distance ,m

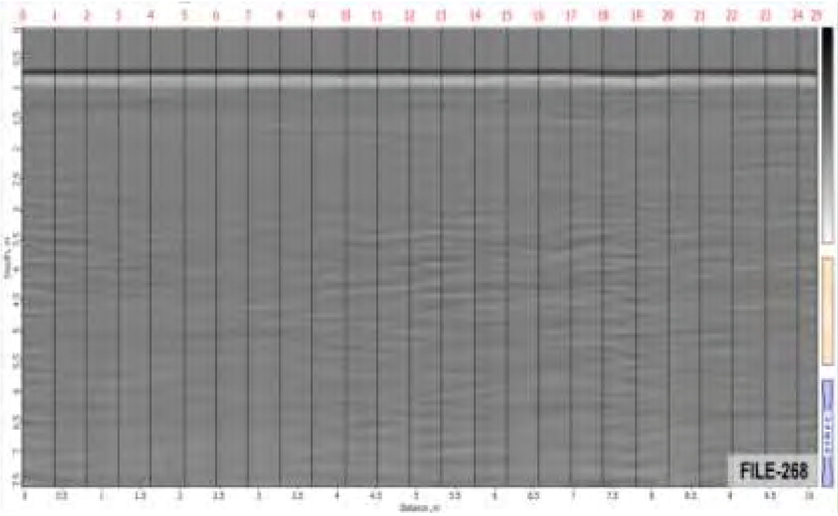

FILE-264
Depth, m
Distance ,m

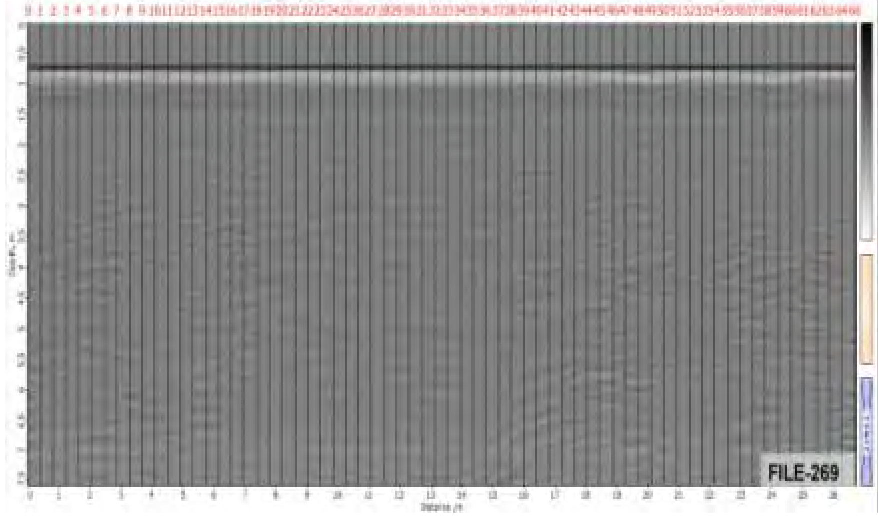

FILE-265

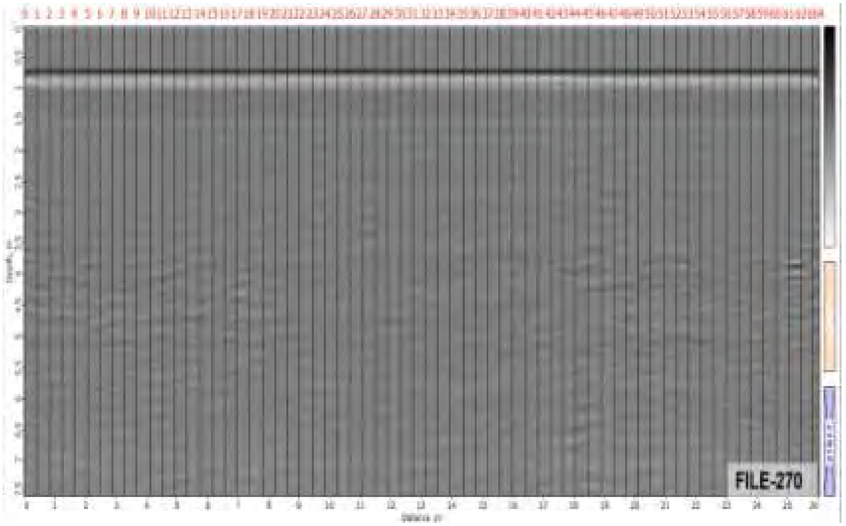
GPR PROFILES ALONG THE ERT LINE-10

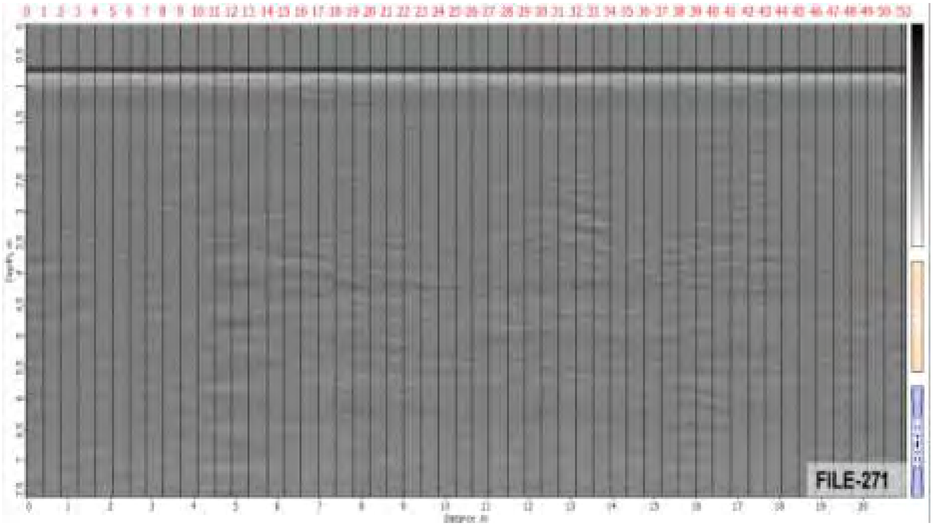


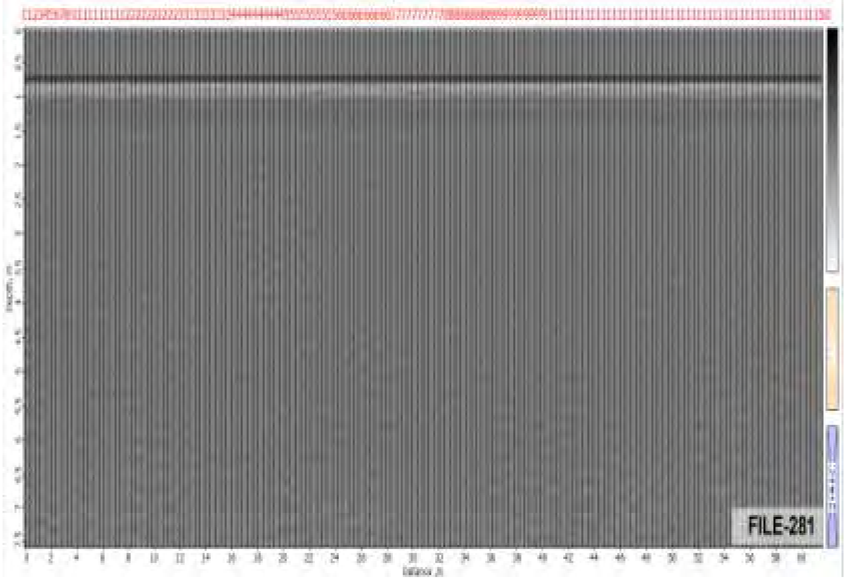


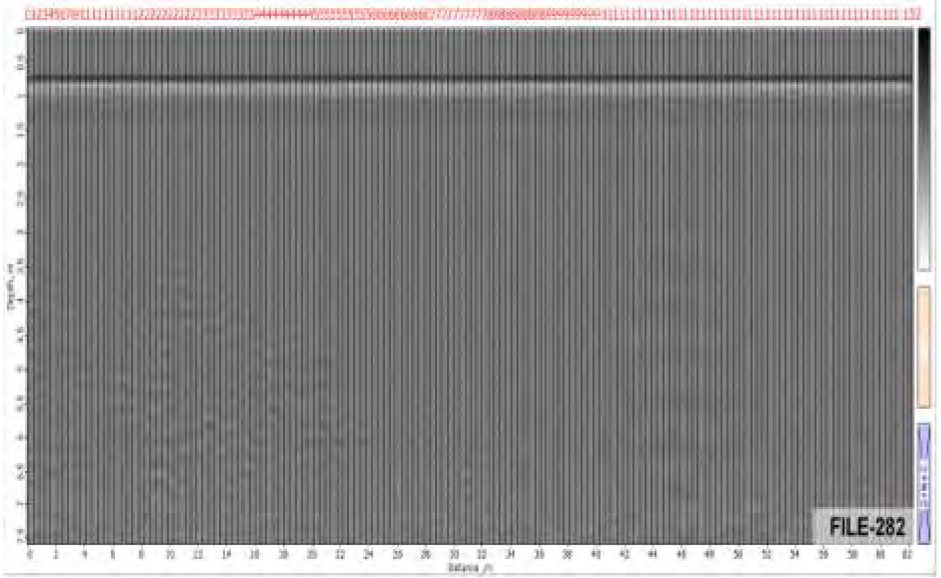


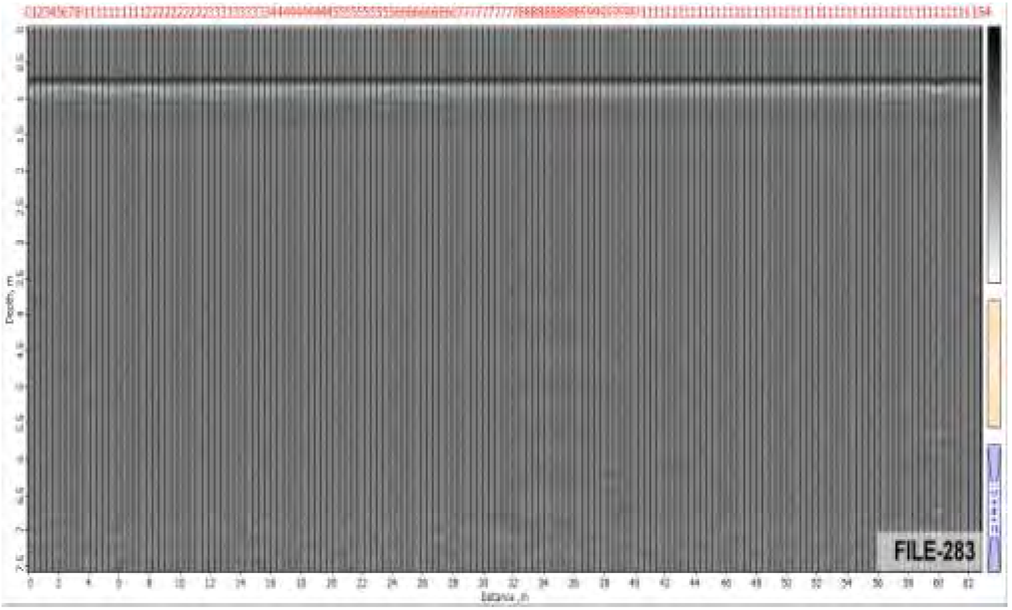



FILE-270


FILE-271


FILE-281

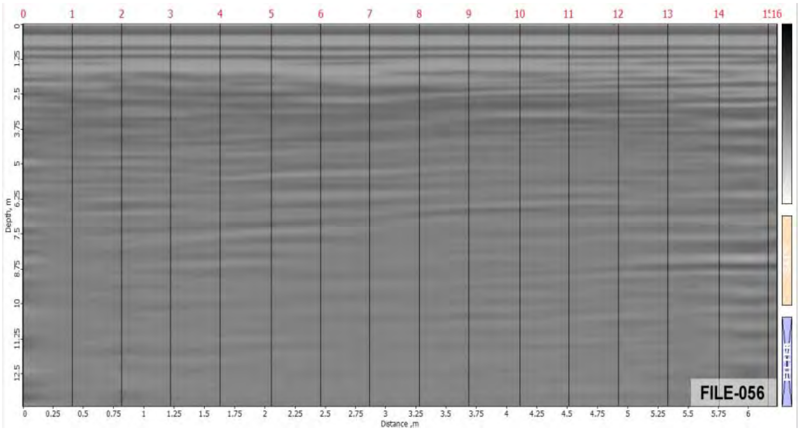

FILE-282

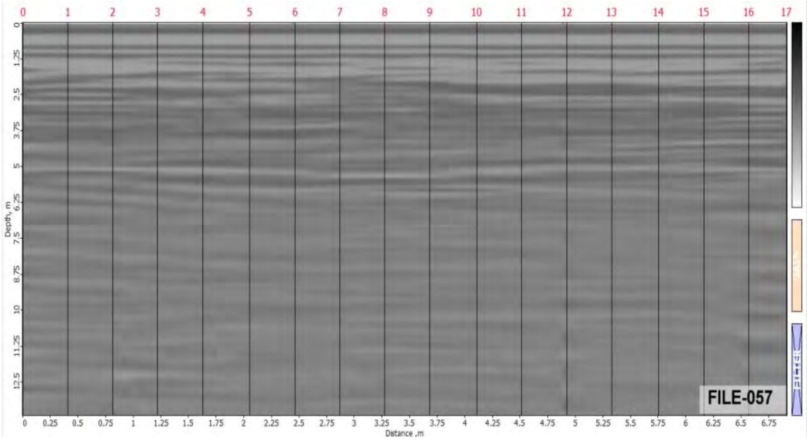

FILE-283
Depth, m
Distance, m

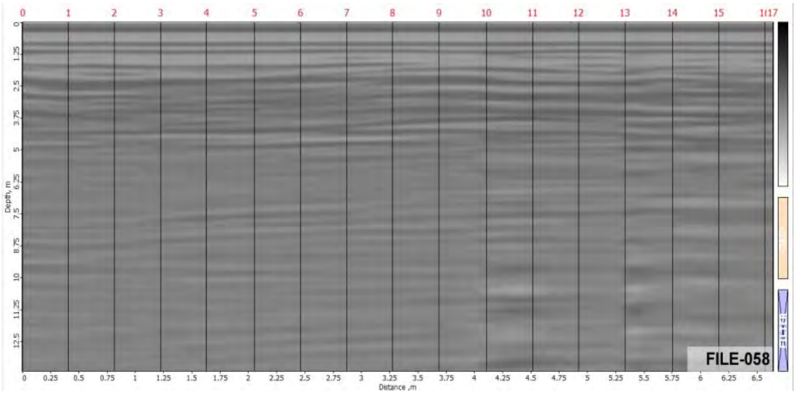
Annexure-V

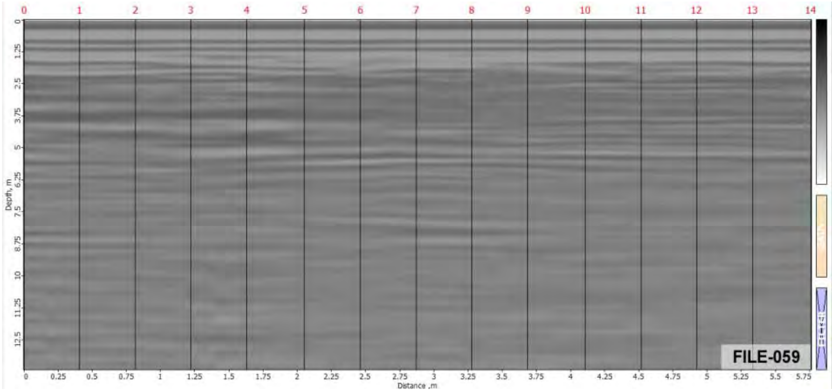
GPR PROFILES WITH 100 MHz ANTENNA

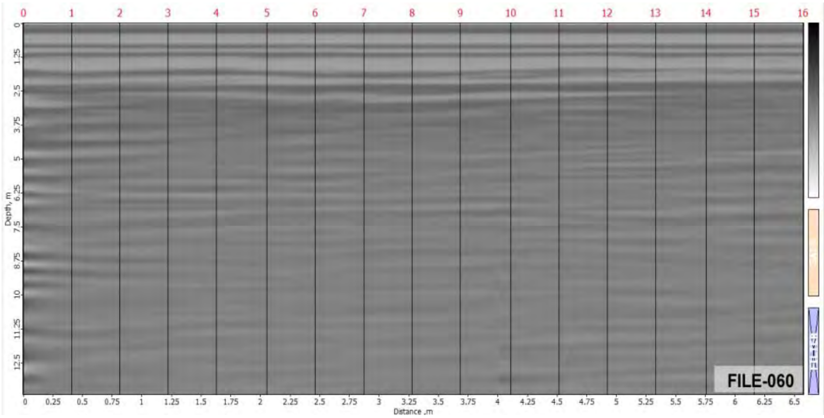
IMAGES OF GPR PROFILE SCANNED ACROSS ERT 1 ALIGNMENT WITH PRISM-2.59 SOFTWARE

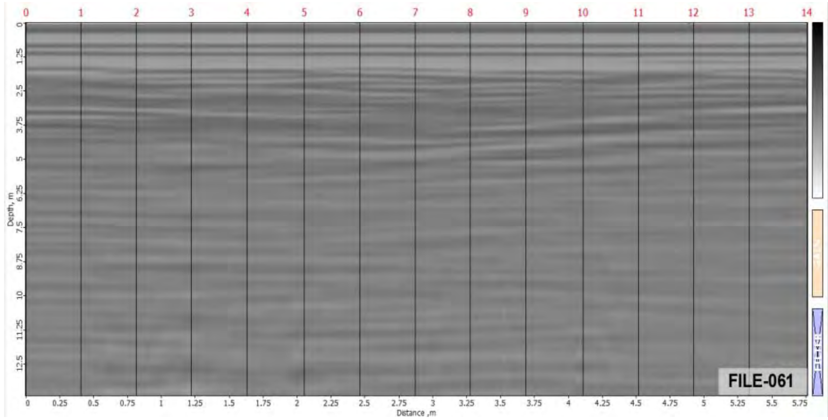


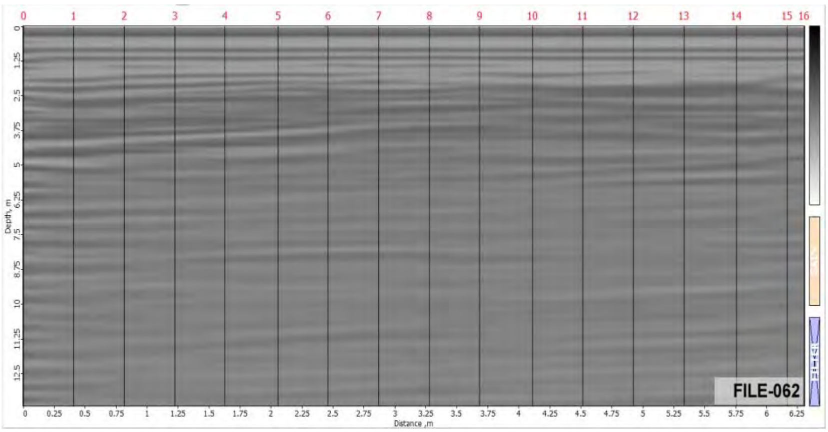


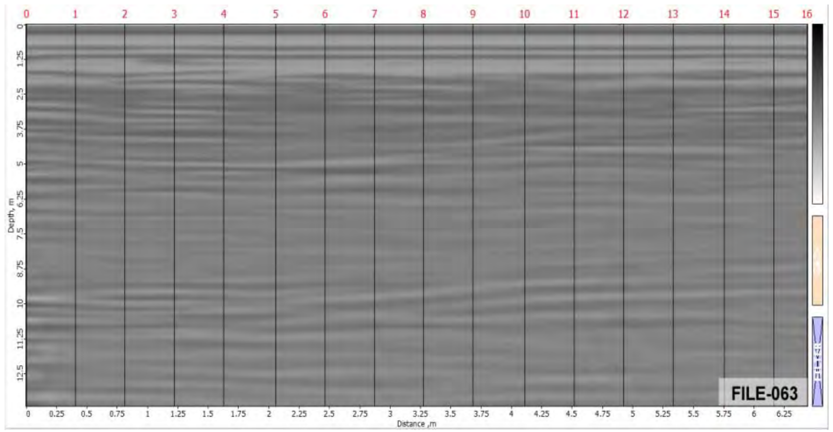


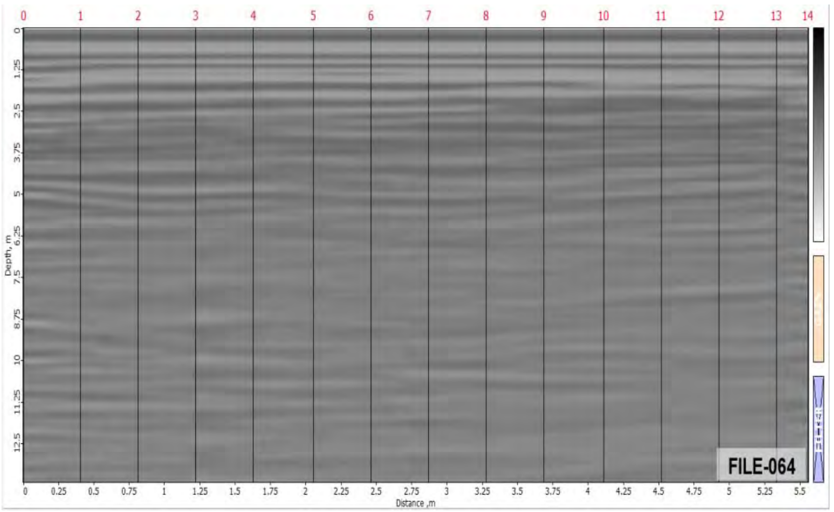


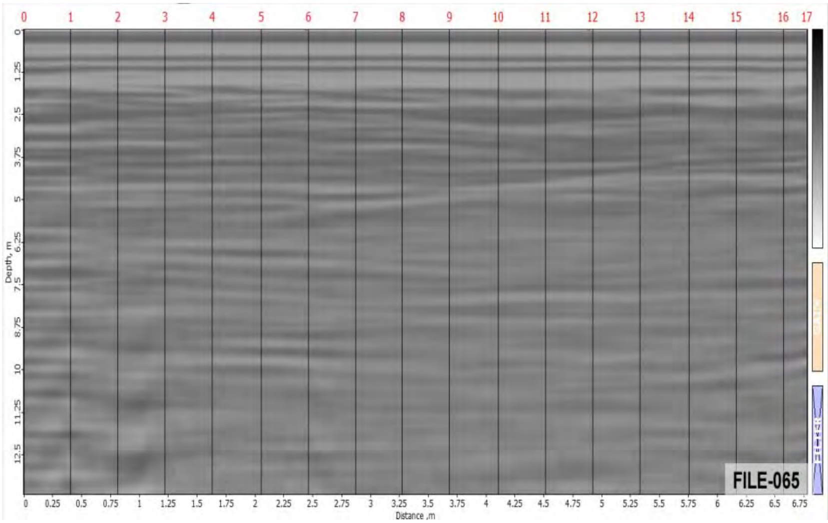

FILE-060

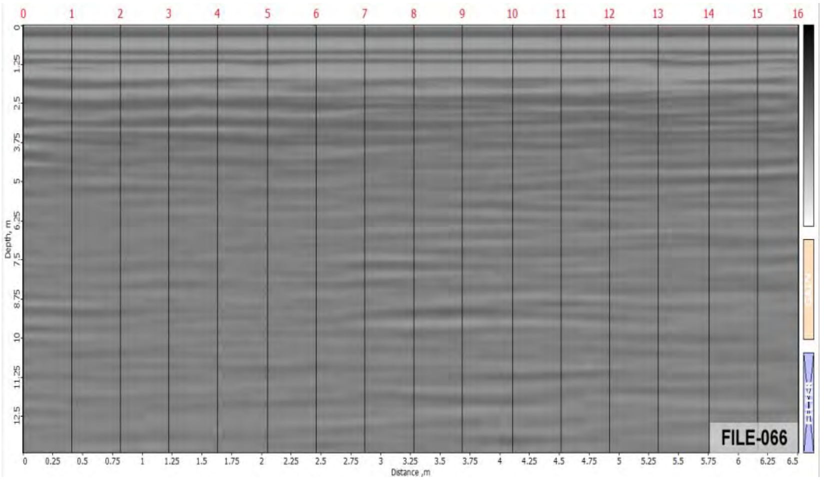

FILE-061


FILE-062


FILE-063


FILE-064
Depth, m
Distance ,m


FILE-065
Depth, m
Distance ,m


FILE-066
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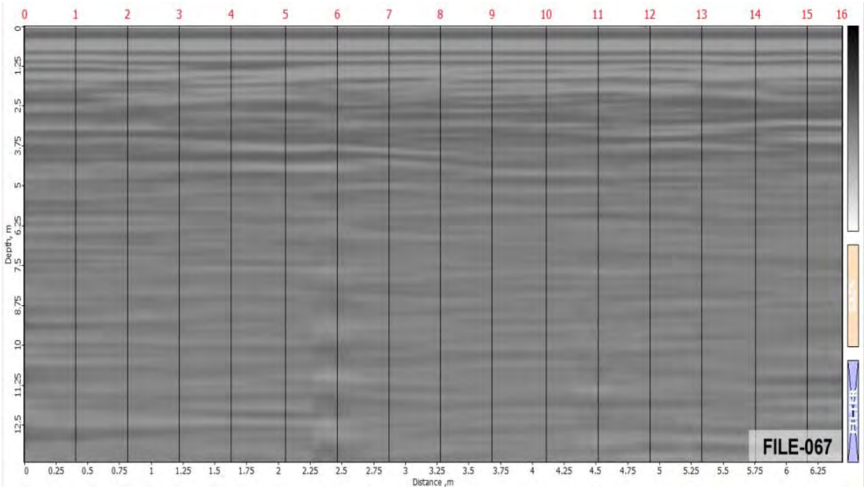
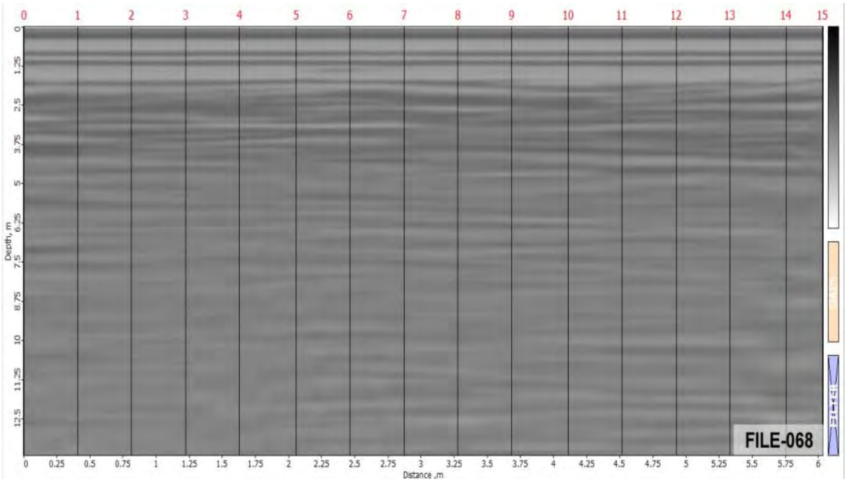
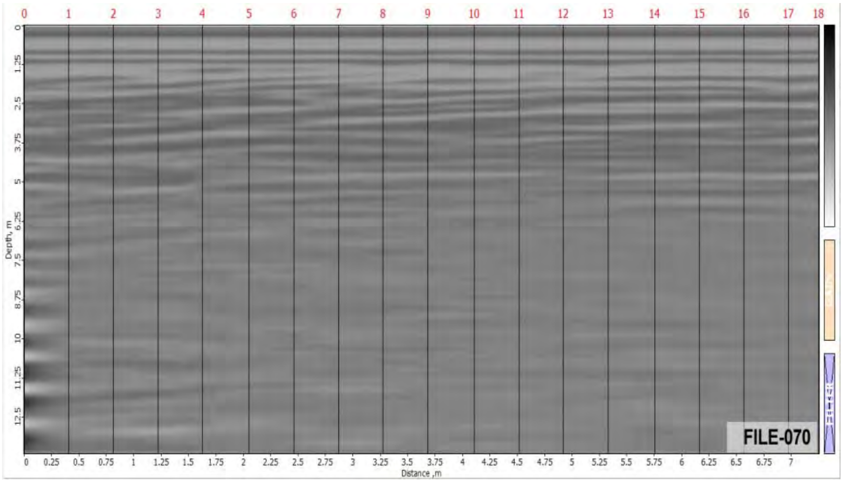
Distance ,m


FILE-067
Depth, m
Distance ,m


FILE-068
Depth, m
Distance ,m


FILE-070
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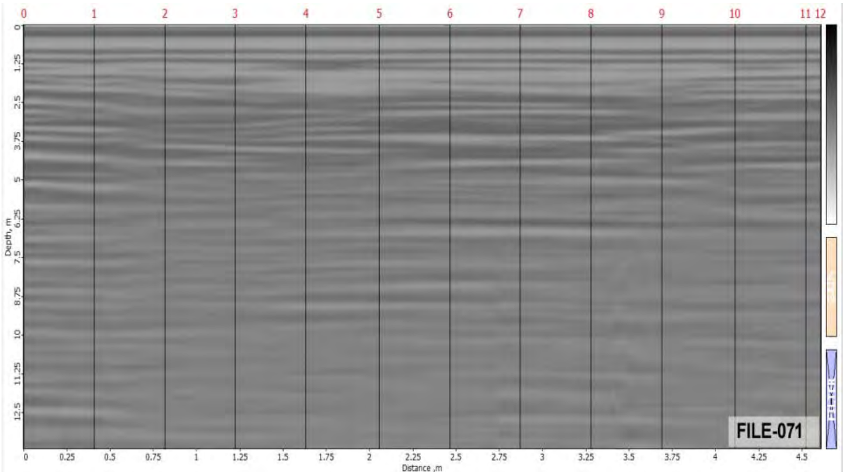
FILE-071
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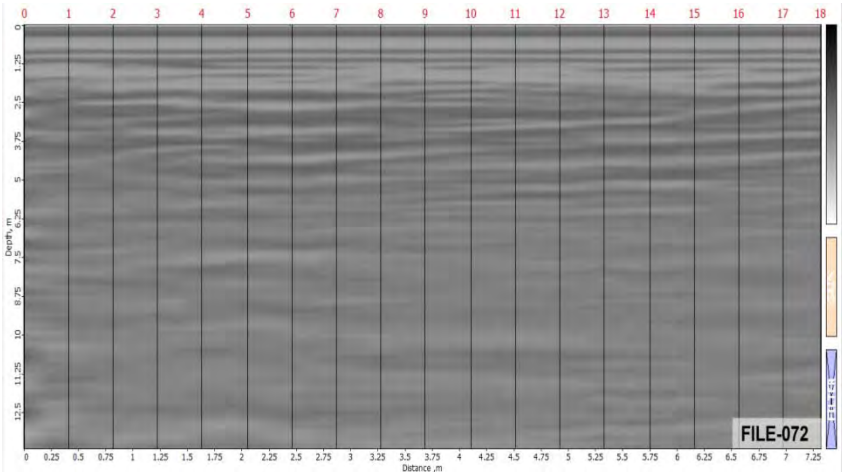
Distance ,m


FILE-072
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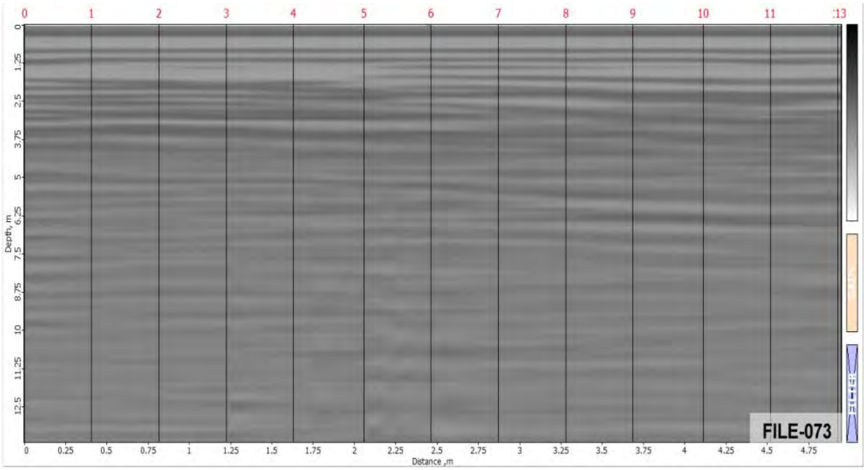
Distance ,m


FILE-073
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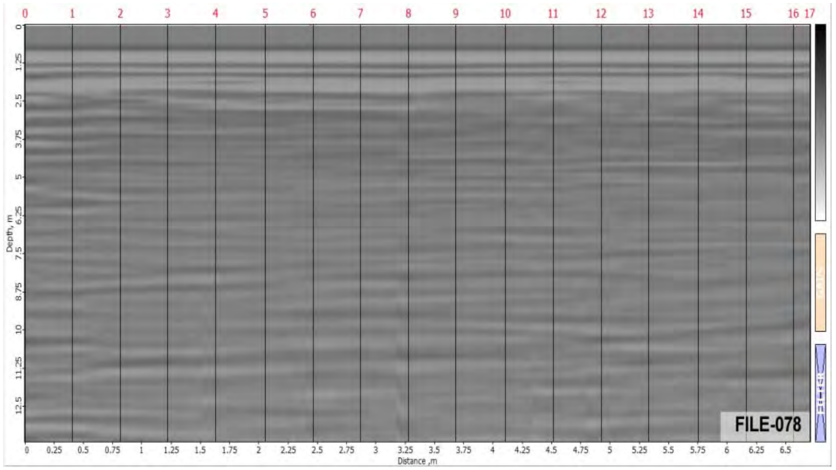
Distance ,m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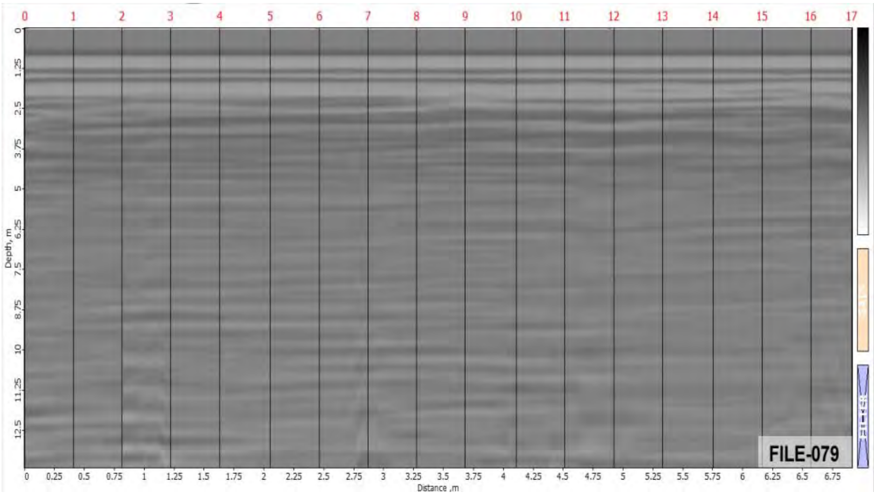
FILE-079
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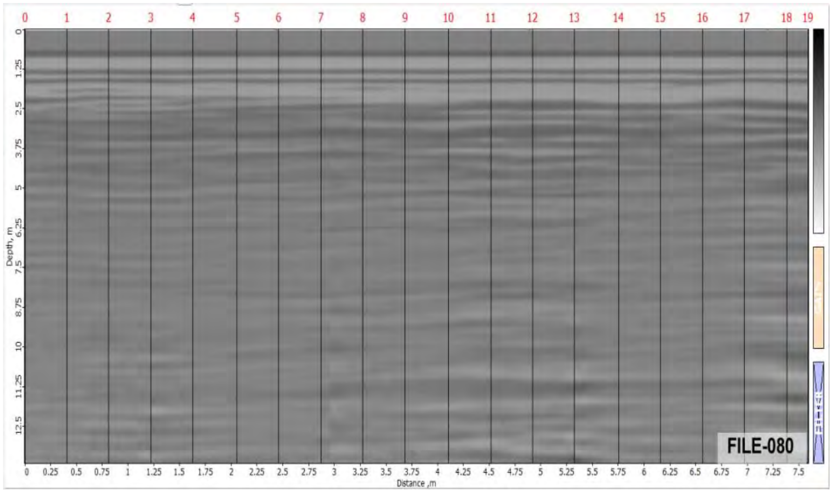
Distance ,m


FILE-080
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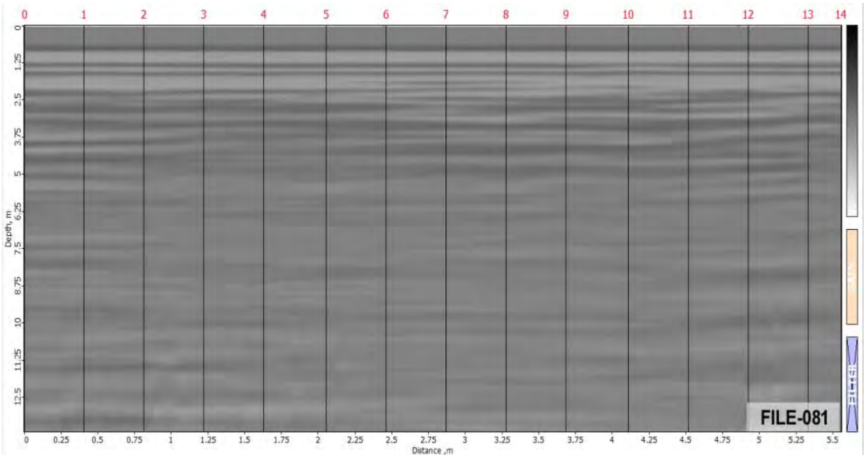
Distance ,m


FILE-081
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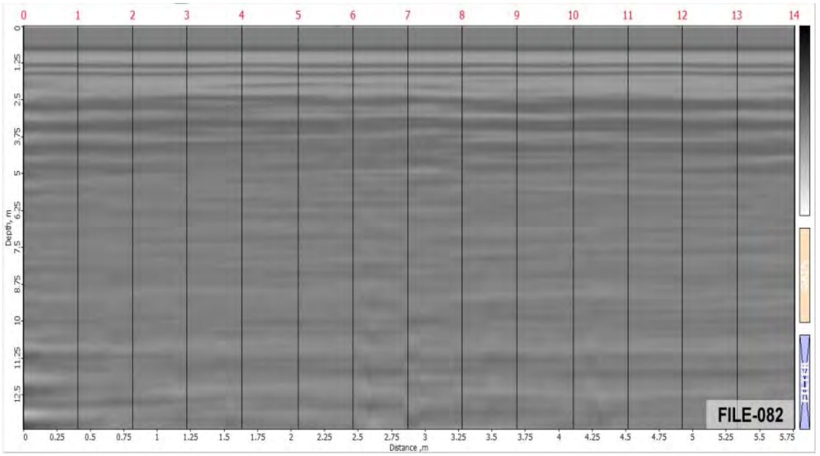
Distance ,m


FILE-082
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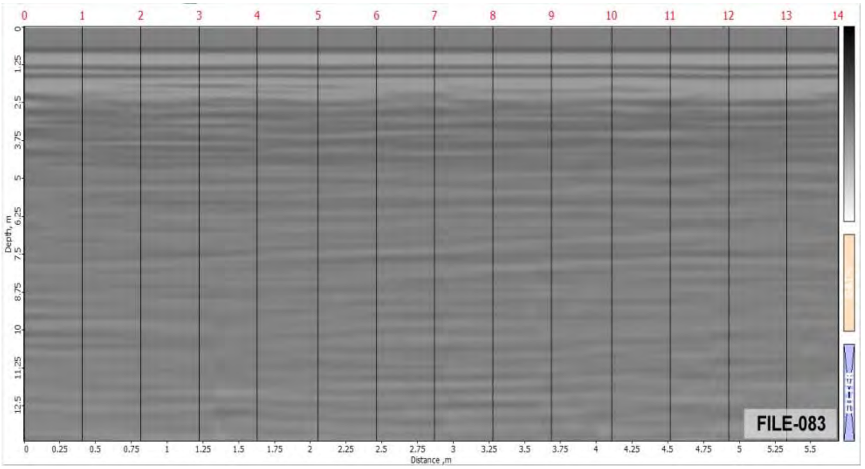
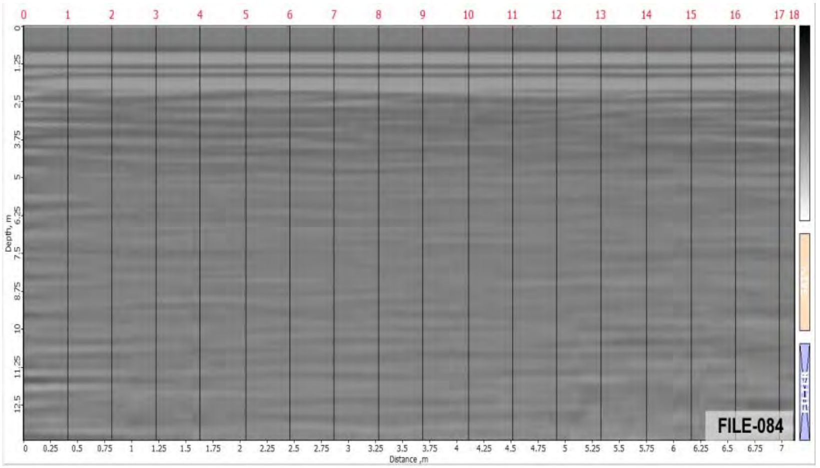
Distance ,m


FILE-083
Depth, m
Distance ,m


FILE-084
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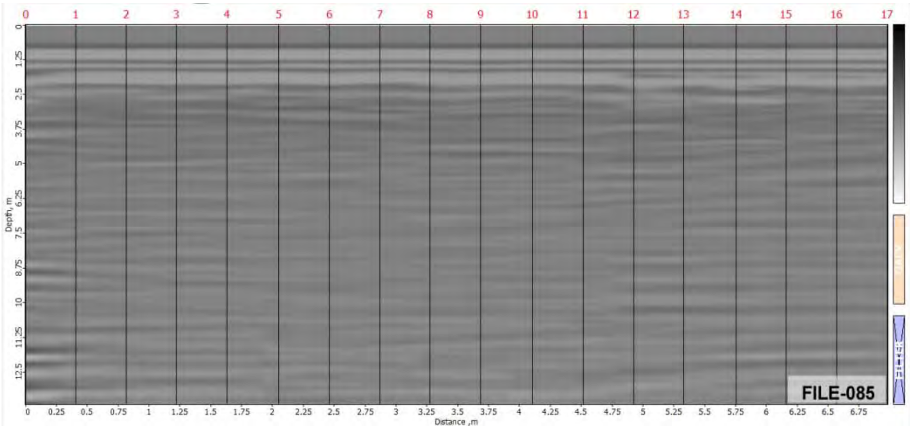
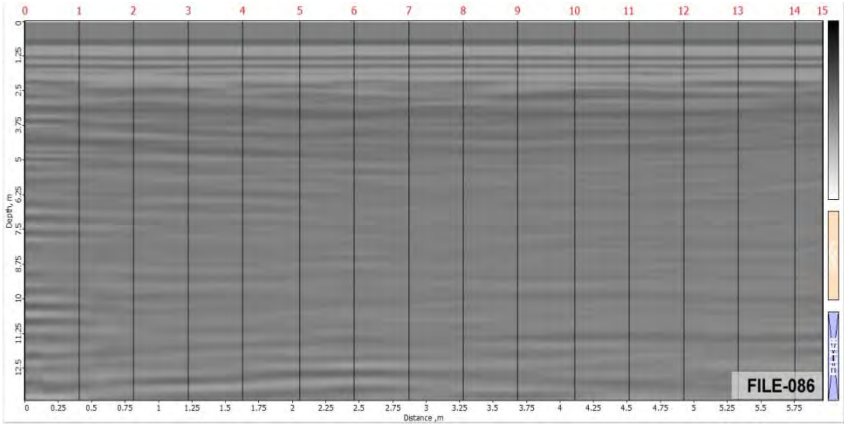
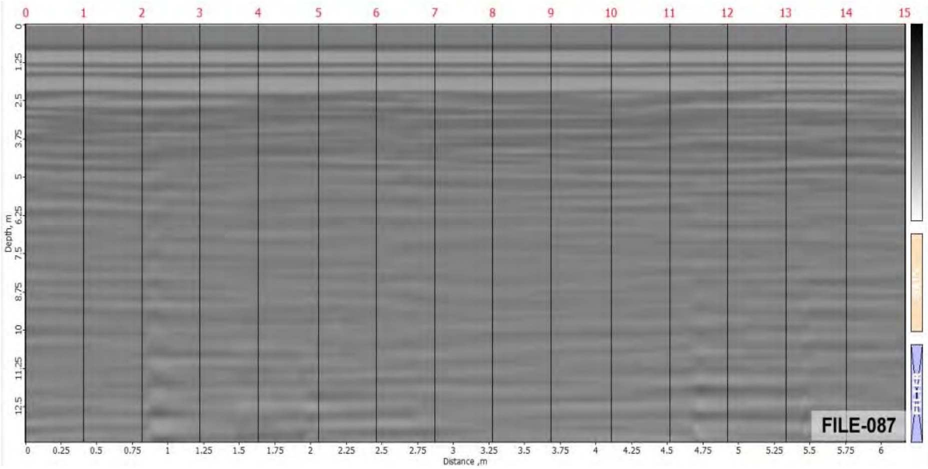
Distance ,m


FILE-085
Depth, m
Distance ,m


FILE-086
Depth, m
Distance ,m


FILE-087
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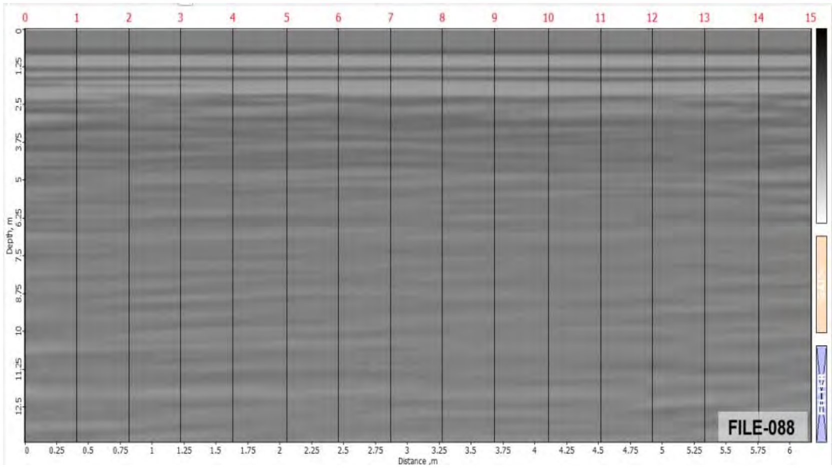
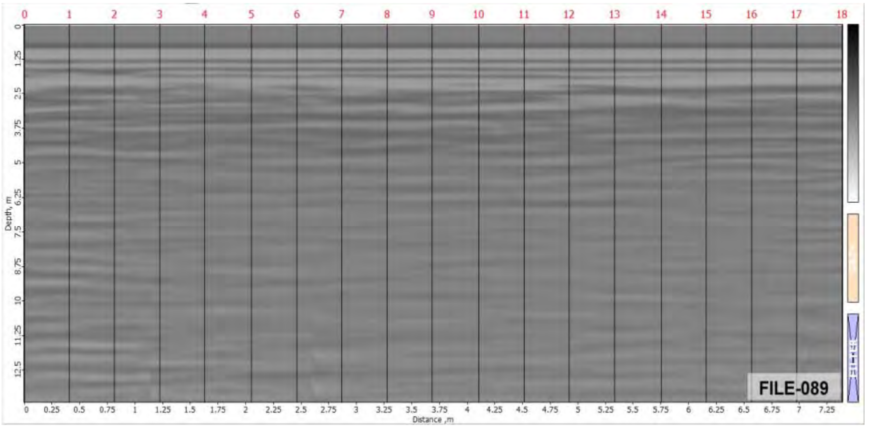
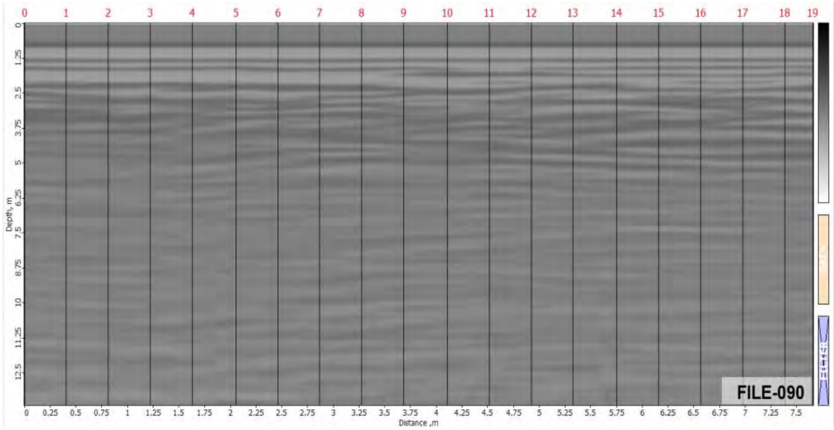
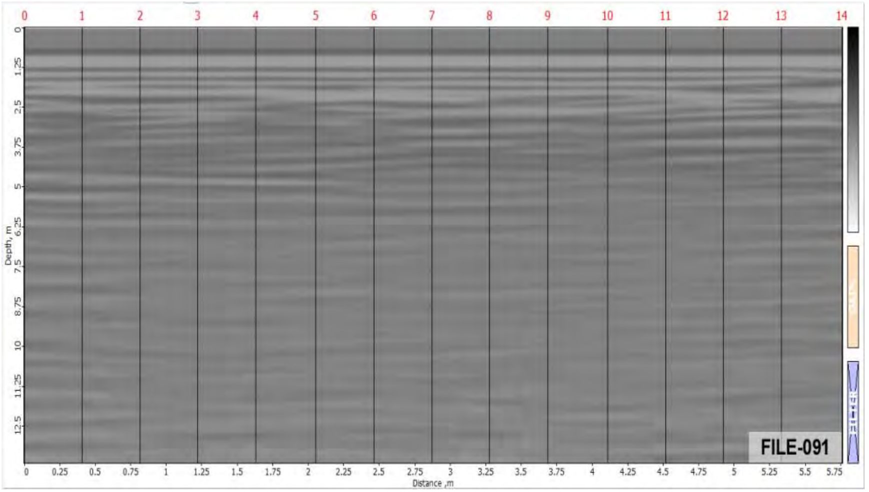
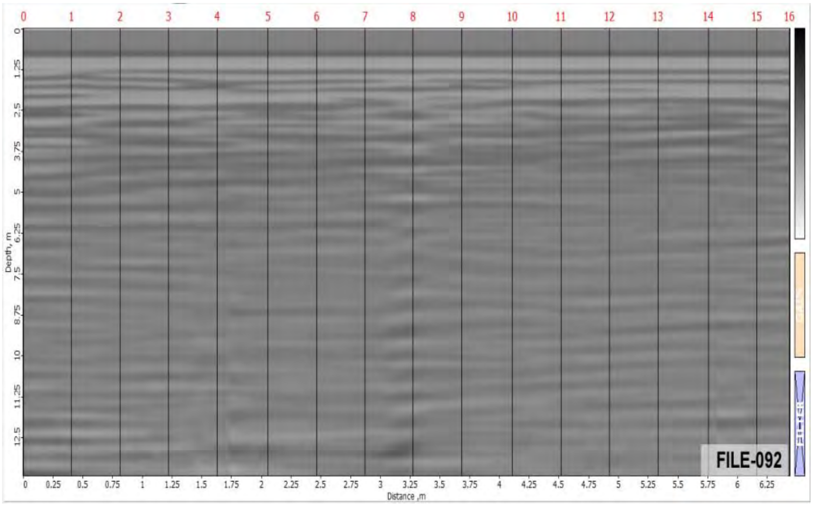
Distance ,m

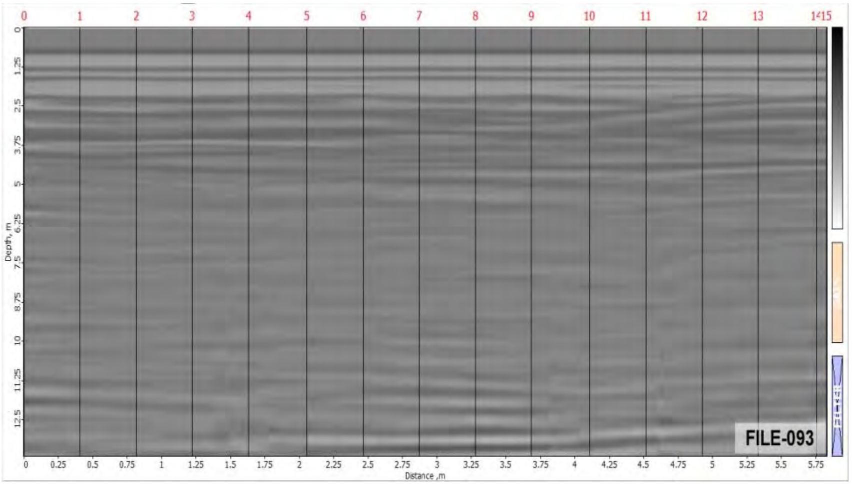

FILE-088
Depth, m
Distance ,m

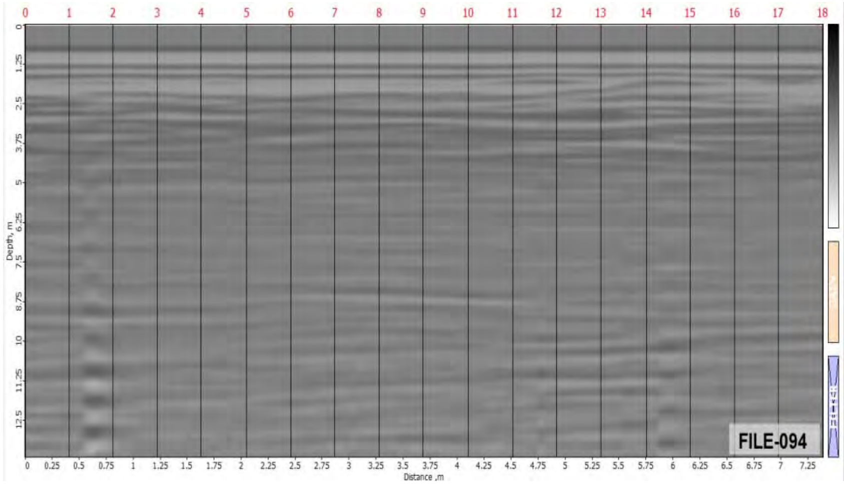

FILE-089
Depth, m
Distance ,m

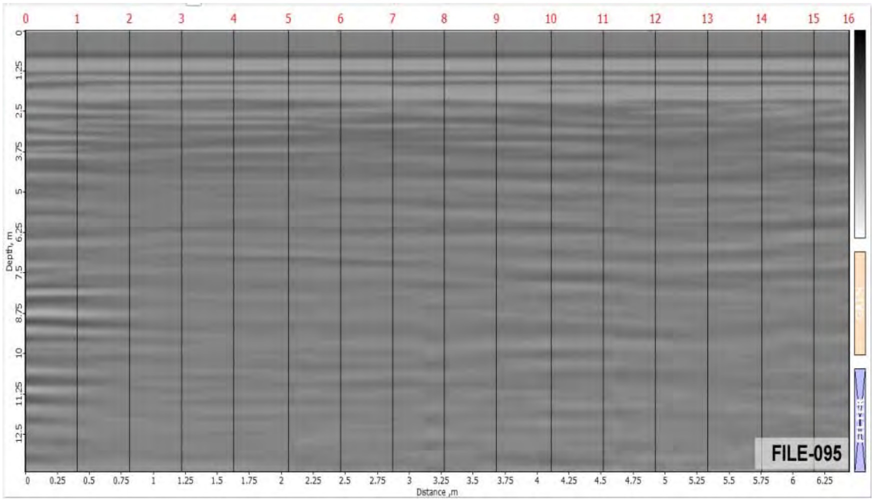

FILE-090
Depth, m
Distance ,m


FILE-091
Depth, m
Distance ,m


FILE-092
Depth, m
Distance ,m


Depth, m
Distance ,m
FILE-093

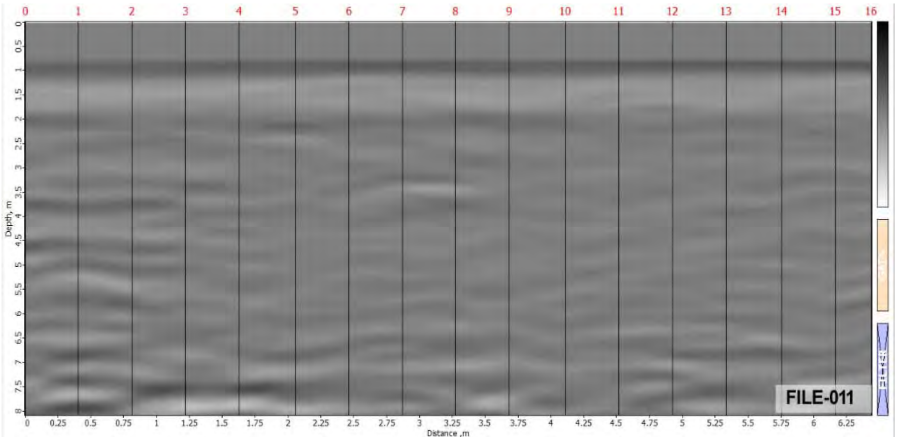

Depth, m
Distance ,m
FILE-094

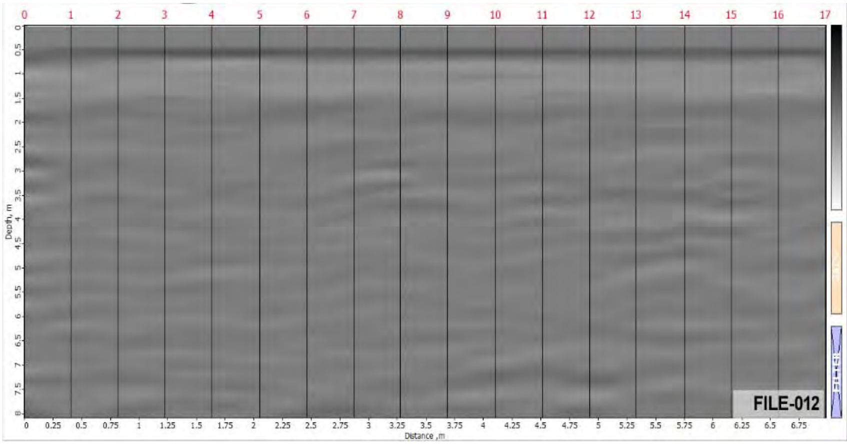

Depth, m
Distance ,m
FILE-095

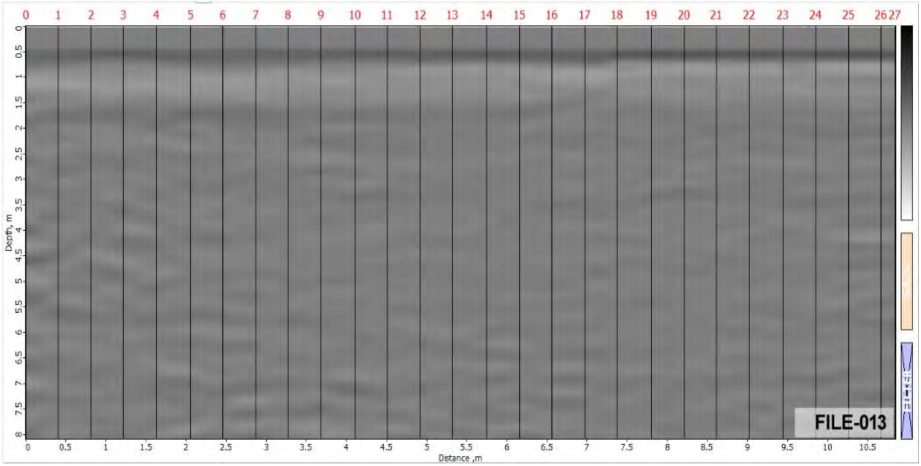
Annexure-VI

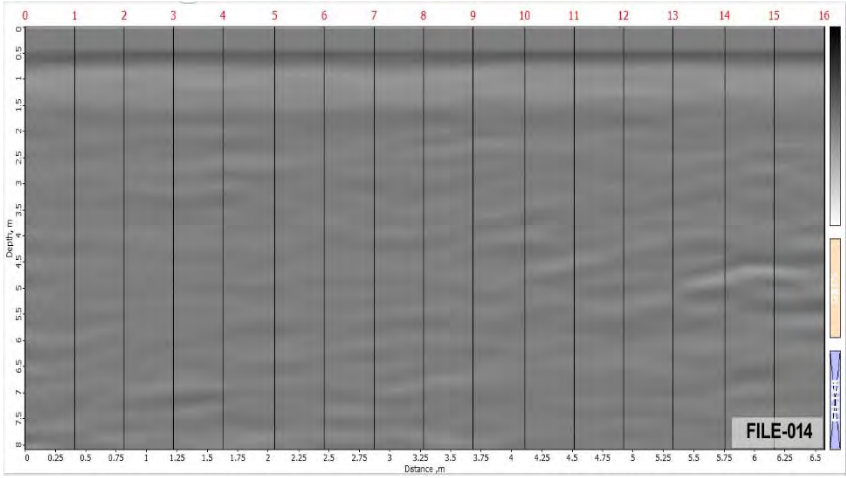
GPR PROFILES WITH 200 MHz ANTENNA

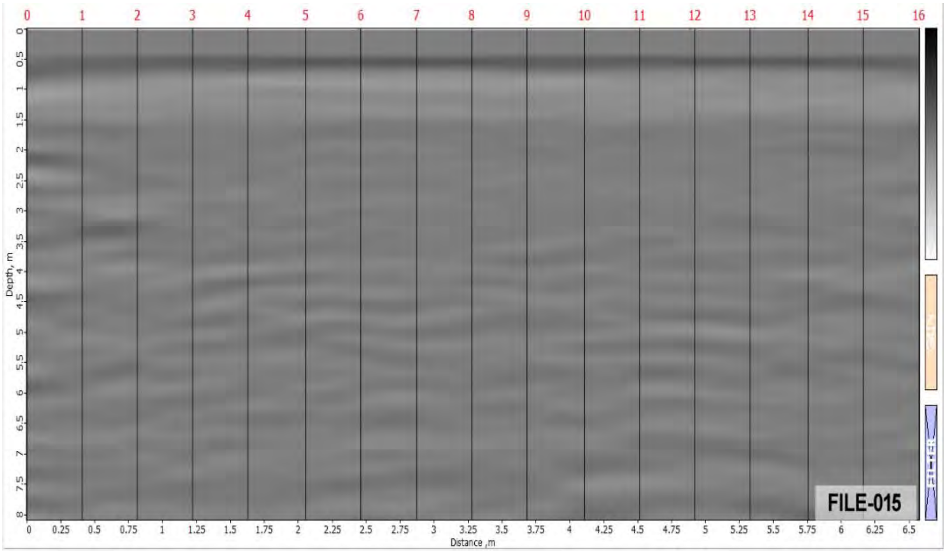
IMAGES OF GPR PROFILE SCANNED ACROSS ERT 1 ALIGNMENT WITH PRISM-2.59 SOFTWARE

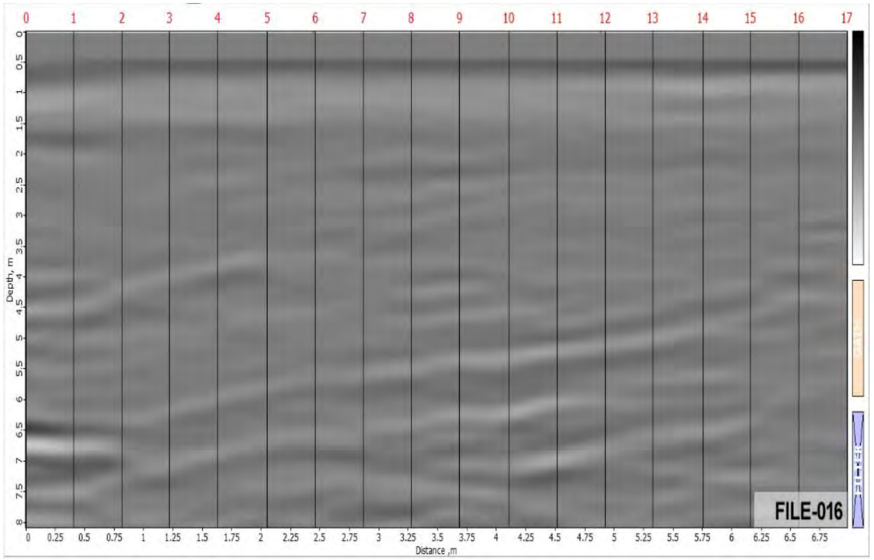


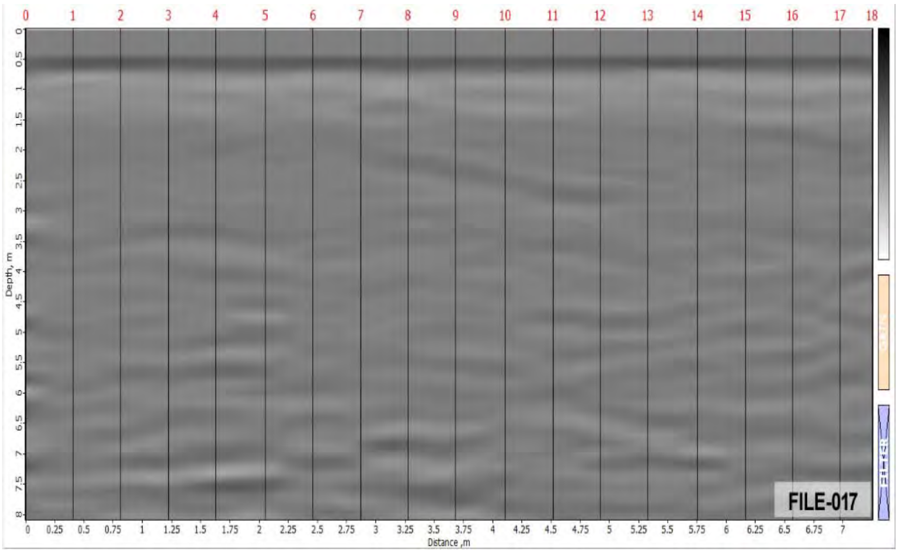


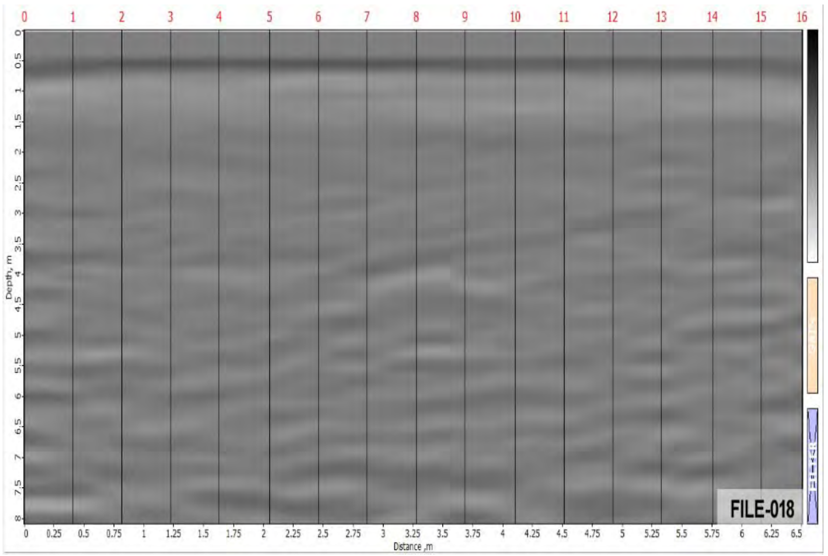


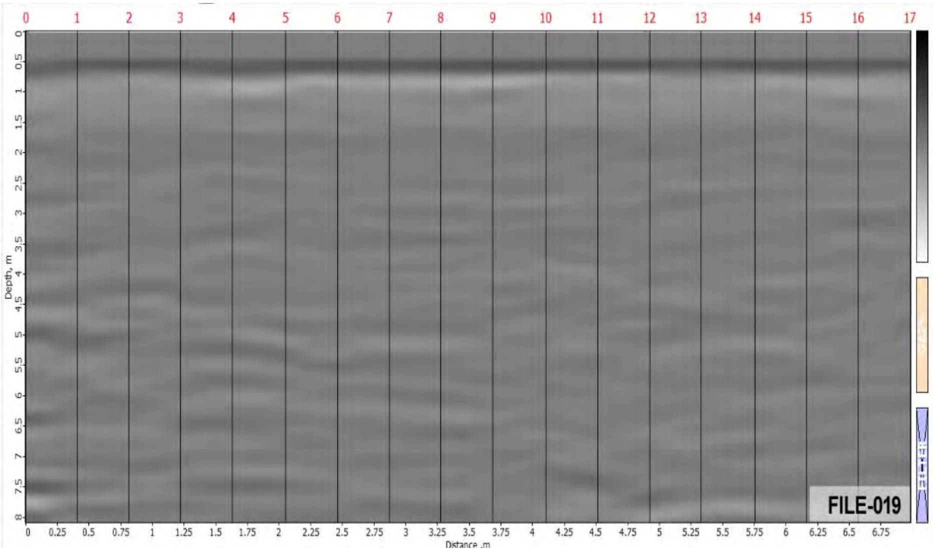


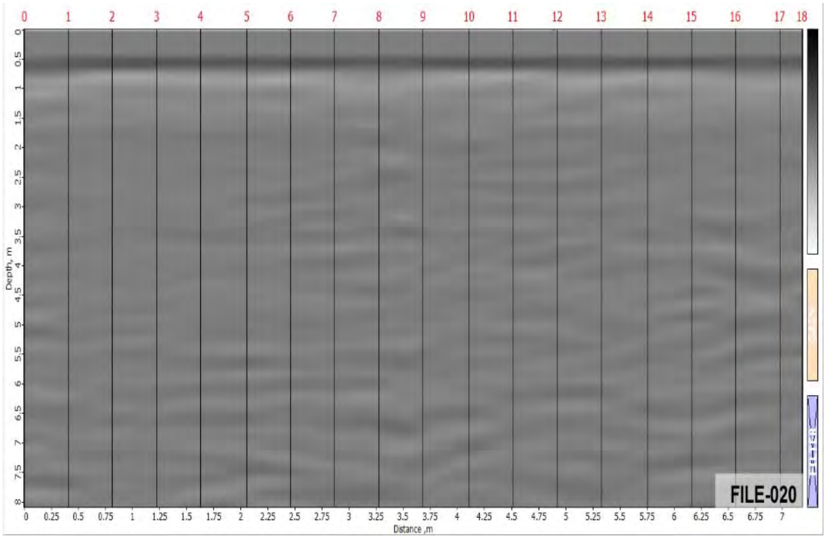

FILE-015
Depth, m
Distance ,m

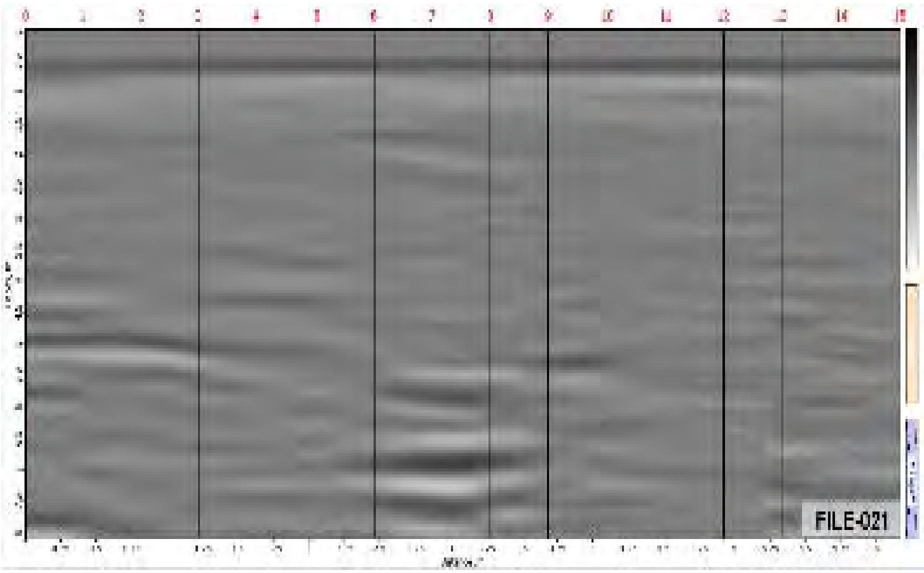

FILE-016
Depth, m
Distance ,m

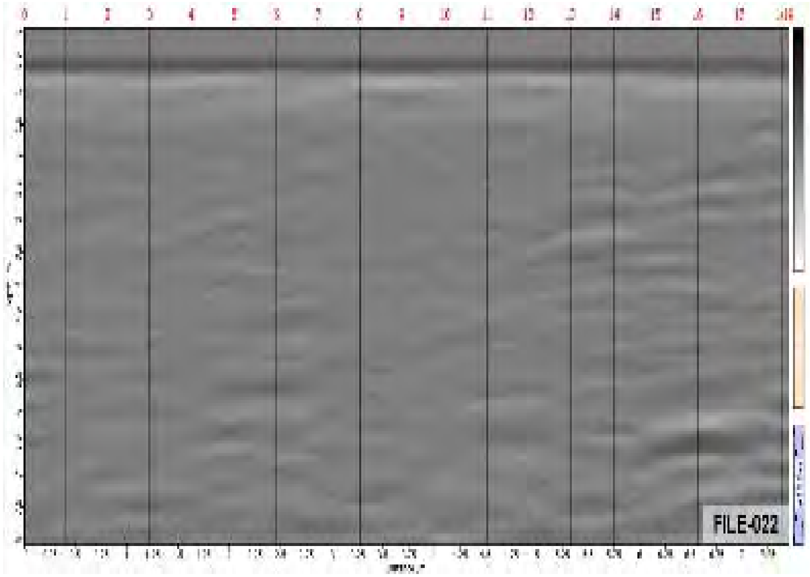

FILE-017
Depth, m
Distance ,m

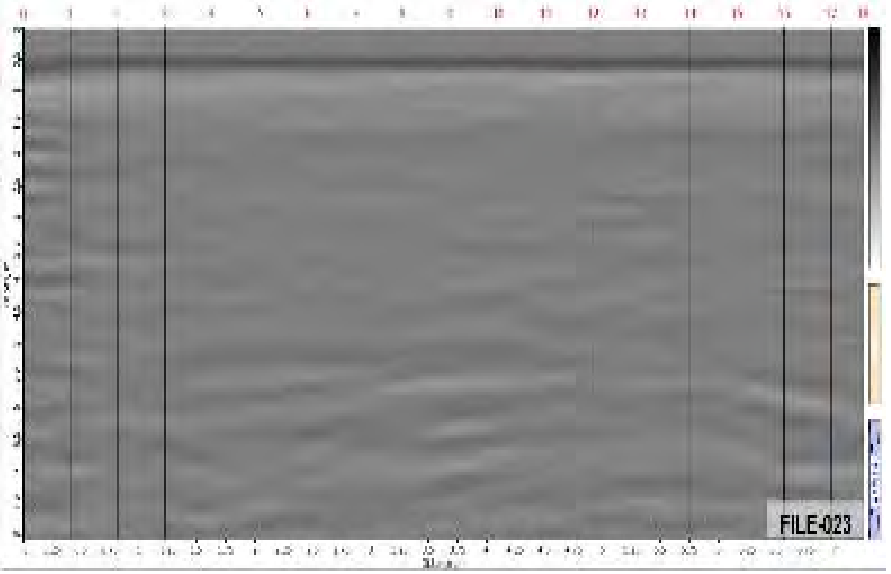

FILE-018
Depth, m
Distance ,m

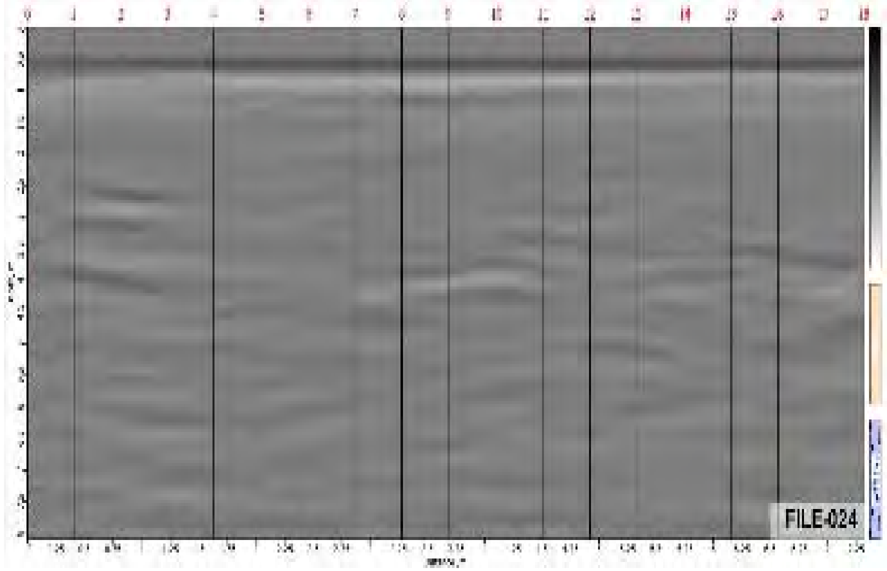

FILE-019
Depth, m
Distance ,m

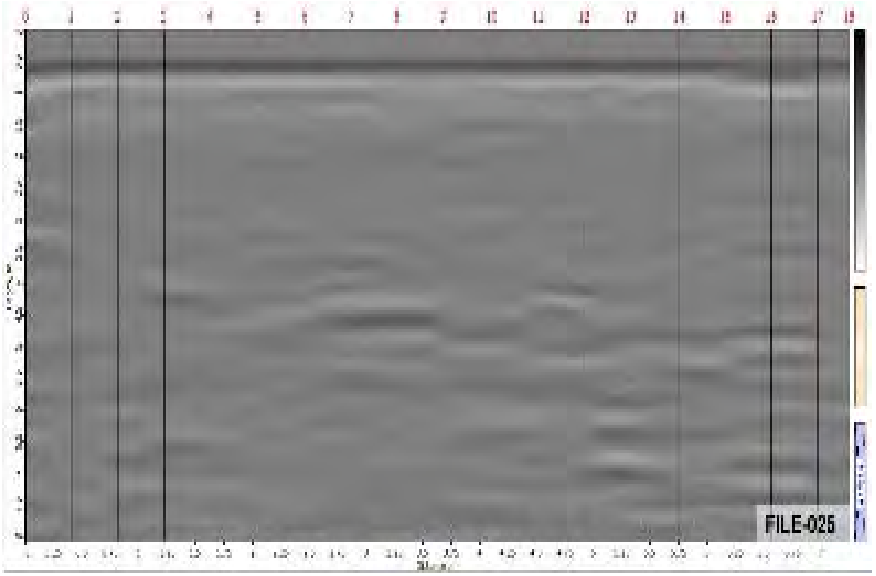

FILE-020
Depth, m
Distance ,m

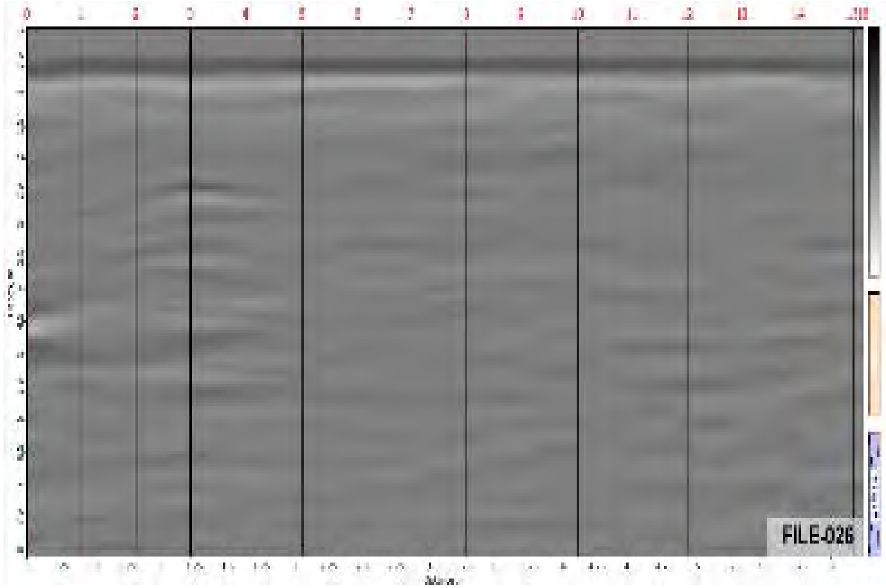

FILE-021

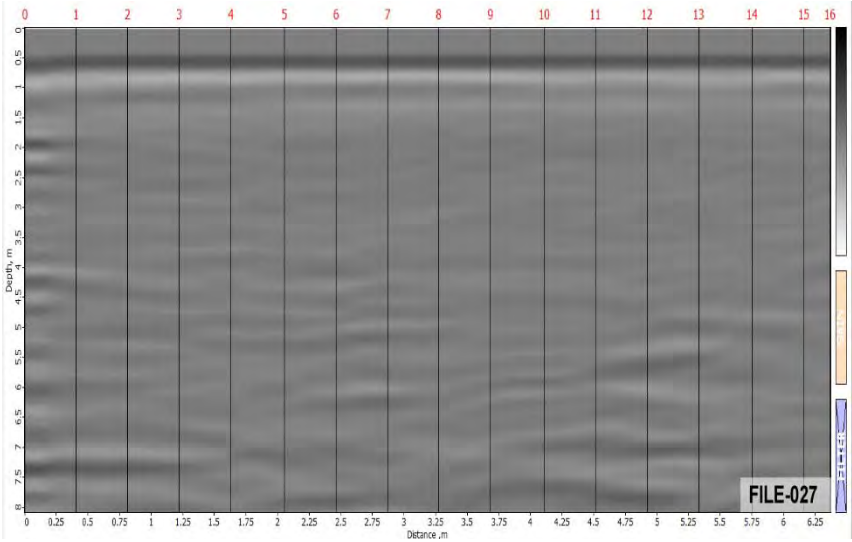

FILE-022

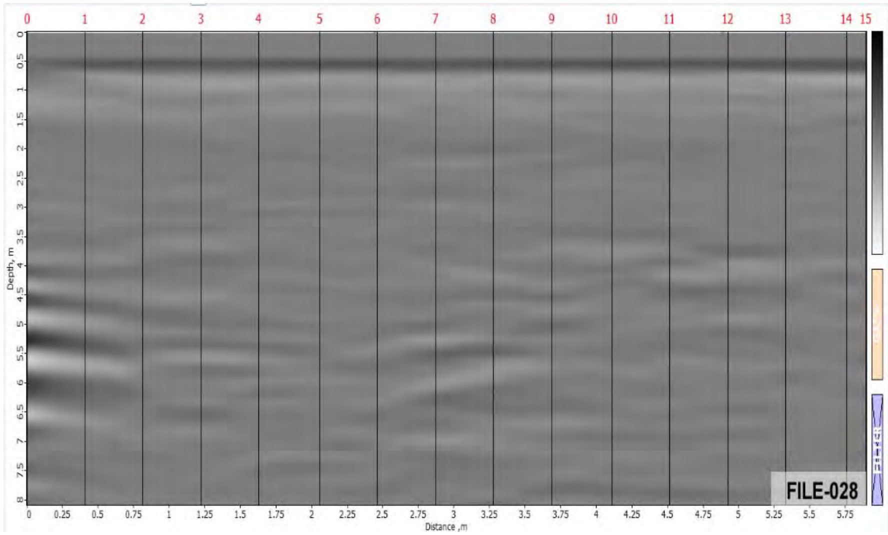

FILE-023

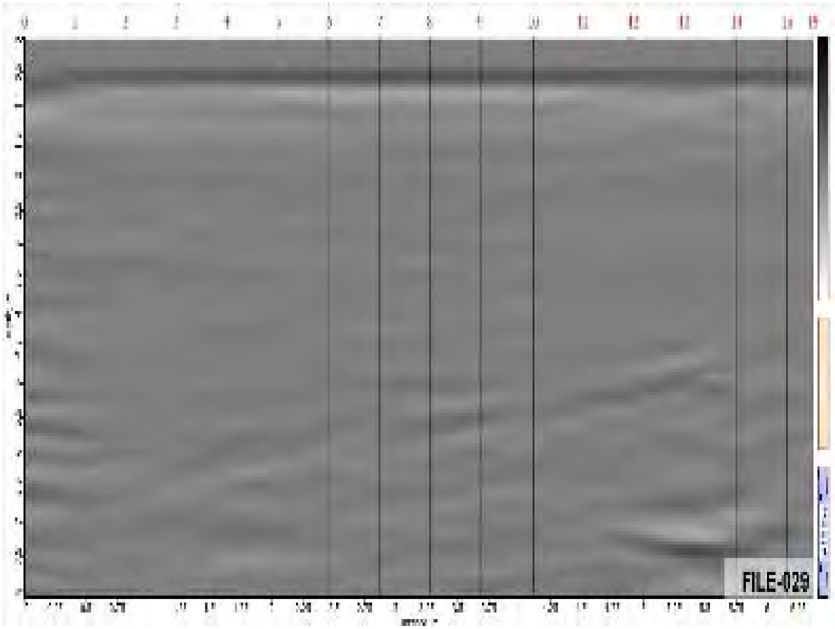

FILE-024

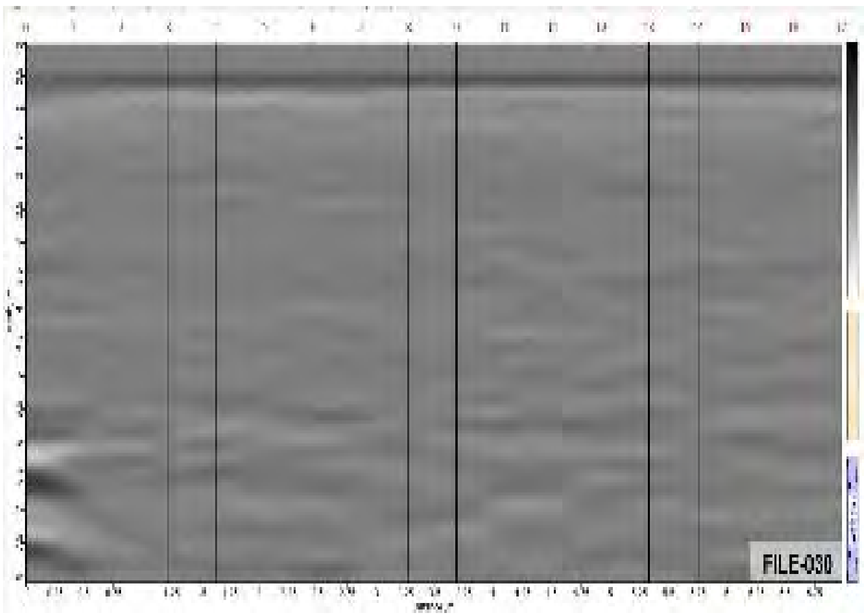

FILE-025

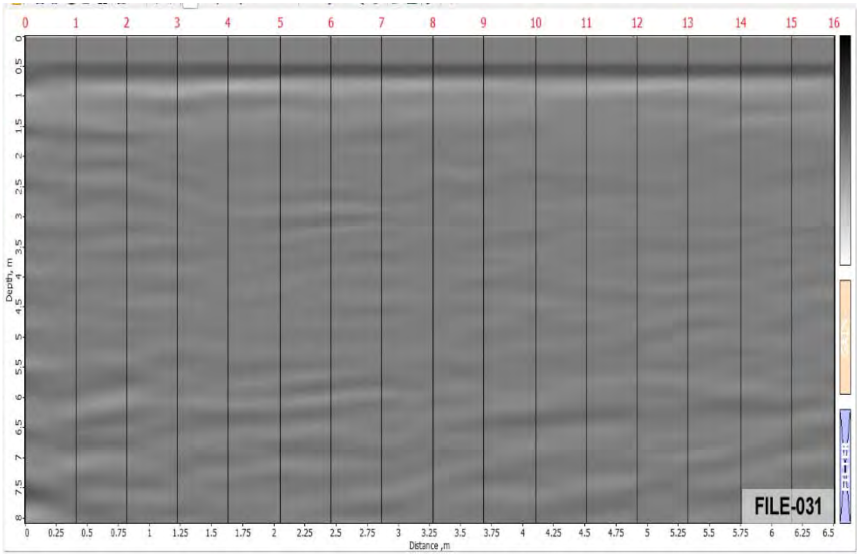

FILE-026

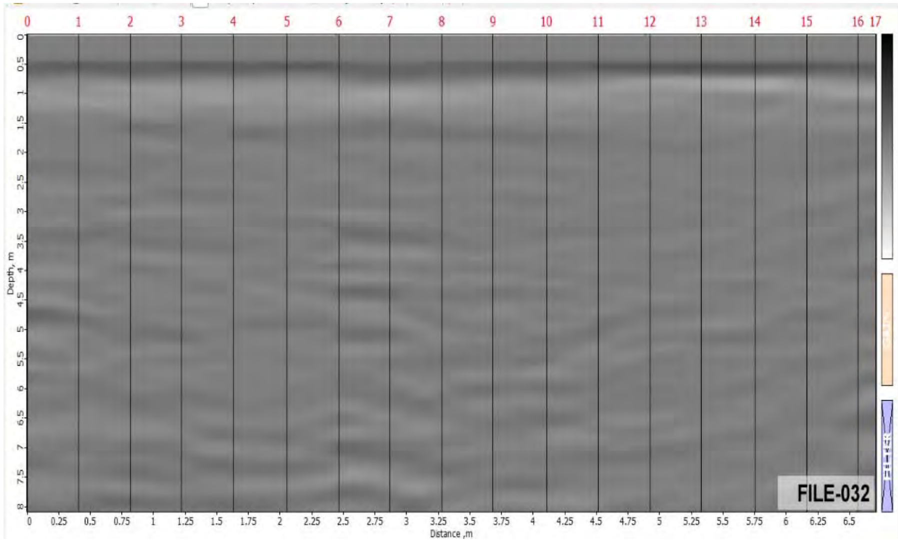

FILE-027
Depth, m
Distance ,m

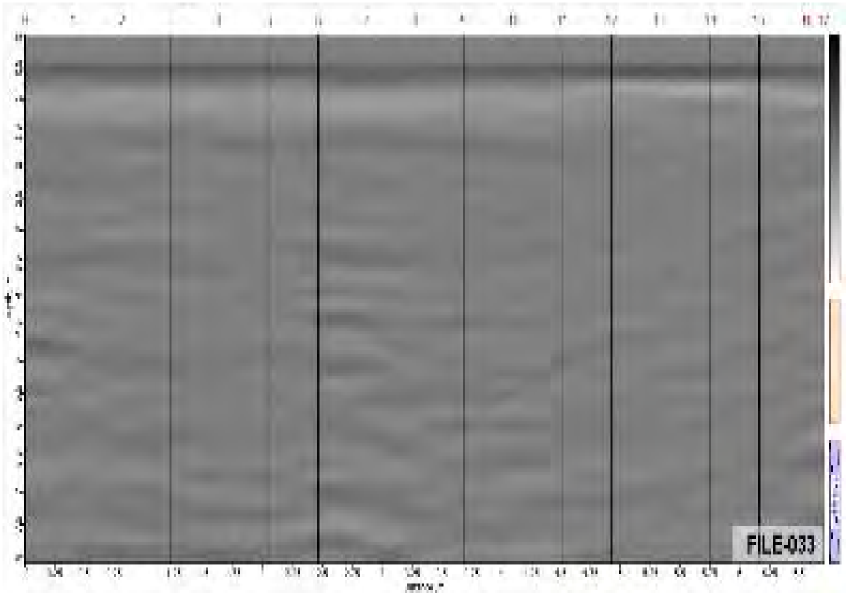

FILE-028
Depth, m
Distance ,m

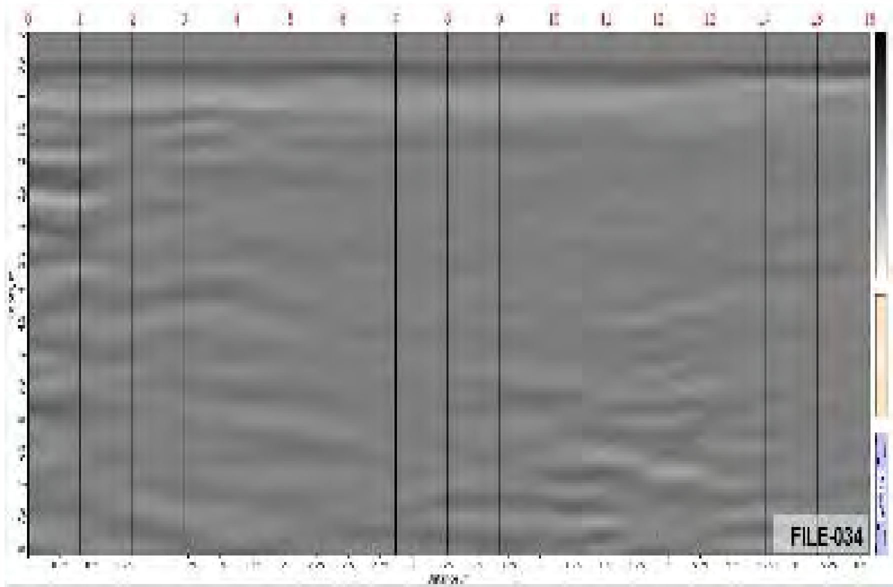

FILE-029

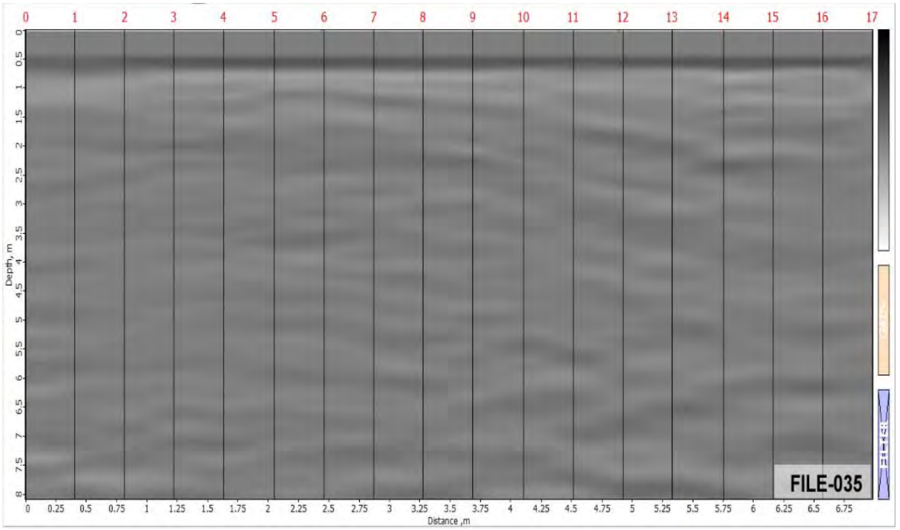

FILE-030

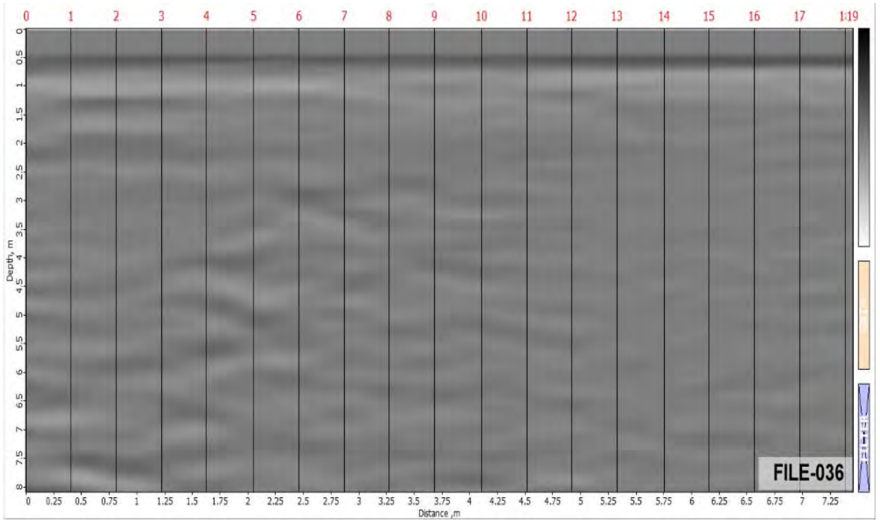

Depth, m
Distance ,m
FILE-031

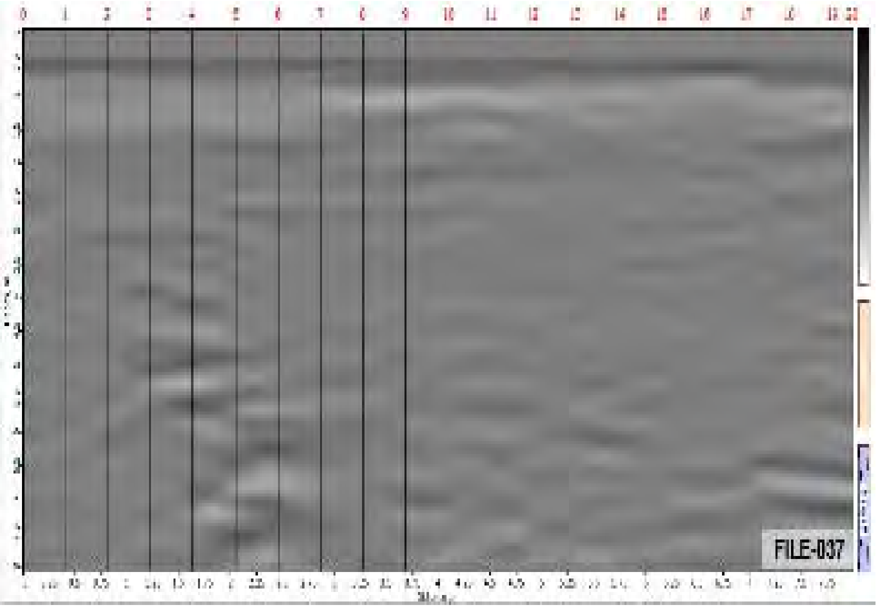

Depth, m
Distance ,m
FILE-032

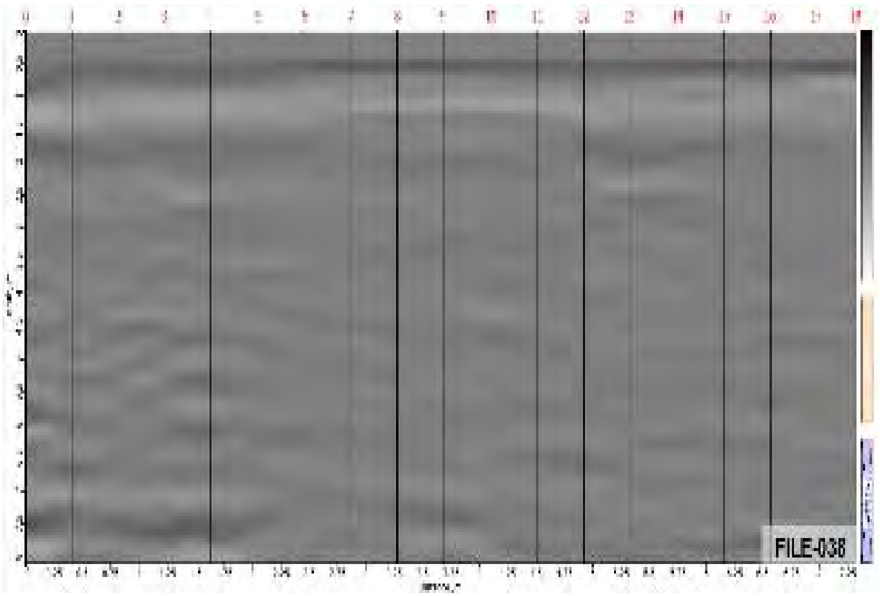

FILE-033

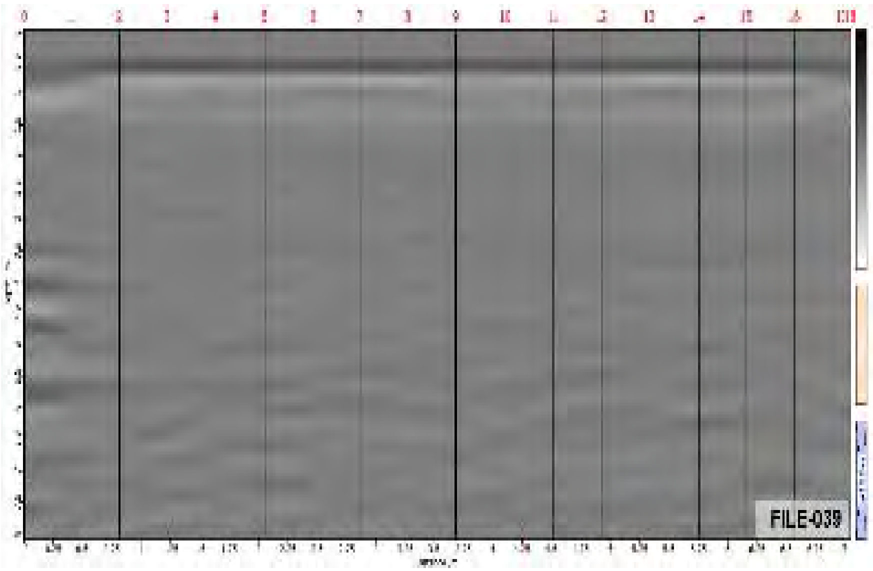

FILE-034

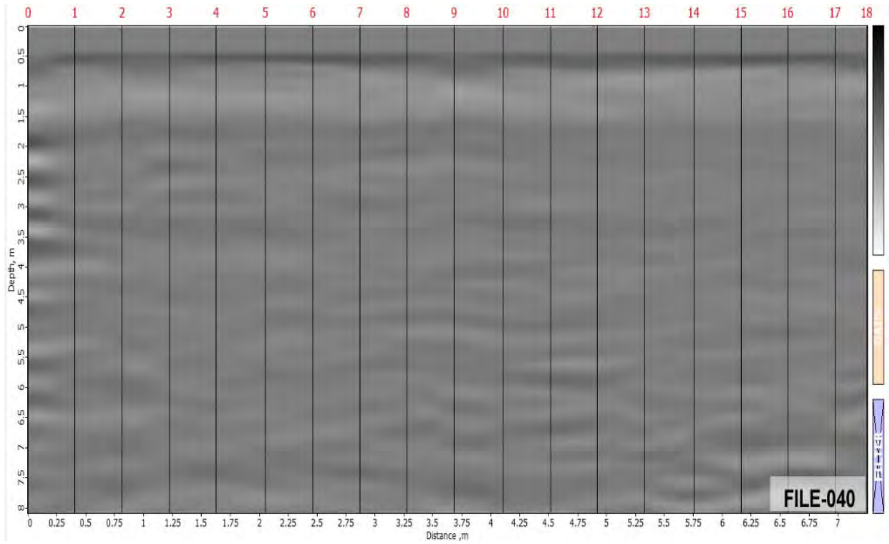

FILE-035
Depth, m
Distance ,m

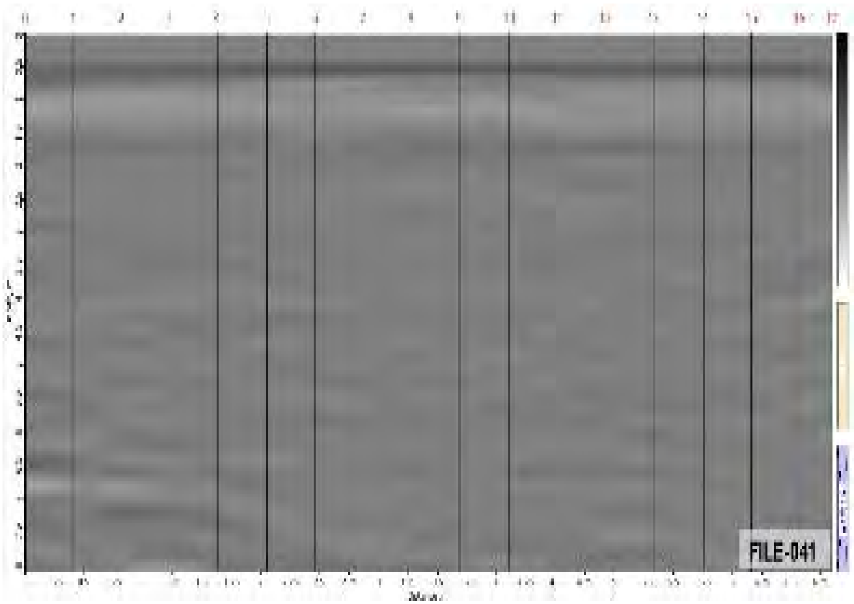

FILE-036
Depth, m
Distance ,m

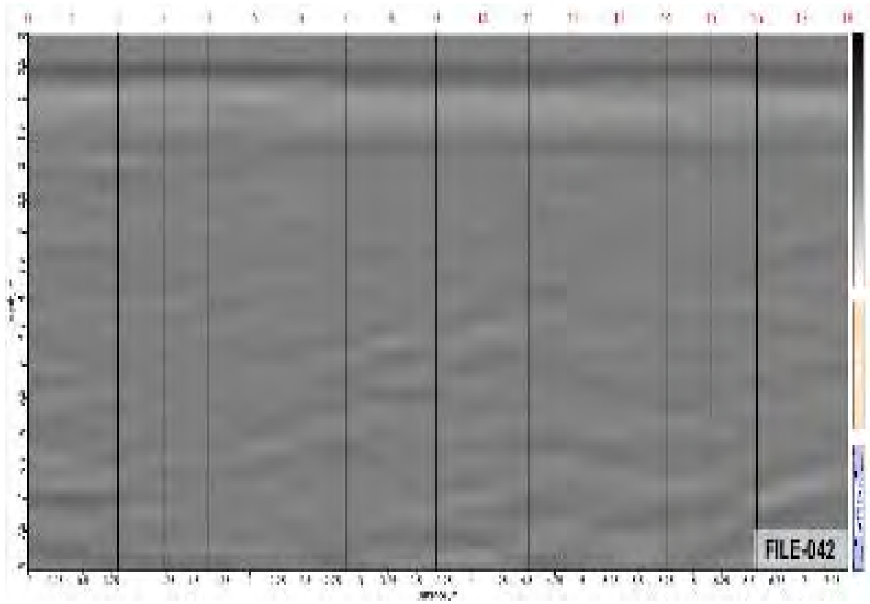

FILE-037

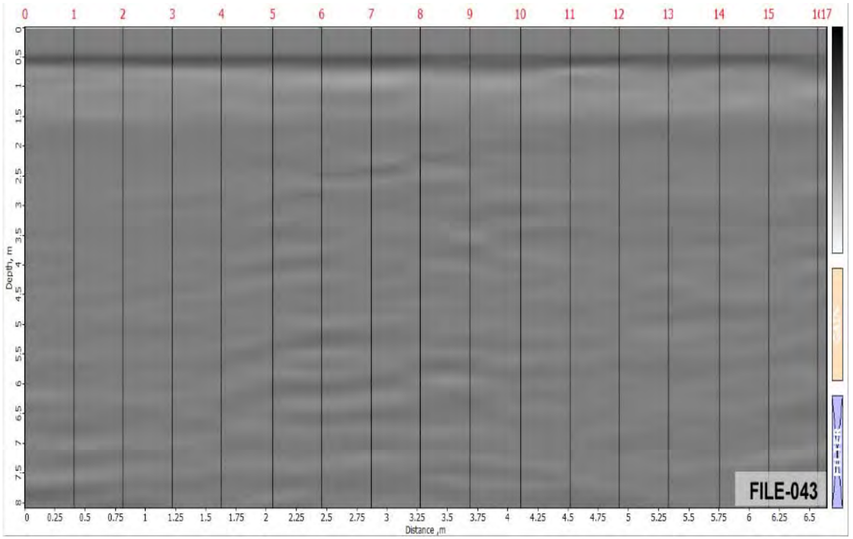

FILE-038

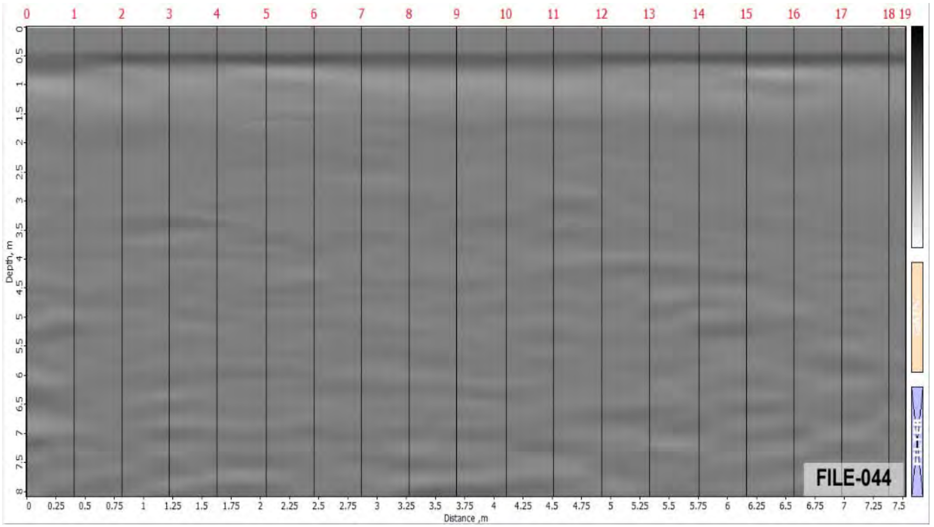

FILE-039

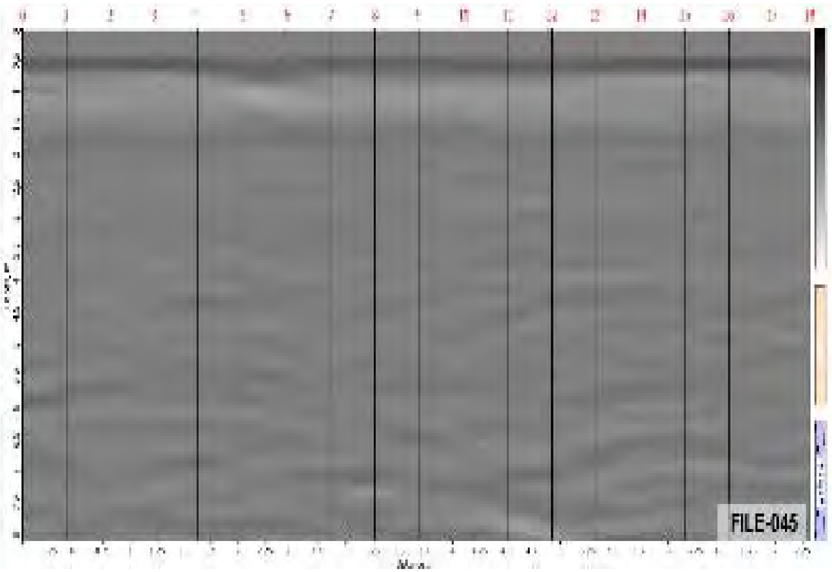

Depth, m
Distance ,m
FILE-040

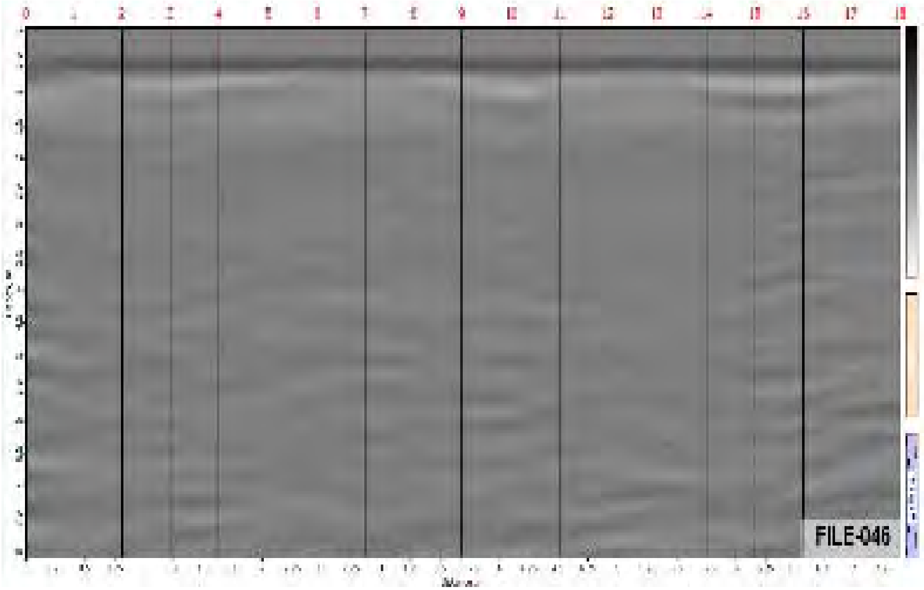

FILE-041

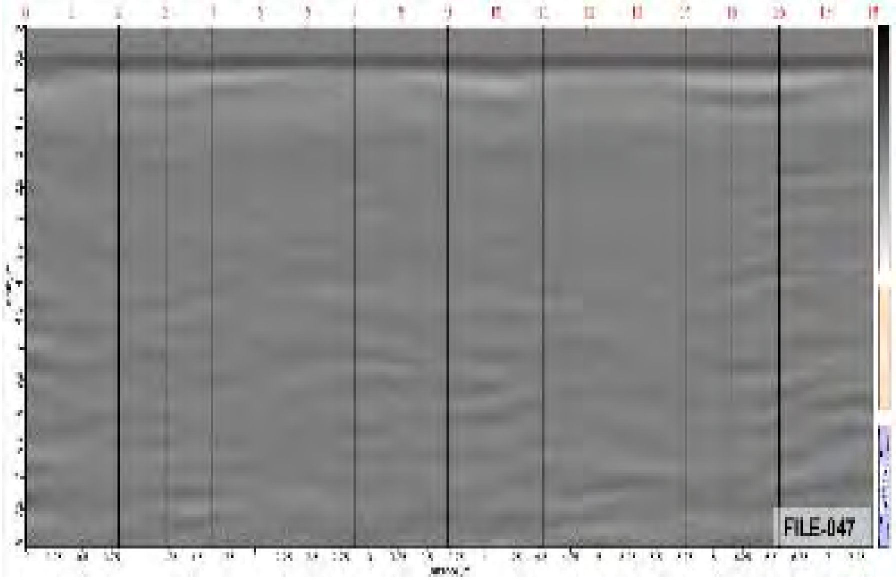

FILE-042

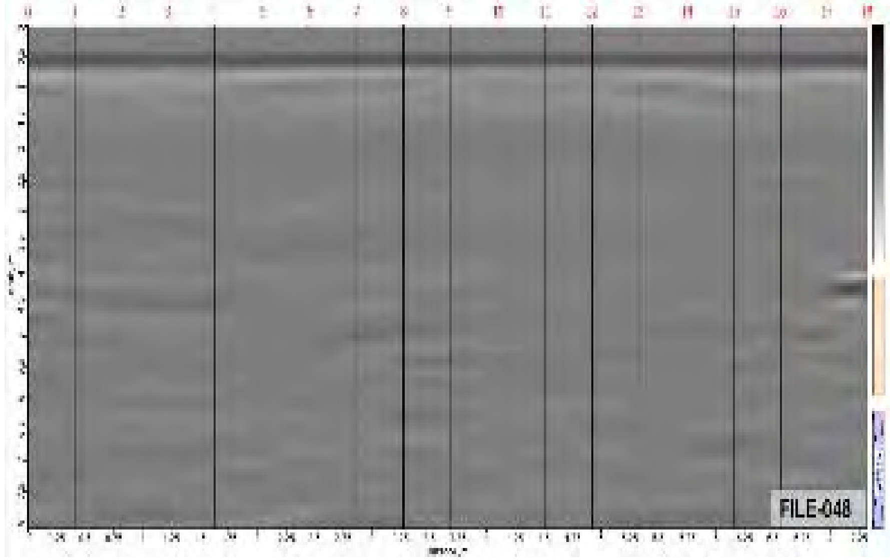

FILE-043
Depth, m
Distance ,m

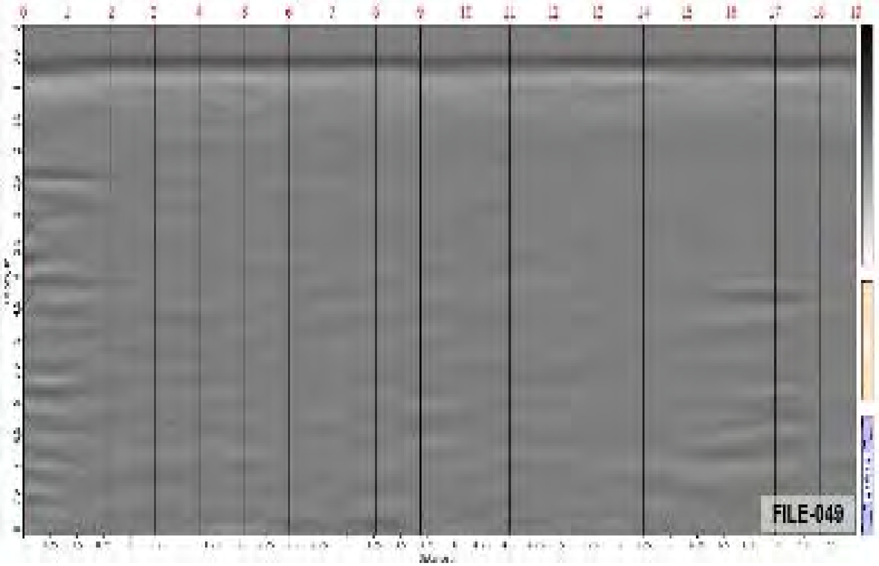

FILE-044
Depth, m
Distance ,m

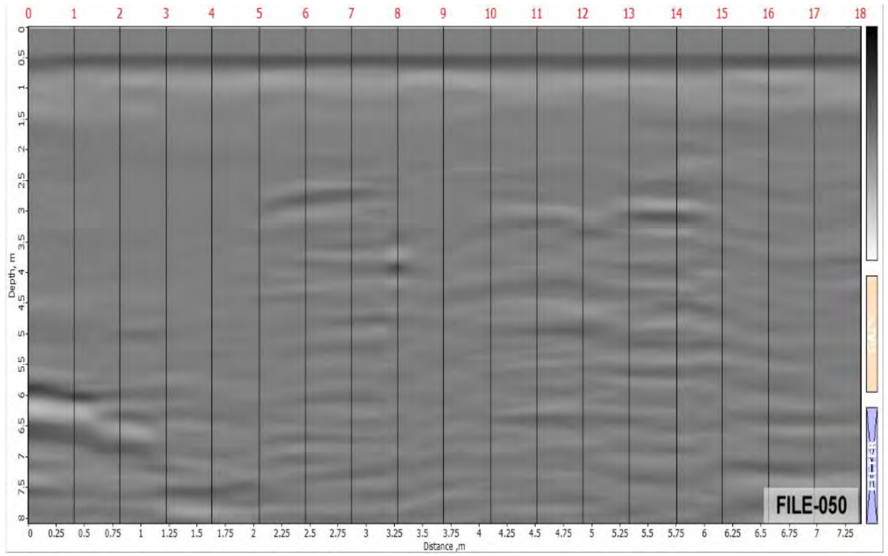

FILE-045

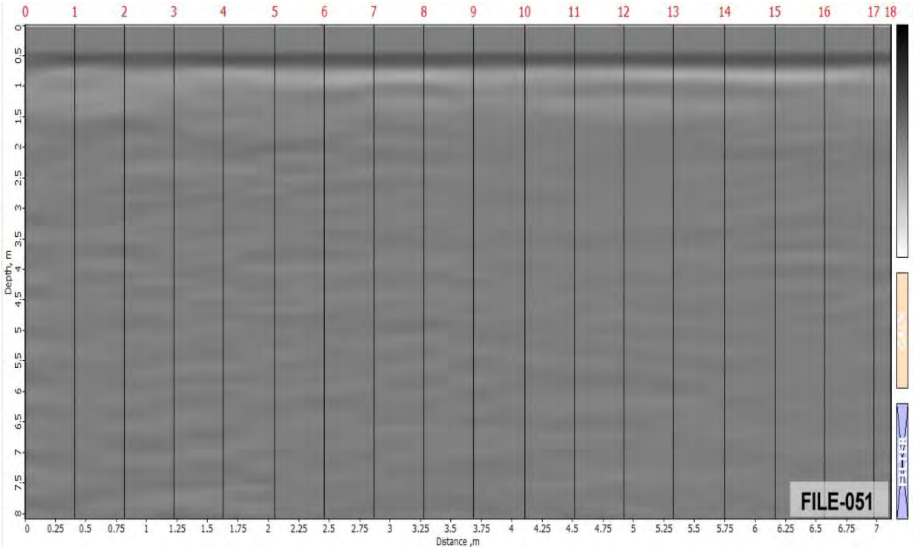

FILE-046

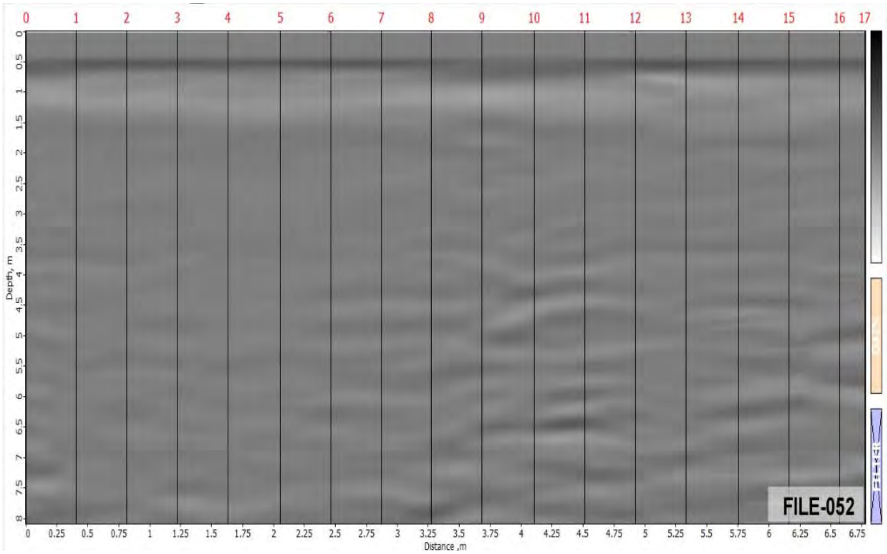

FILE-047

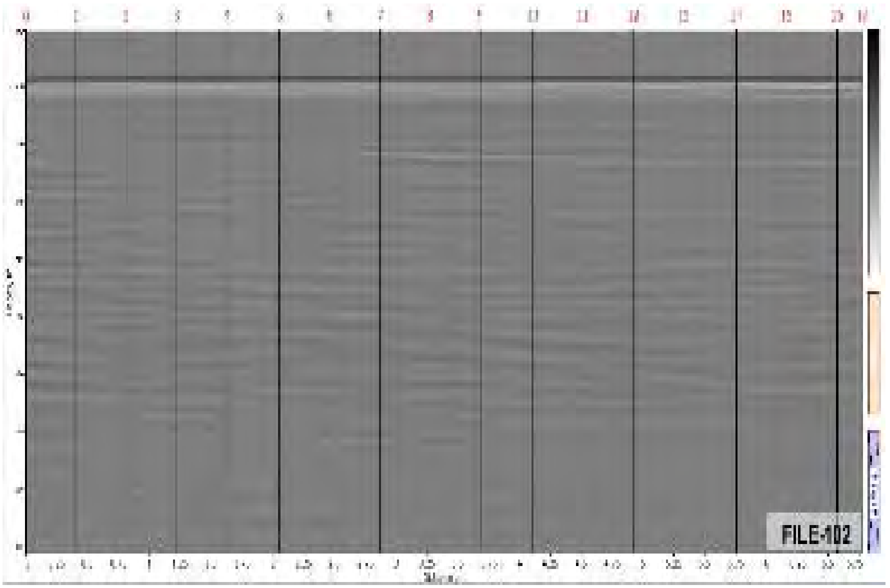

FILE-048

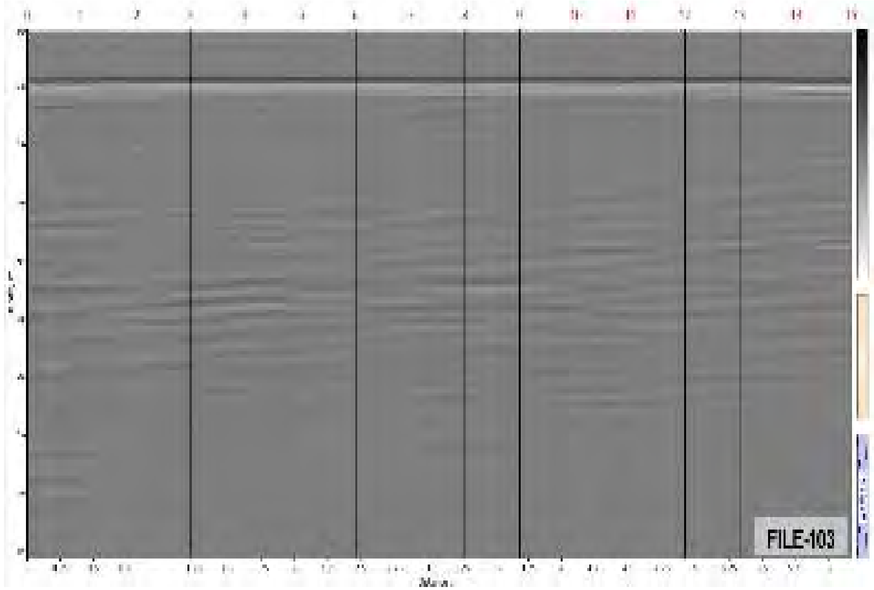

FILE-049

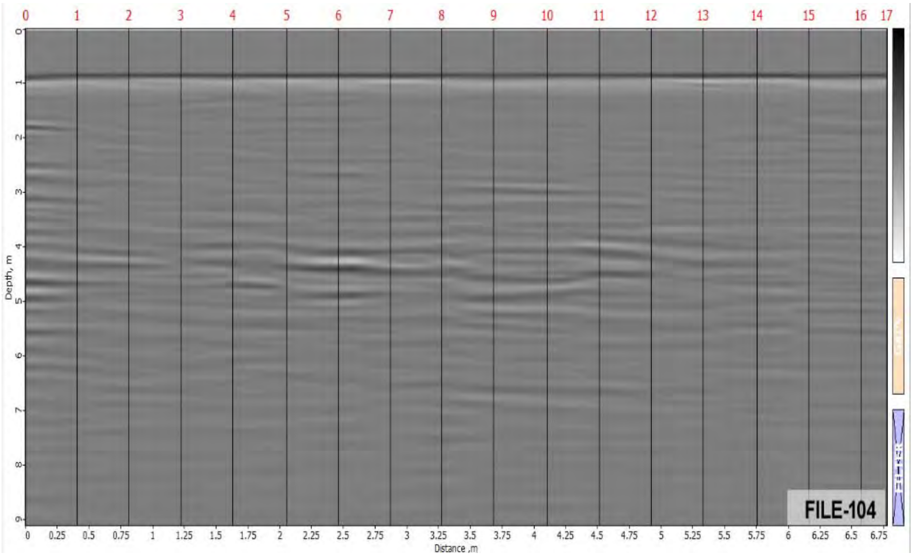

Depth, m
Distance ,m
FILE-050

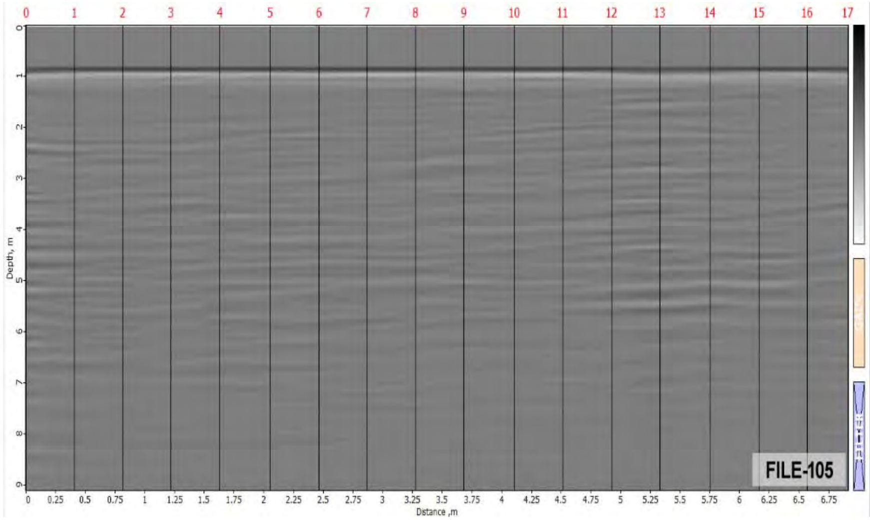

FILE-051
Depth, m
Distance ,m

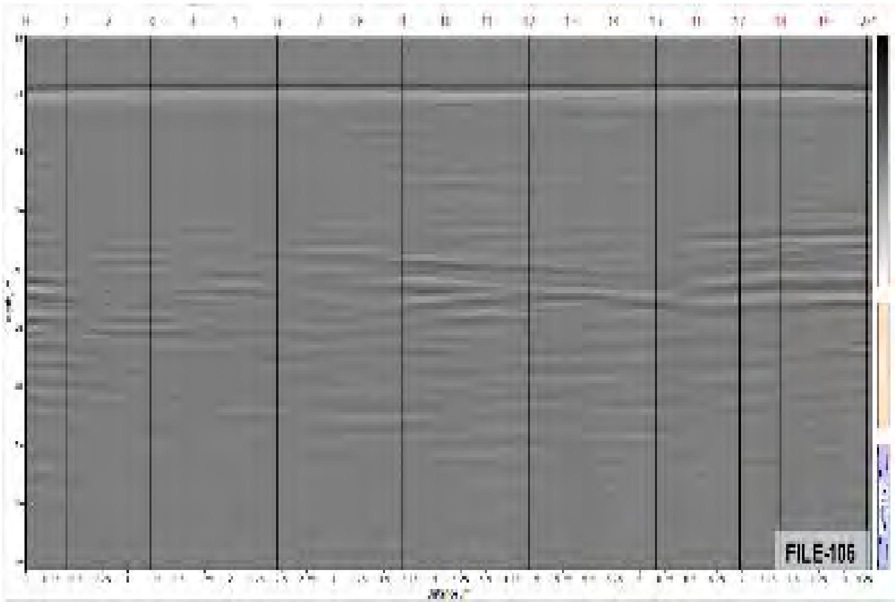

FILE-052
Depth, m
Distance ,m

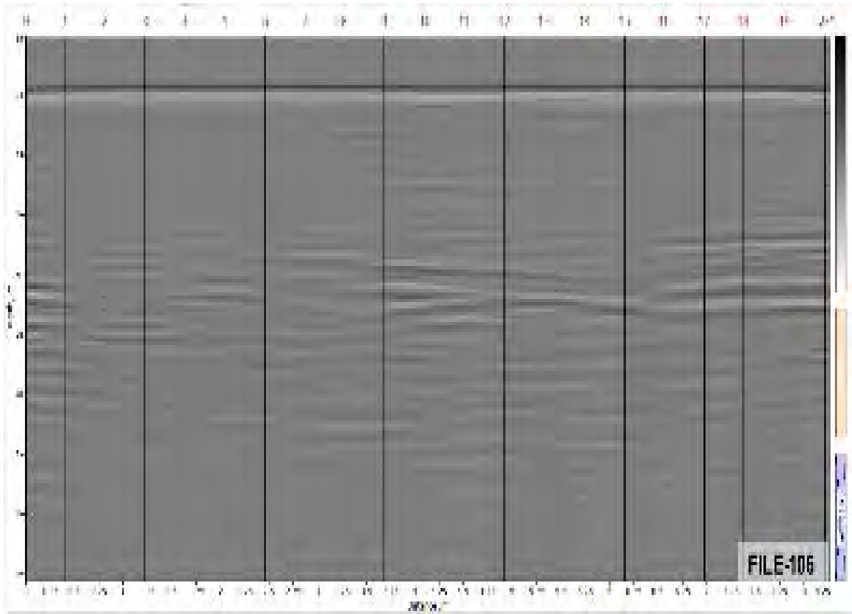

FILE-102

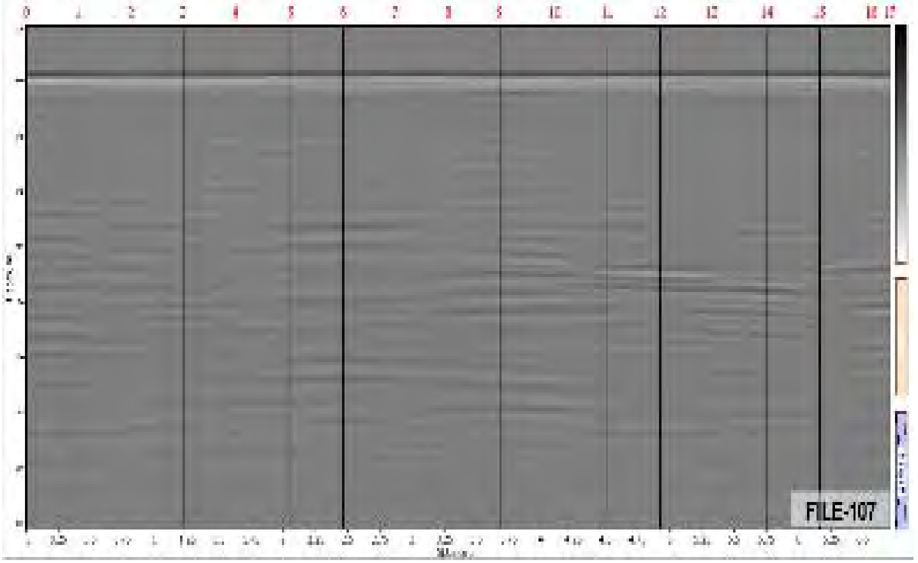

FILE-103

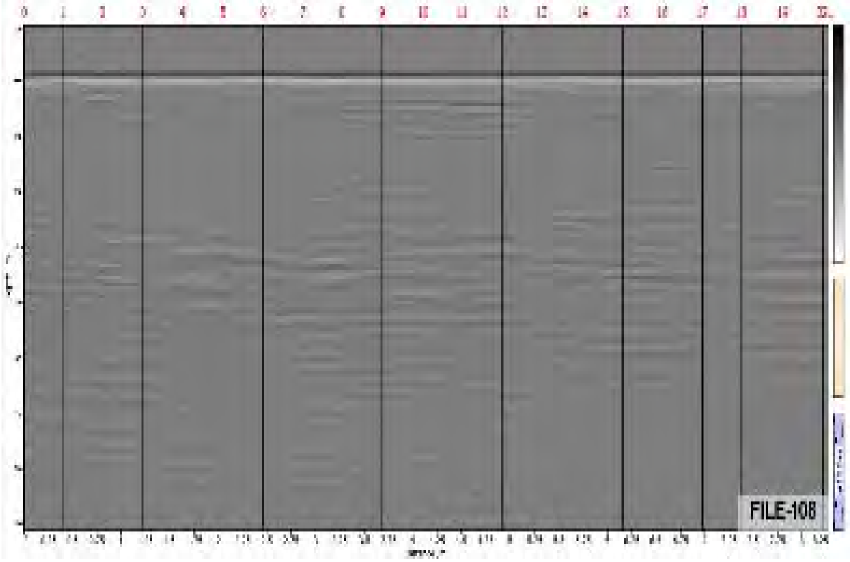

FILE-104
Depth, m
Distance ,m

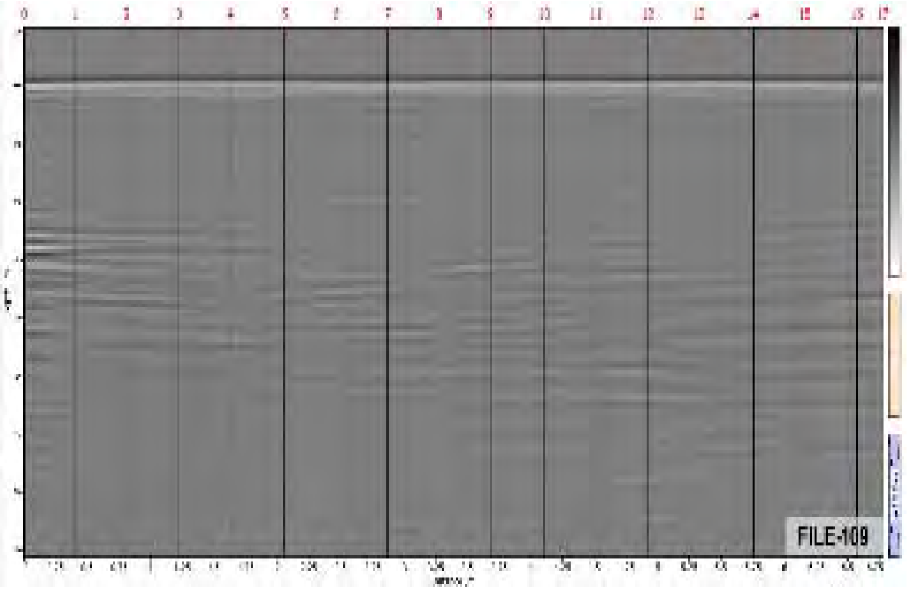

FILE-105
Depth, m
Distance ,m

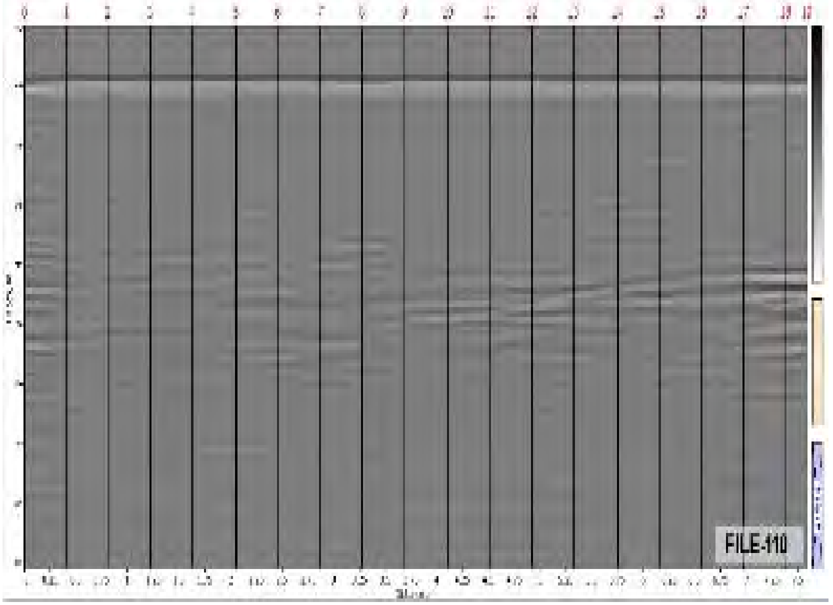

FILE-106

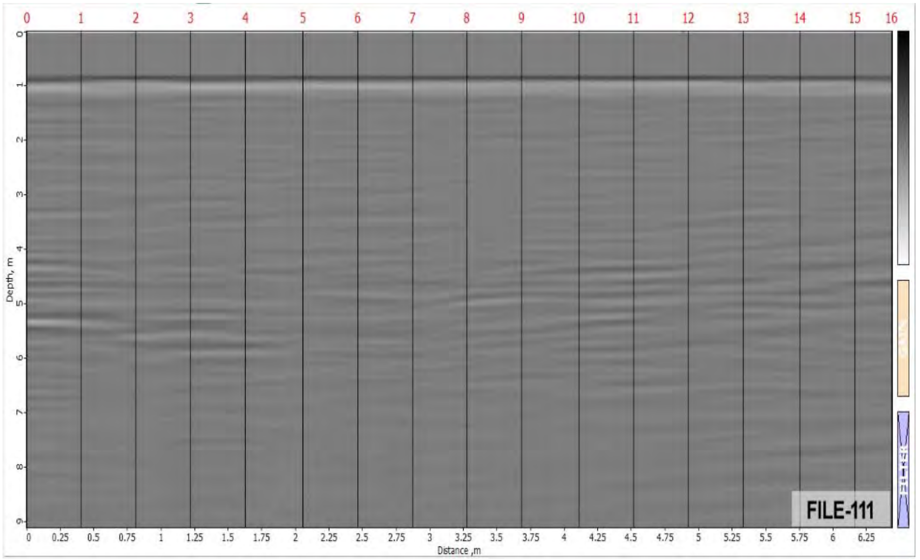

FILE-106

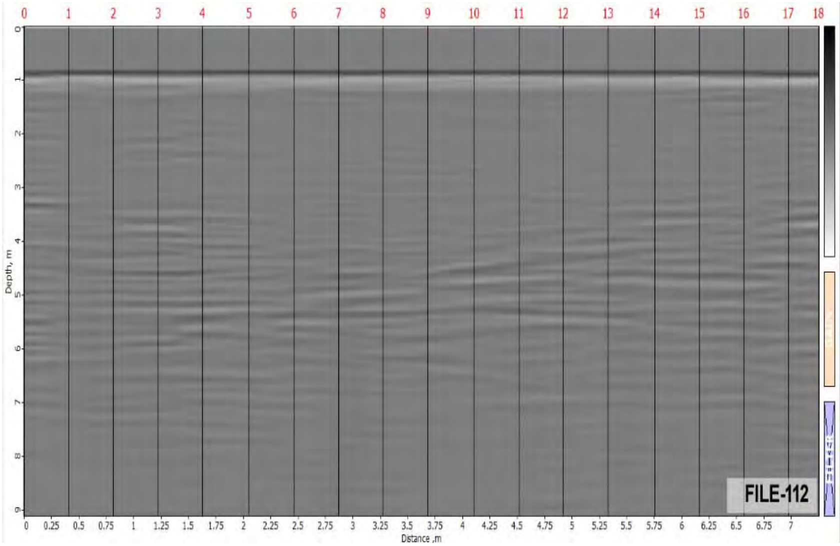

FILE-107

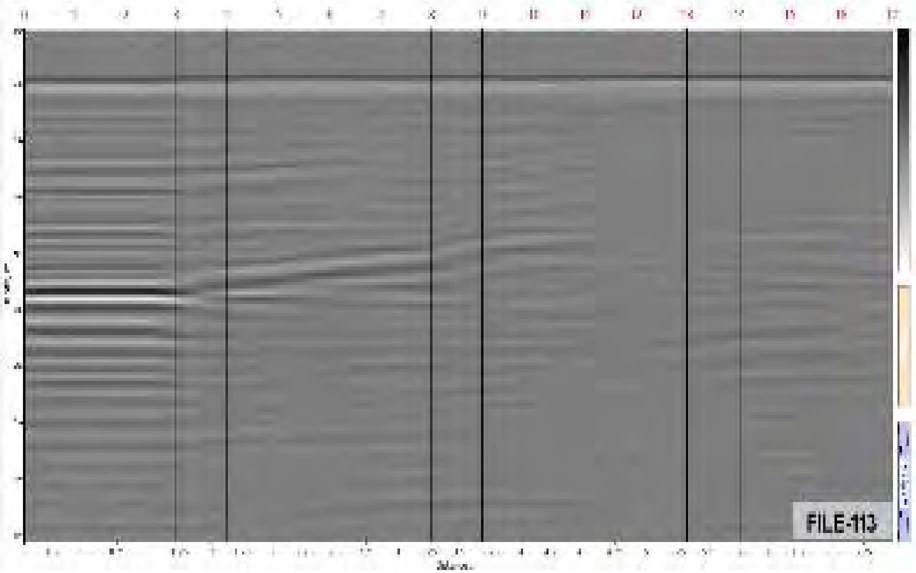

FILE-108

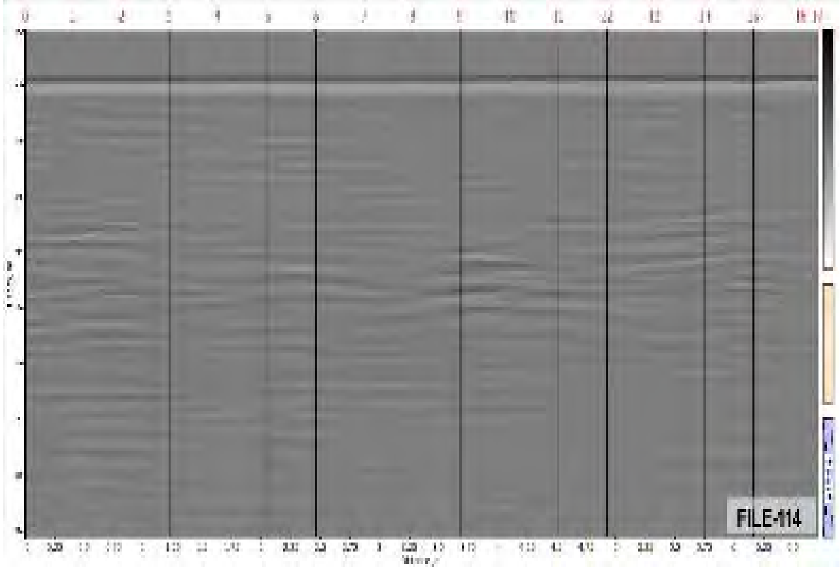

FILE-109

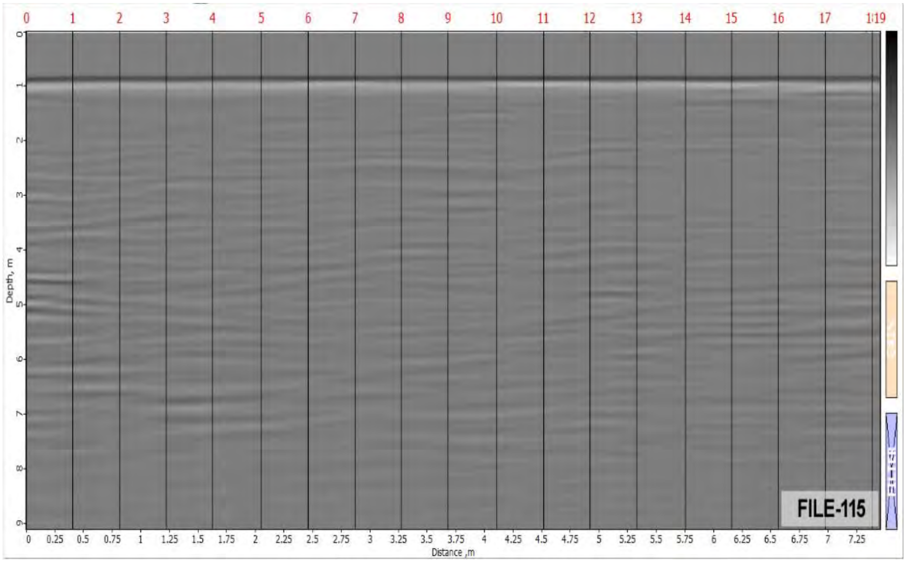

FILE-110

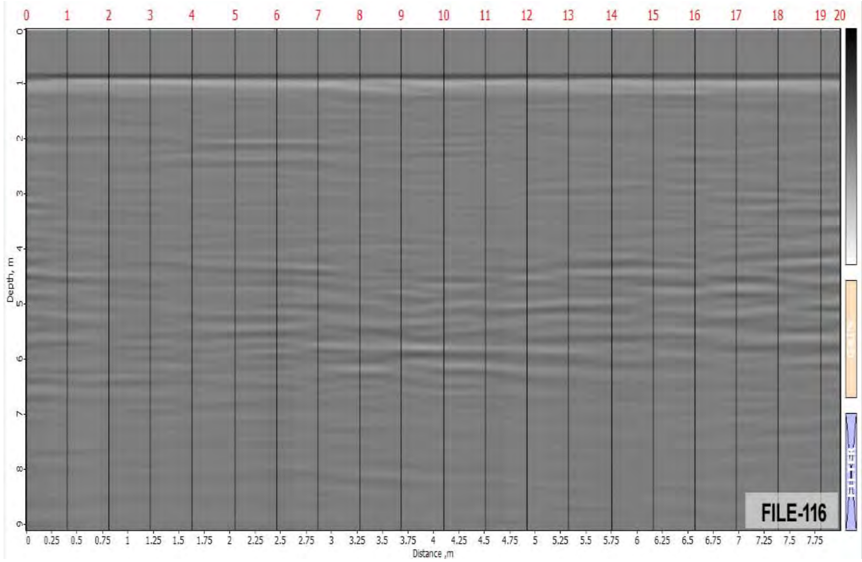

FILE-111
Depth, m
Distance ,m

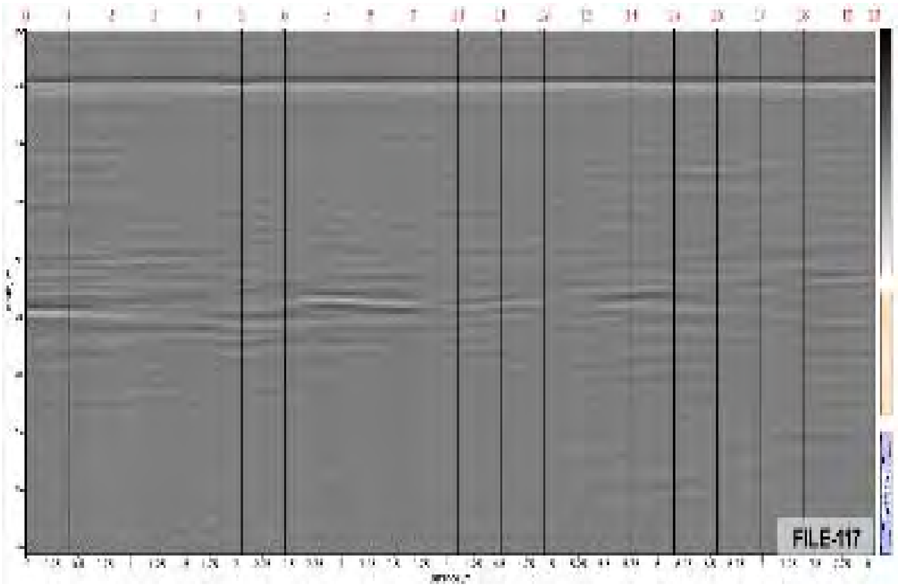

FILE-112
Depth, m
Distance ,m

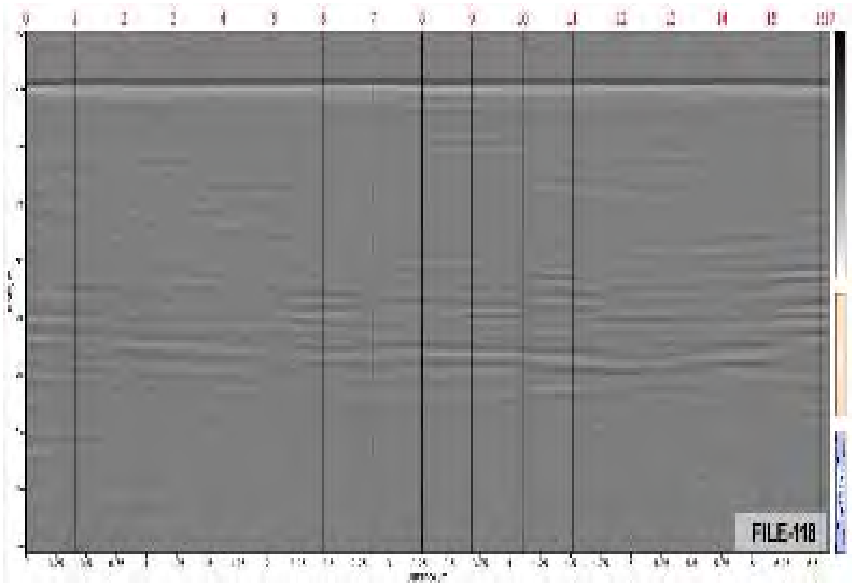

FILE-113


FILE-114


FILE-115
Depth, m
Distance ,m


FILE-116
Depth, m
Distance ,m

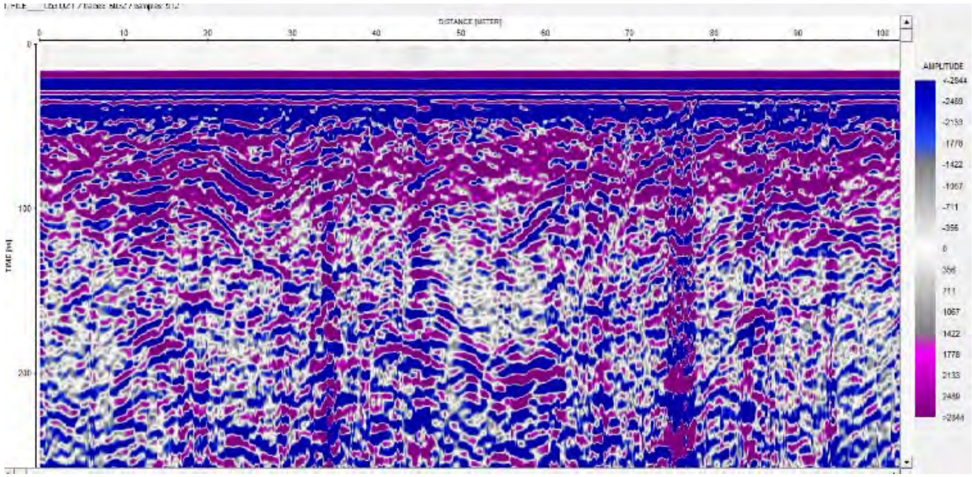

FILE-117

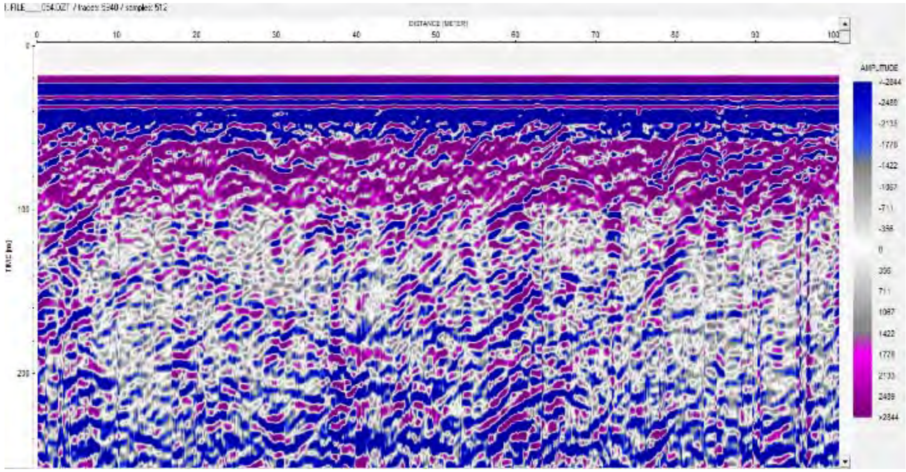

FILE-118

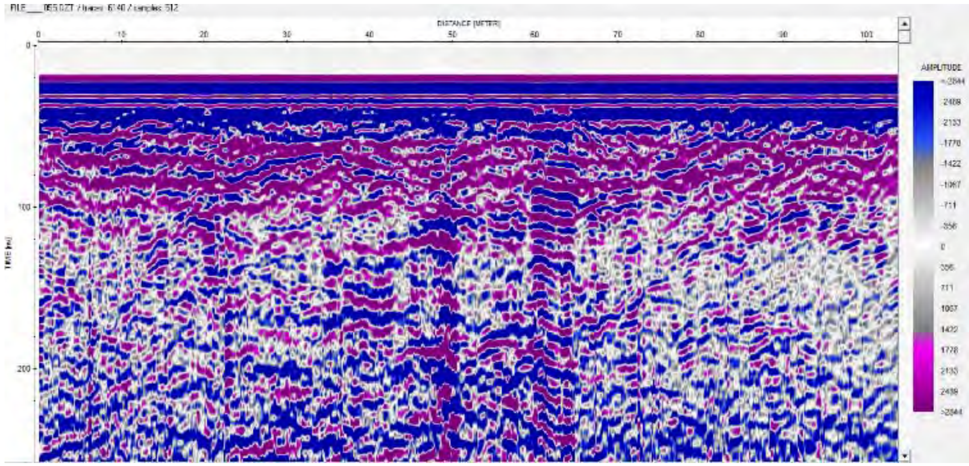
Annexure-VII

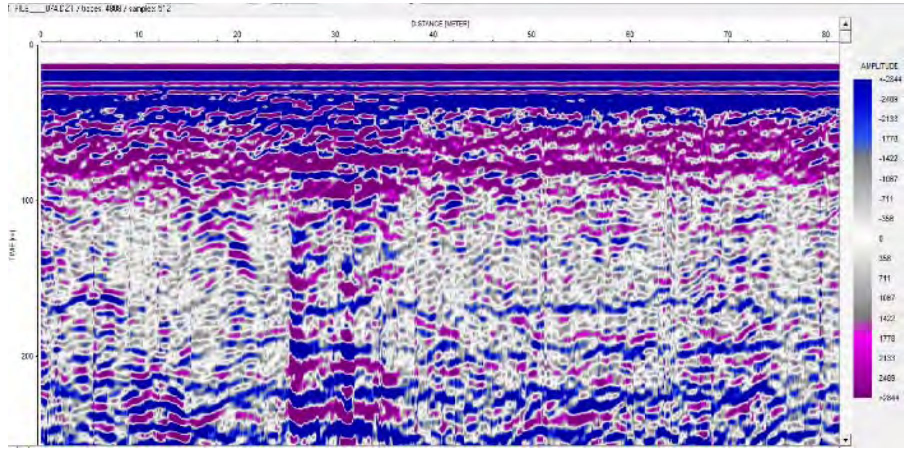
GPR PROFILES WITH 100 MHZ ANTENNA (SAVED FROM REFLEX2DQUICK SOFTWARE)

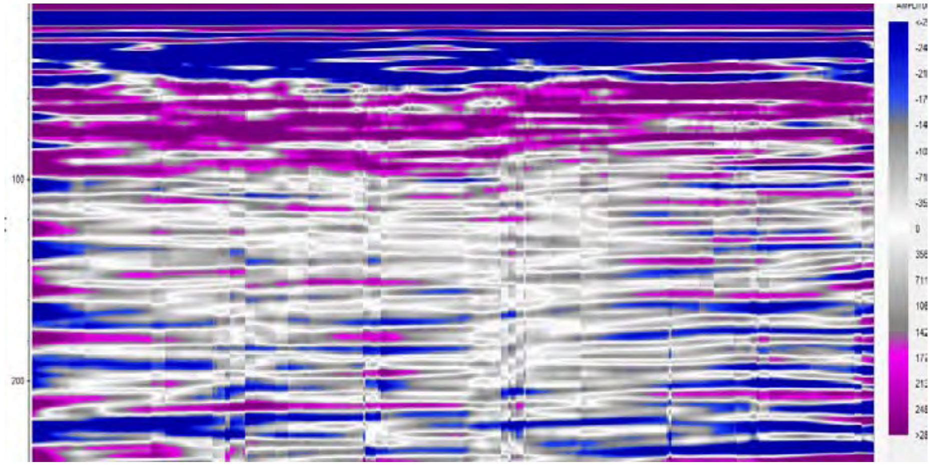
IMAGES OF GPR PROFILE SCANNED ALONG ERT-1

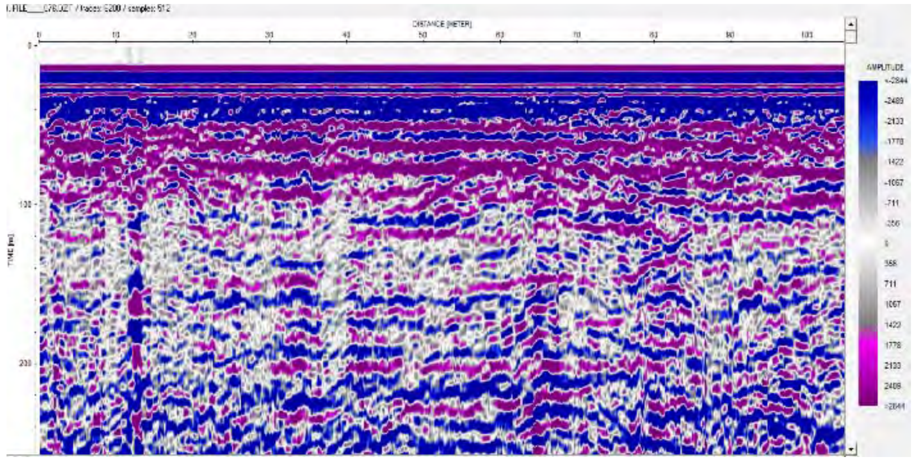


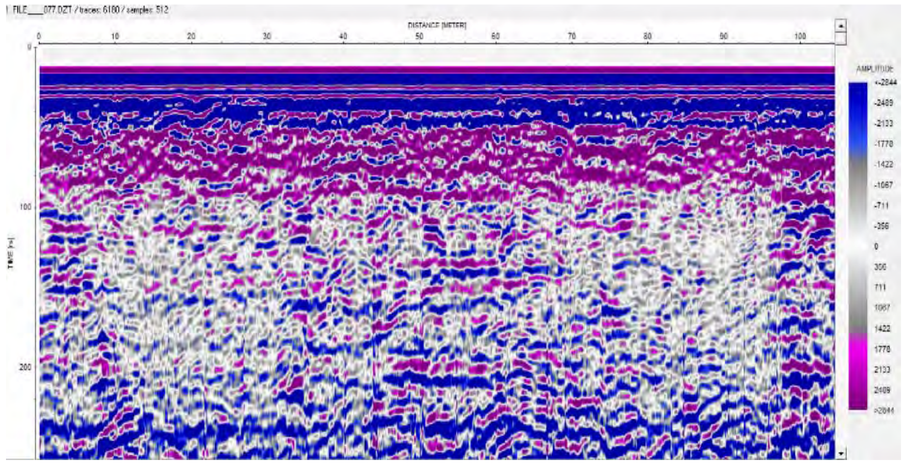




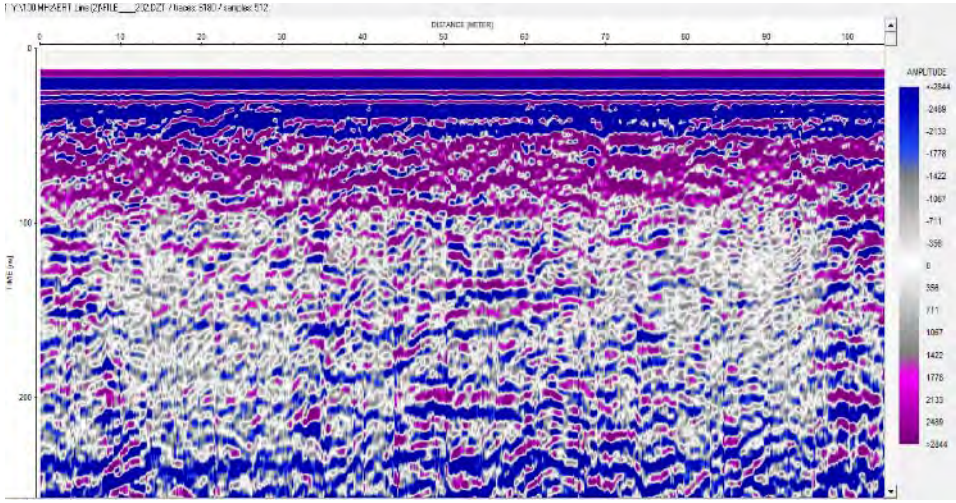


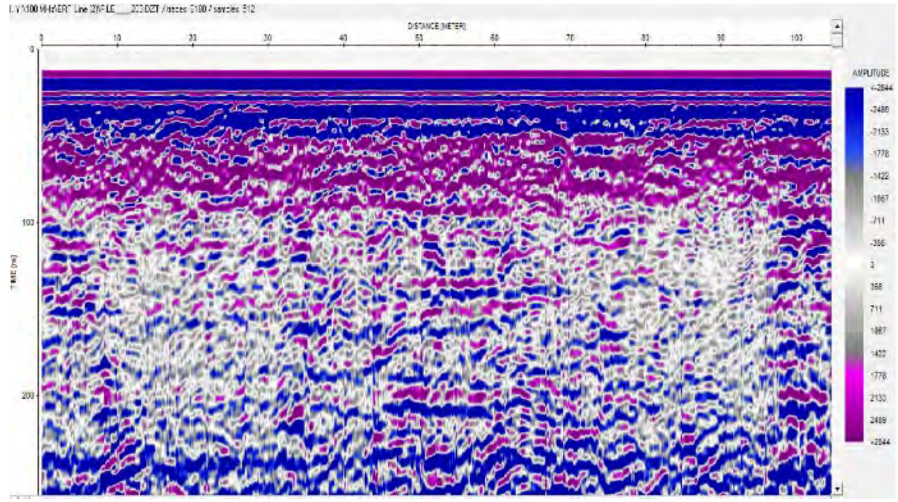


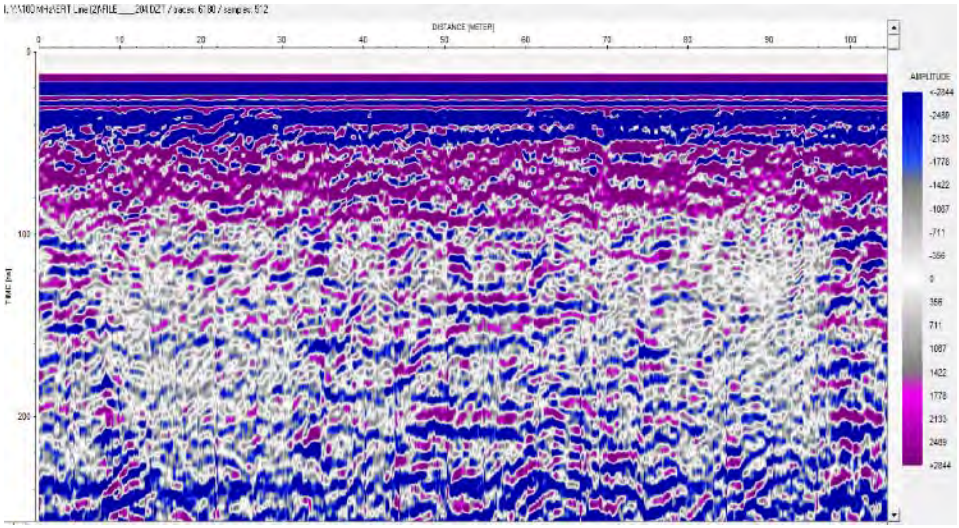

DISTANCE [METER]
AMPLITUDE

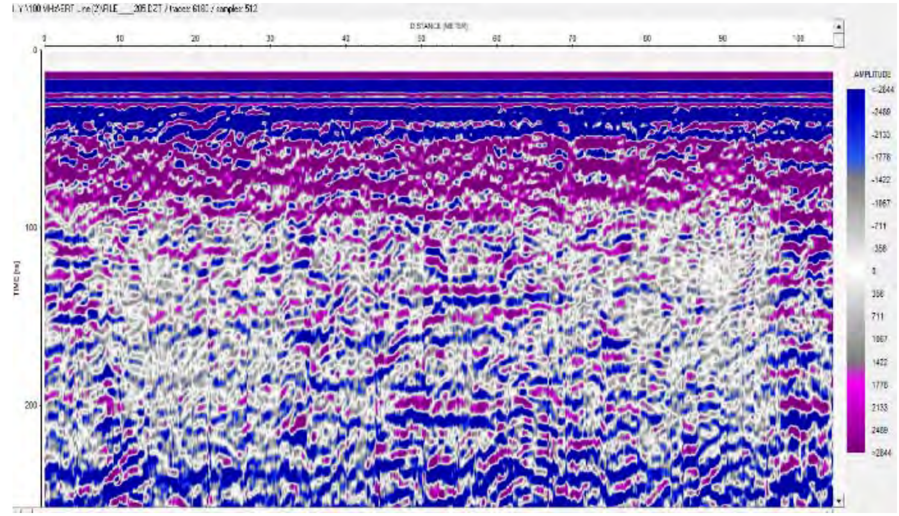

DISTANCE [METER]
AMPLITUDE

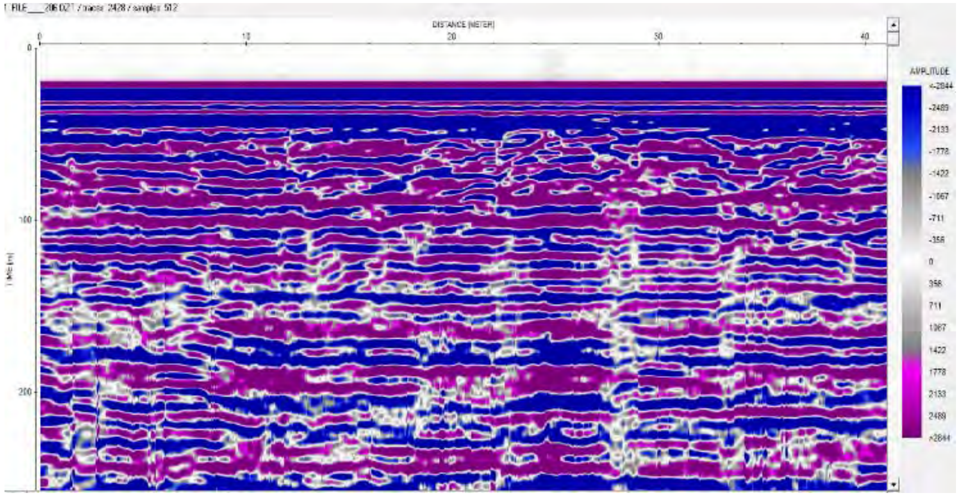
IMAGES OF GPR PROFILE SCANNED ALONG ERT-2

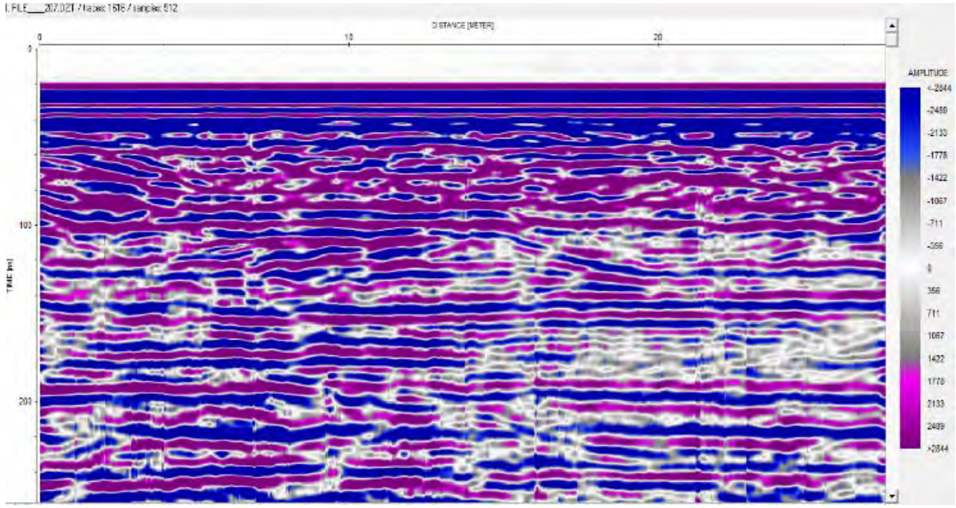


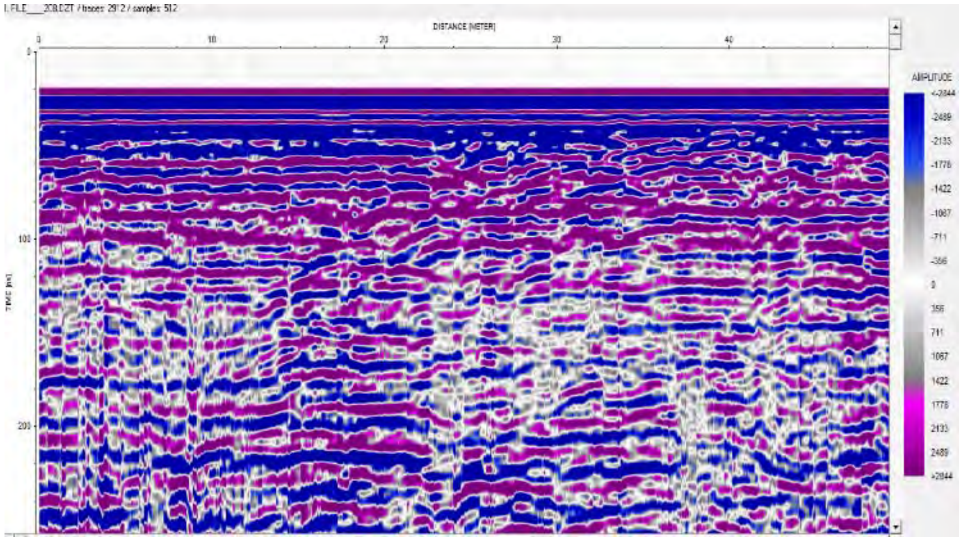


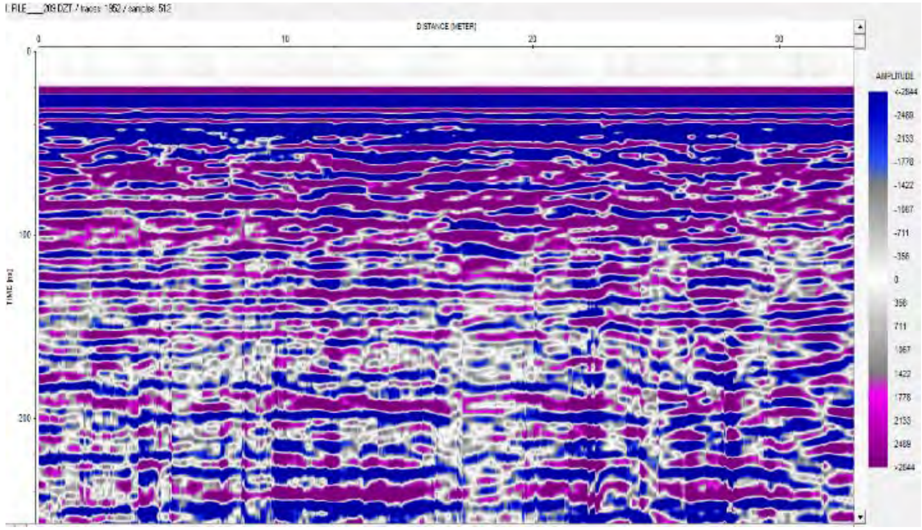




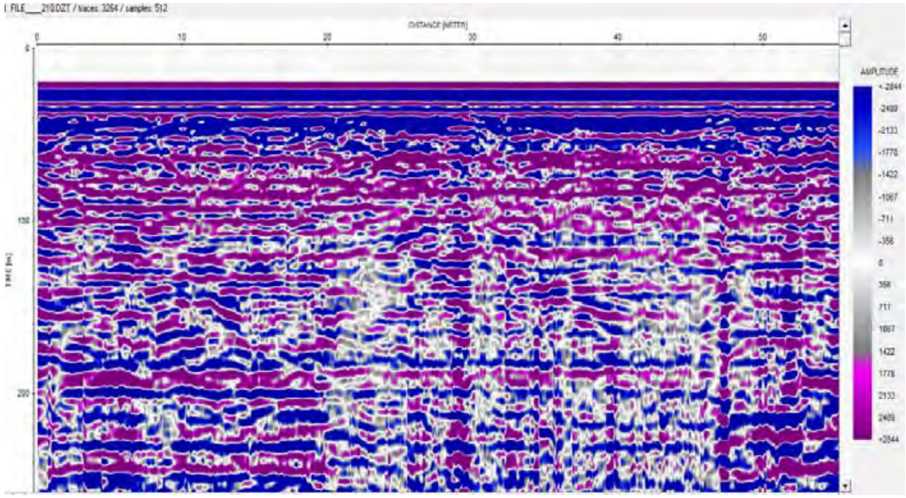

DISTANCE [METER]
AMPLITUDE

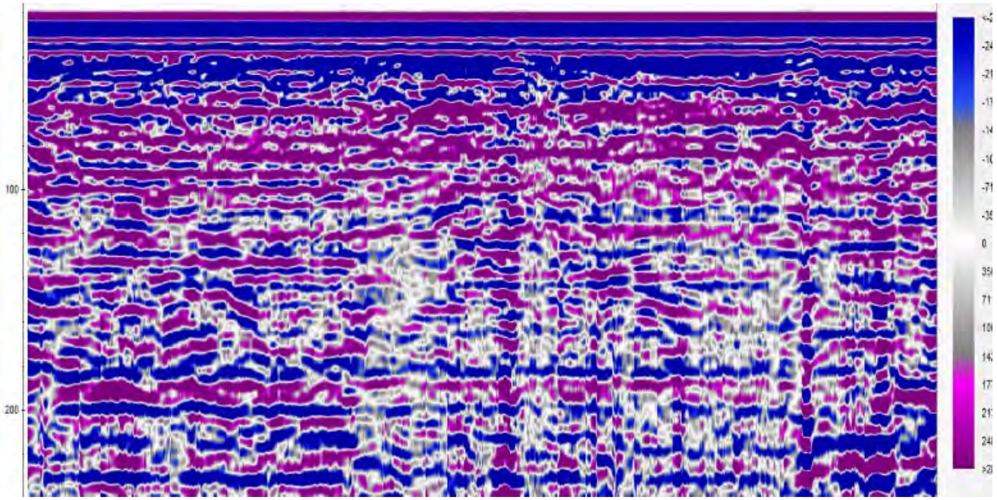

DISTANCE [METER]
AMPLITUDE

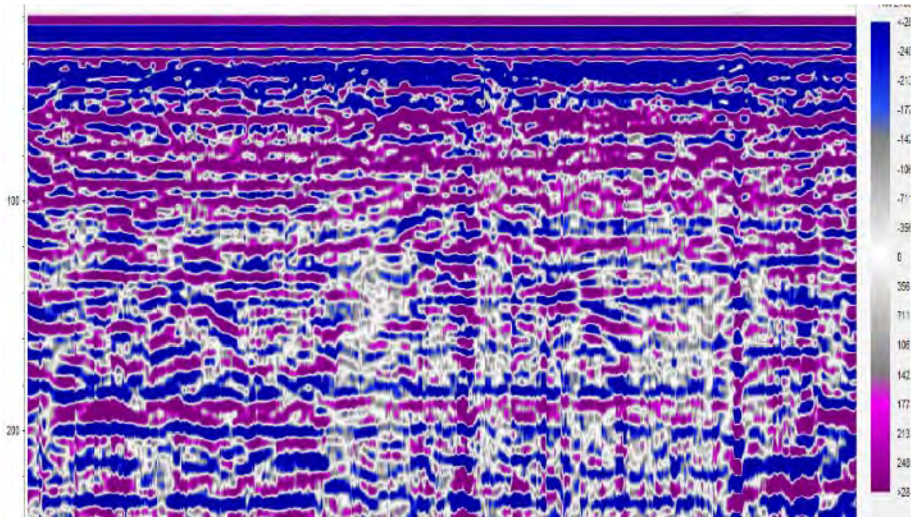

DISTANCE [METER]
AMPLITUDE

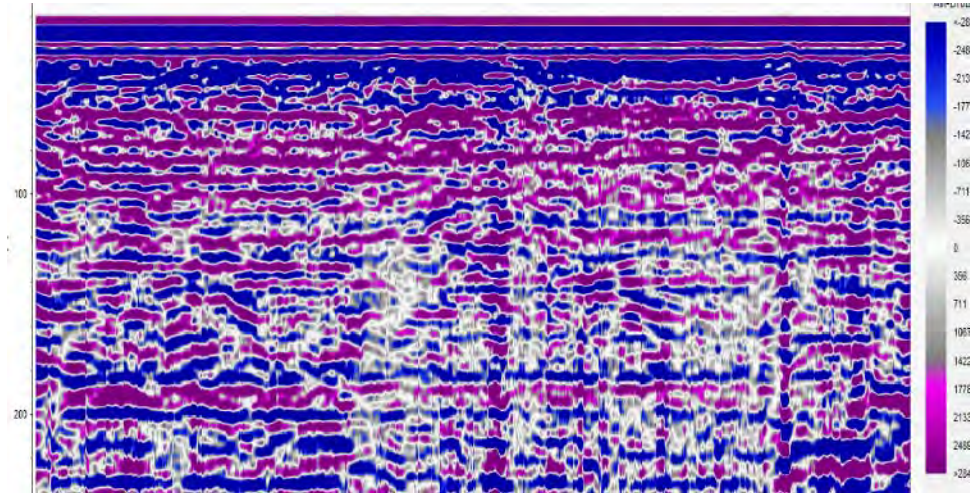

DISTANCE [METER]
AMPLITUDE

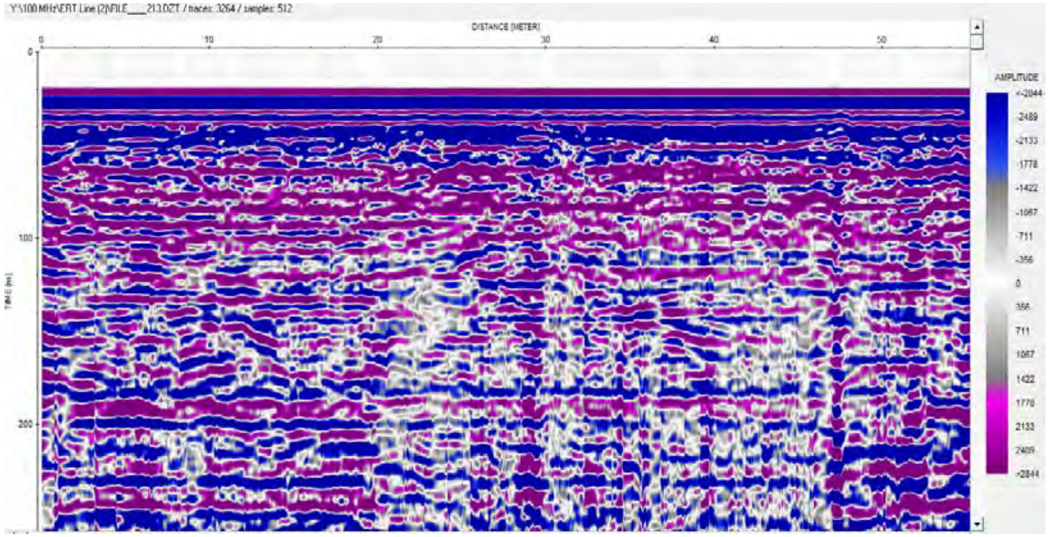
Annexure-VII: GPR Profiles with 100MHz Antenna using Reflex2DQuick software



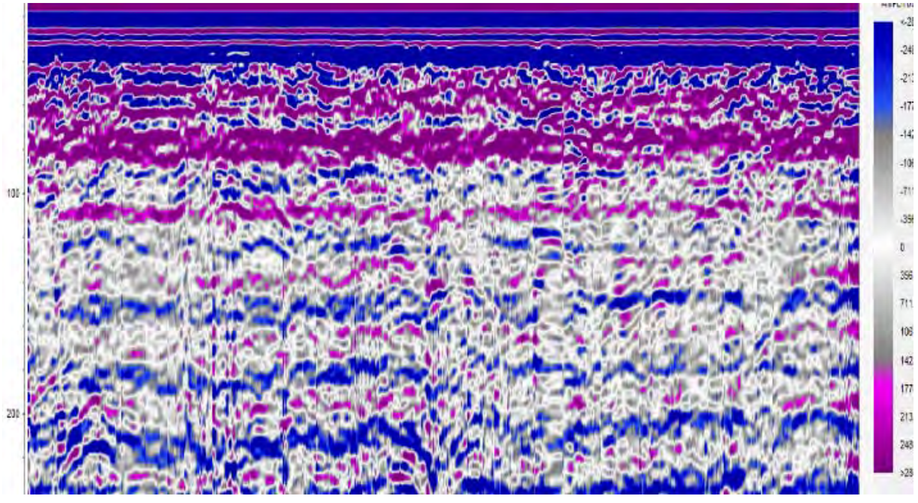


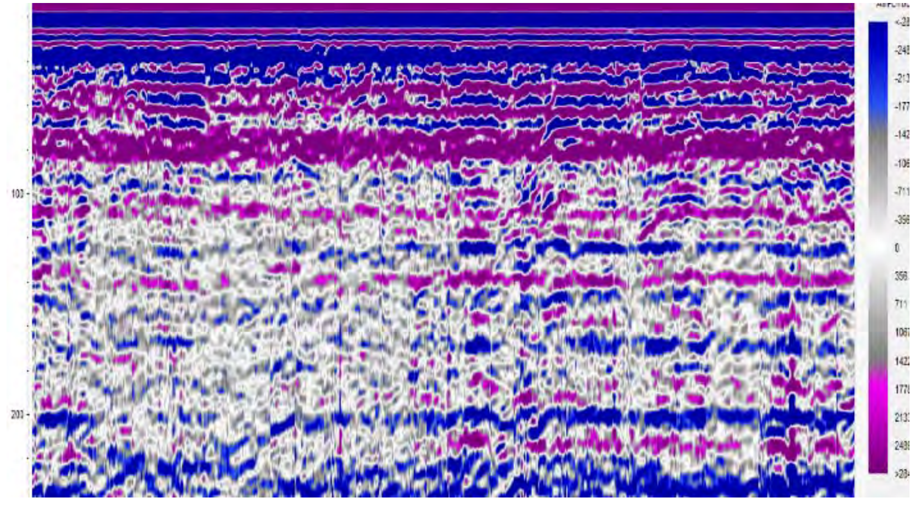


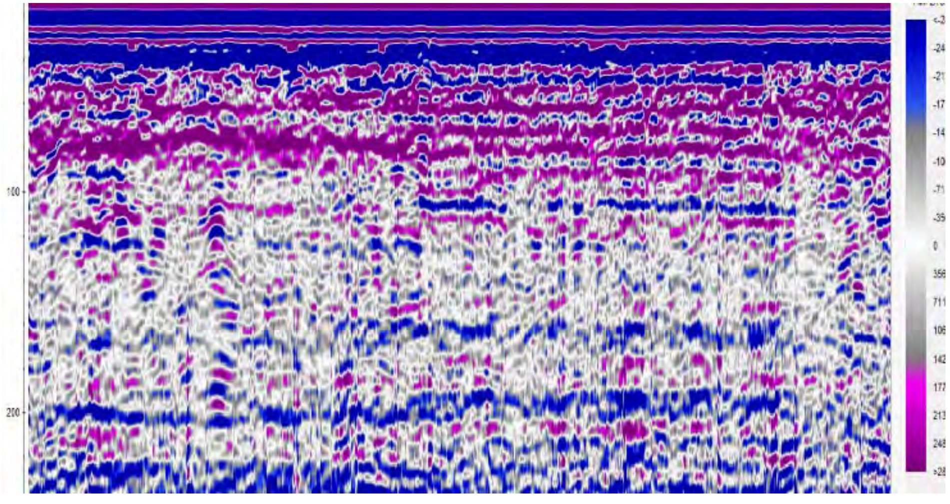


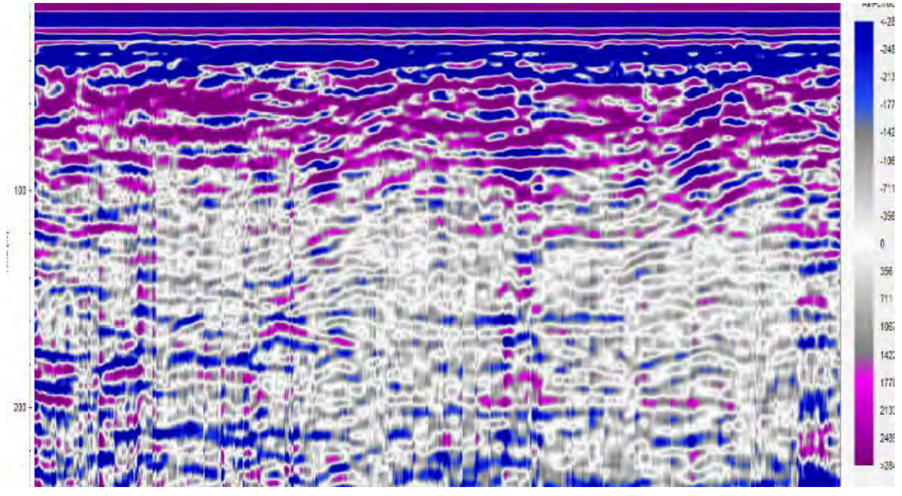

Y:\100 MHz\ERT Line (2)\FILE____213.DZT / traces: 3264 / samples: 512
DISTANCE [METER]
0
10
20
30
40
50
0
100
200
TIME [ns]
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

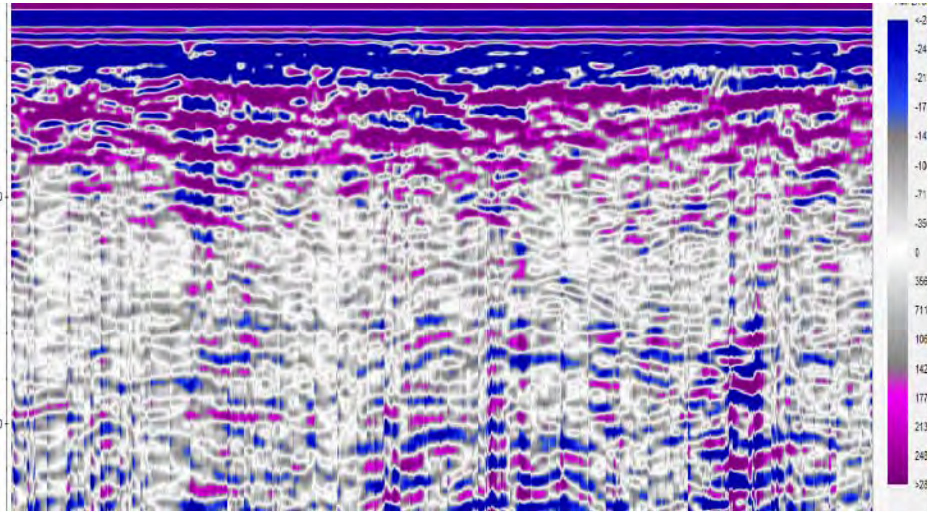
IMAGES OF GPR PROFILE SCANNED ALONG ERT-3

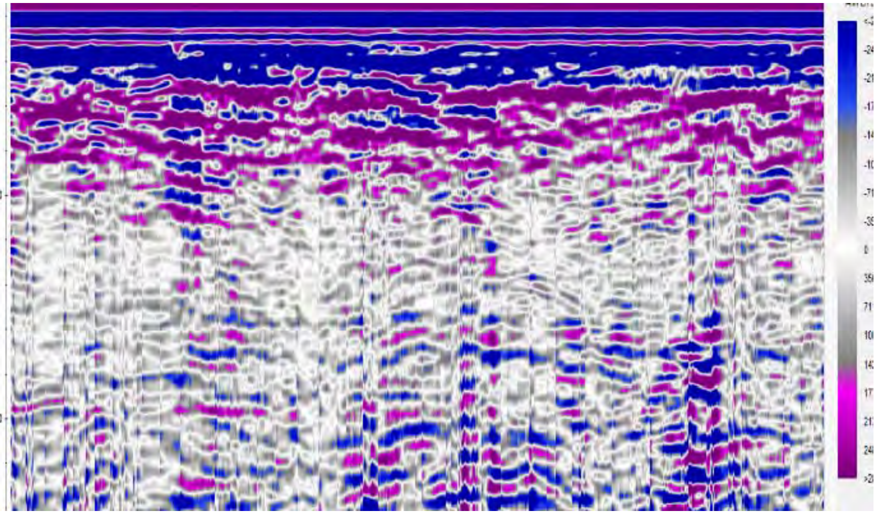


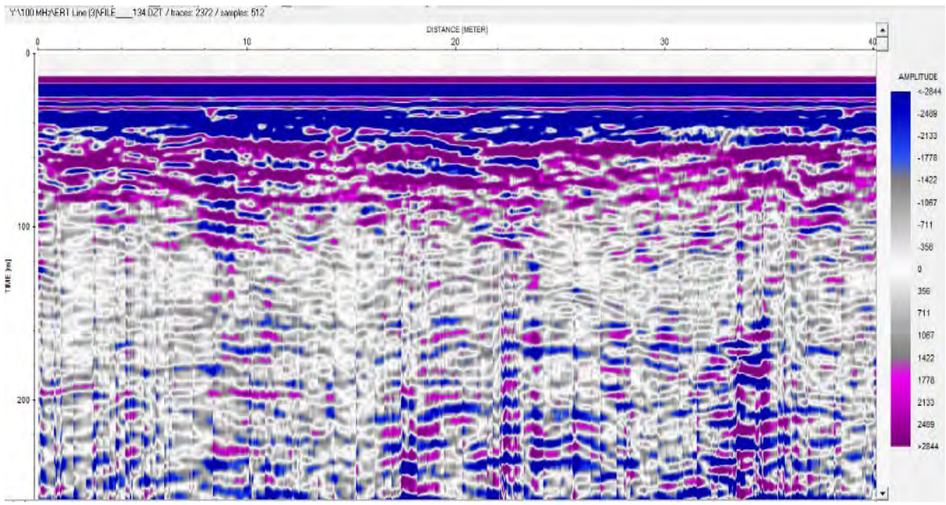


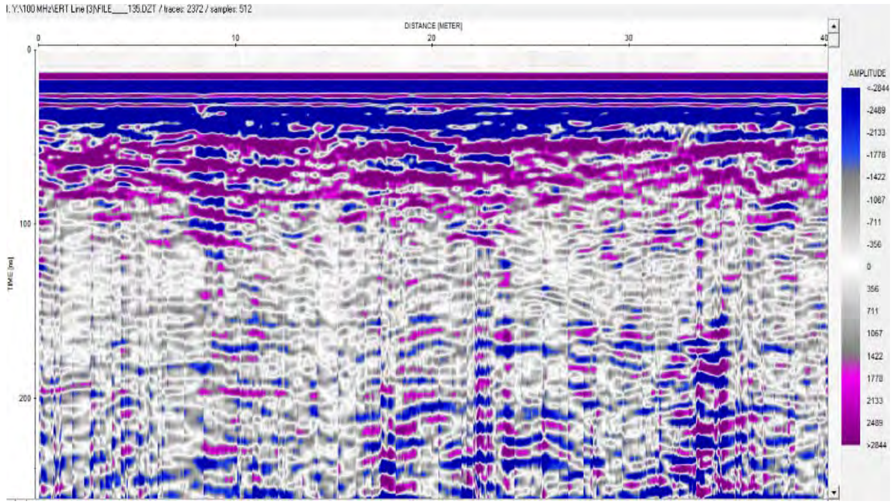




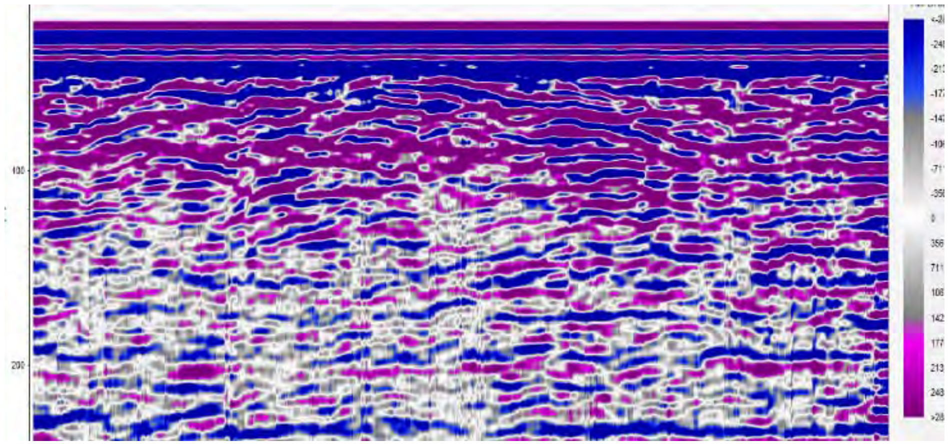

100
200

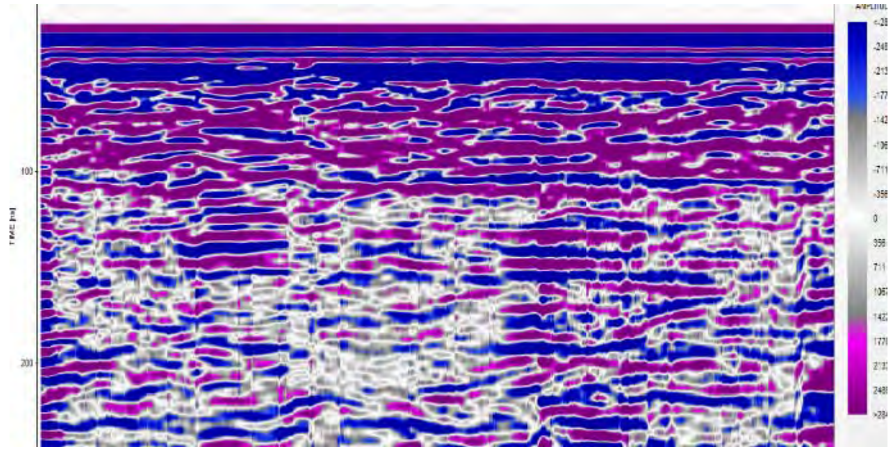

100
200

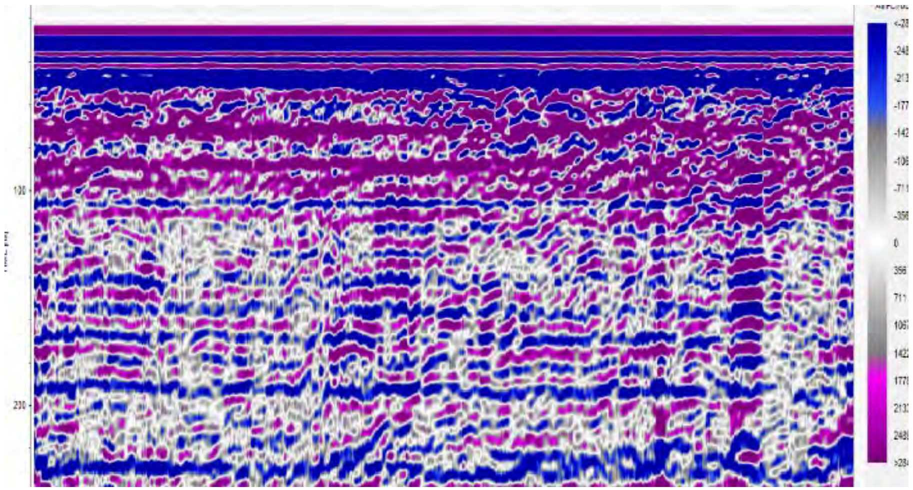

Y:\100 MHz\ERT Line (3)\FILE___134.DZT / traces: 2372 / samples: 512
DISTANCE (METER)
0
10
20
30
40
TIME [ns]
100
200
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

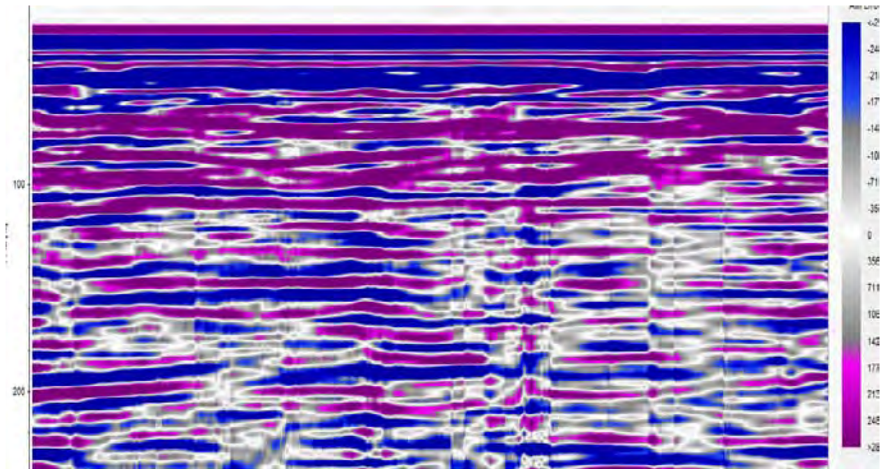

Y:\100 MHz\ERT Line (3)\FILE___135.DZT / traces: 2372 / samples: 512
DISTANCE (METER)
0
10
20
30
40
TIME [ns]
100
200
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

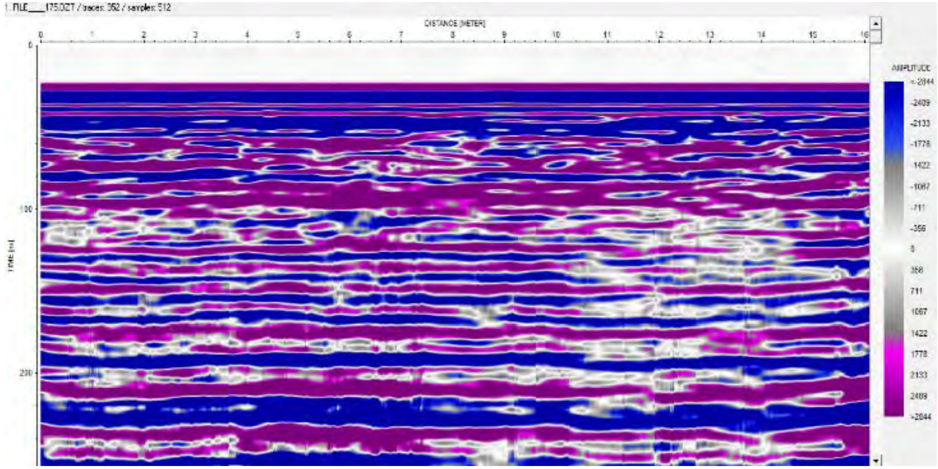
IMAGES OF GPR PROFILE SCANNED ALONG ERT-4

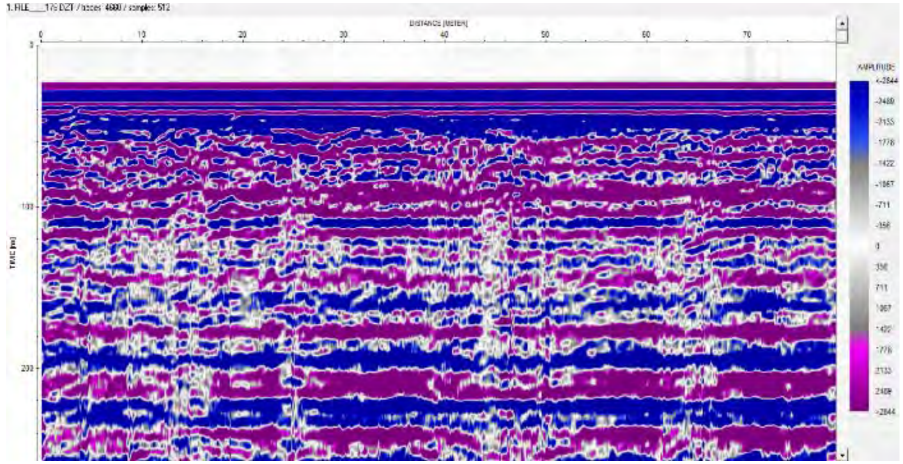


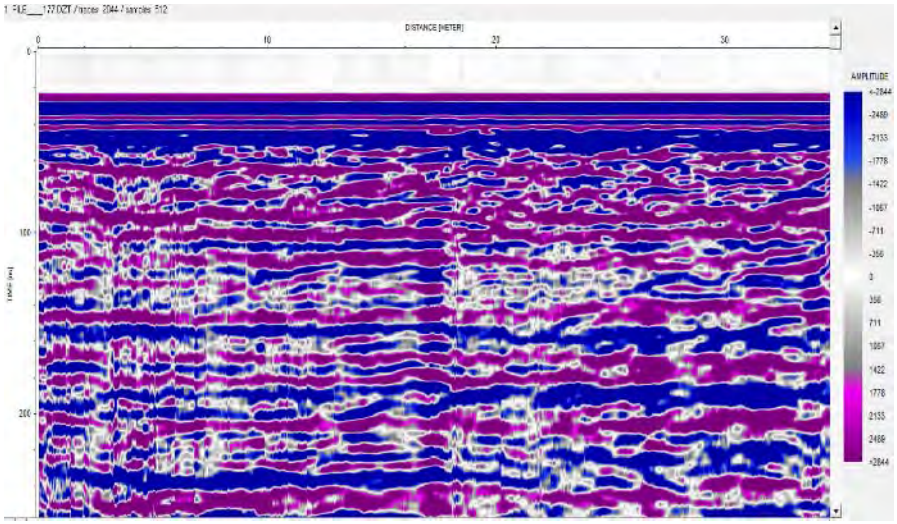


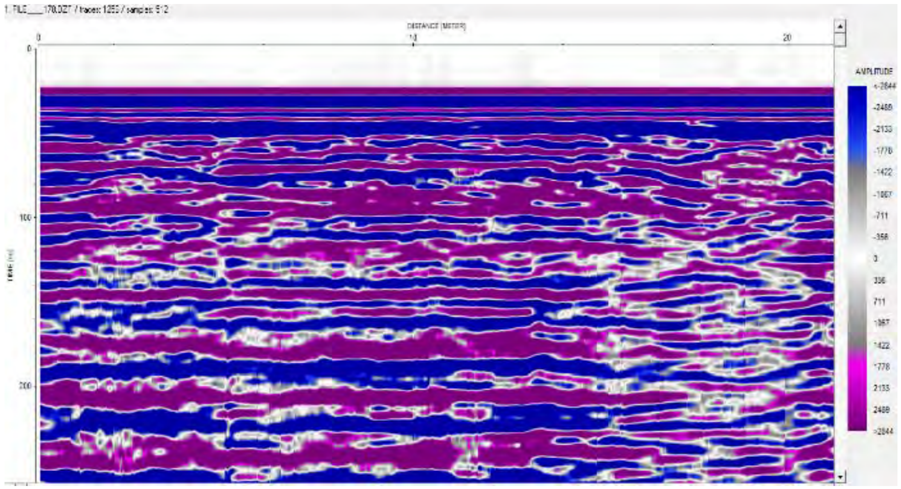


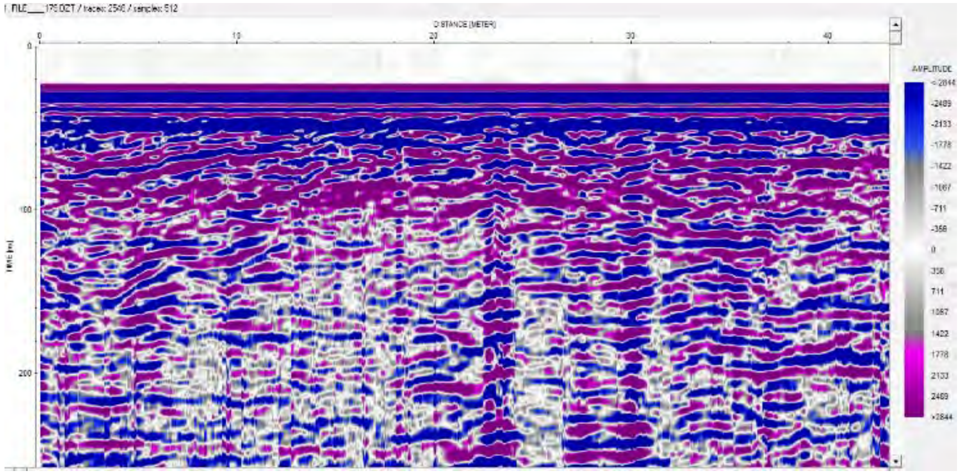


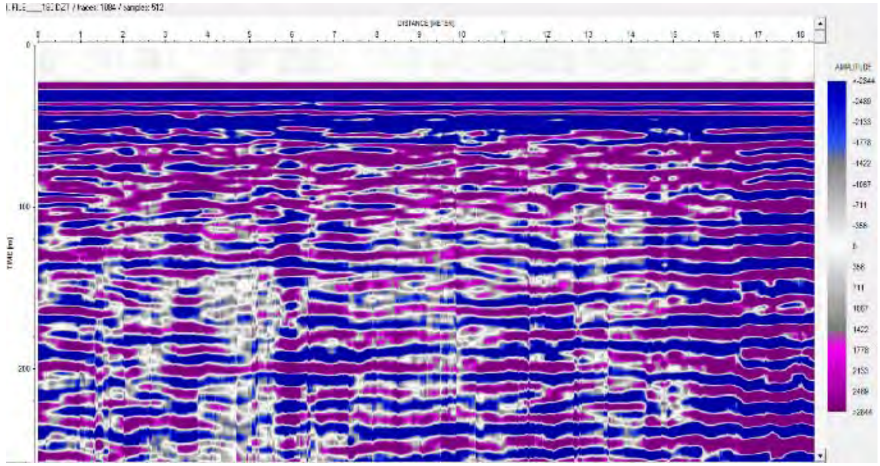


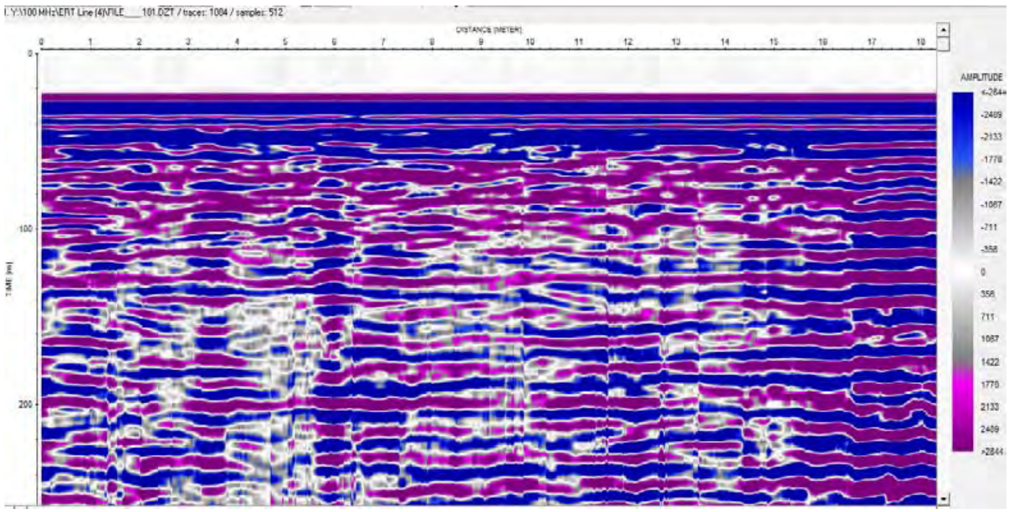




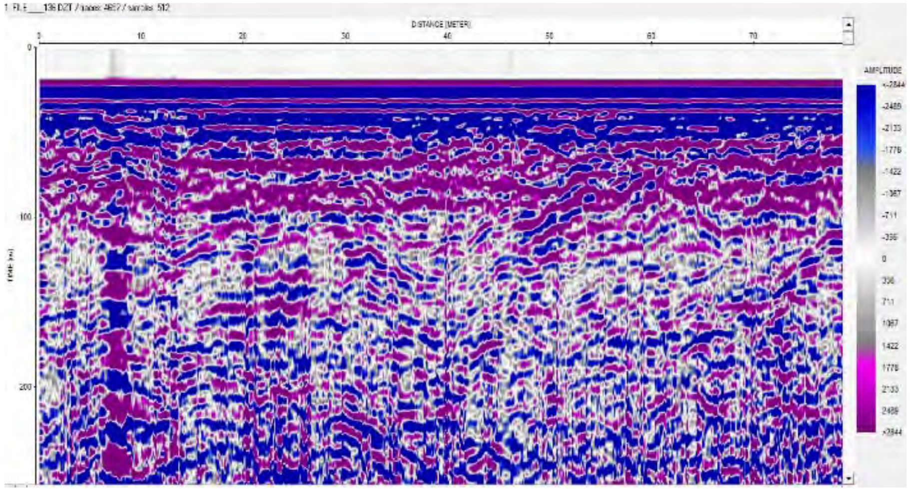


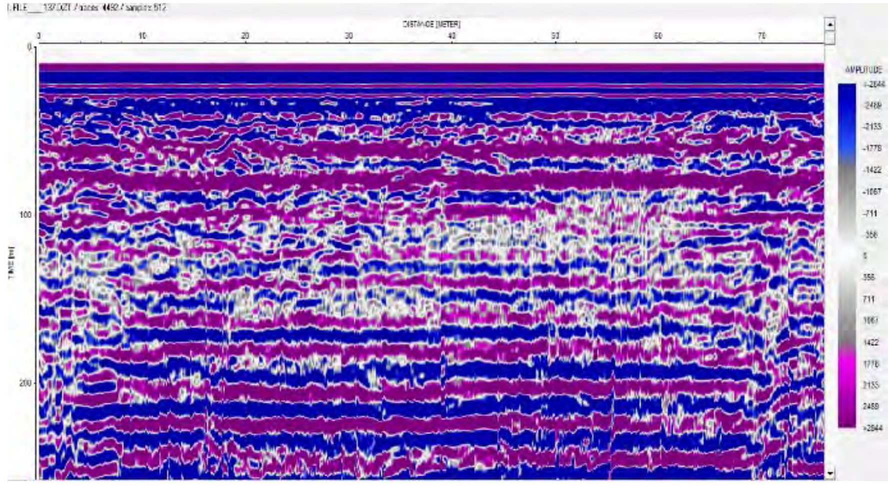

FILE___175.DZT / traces: 2540 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]

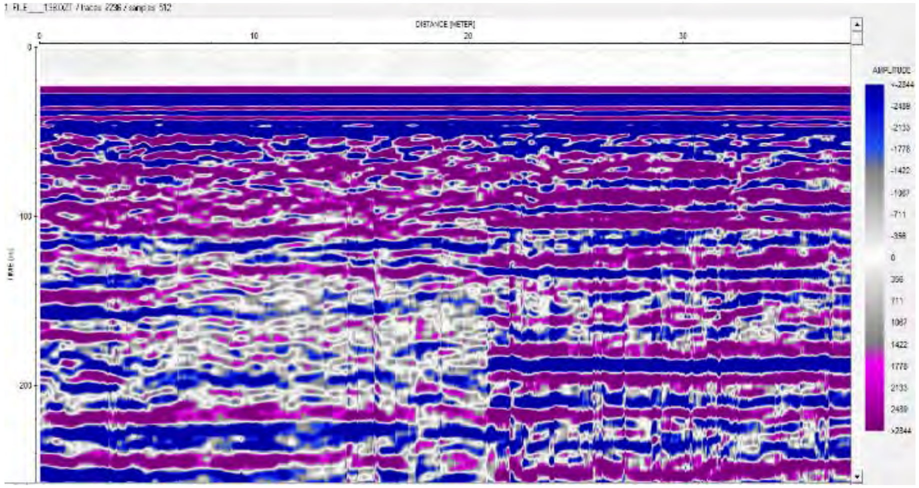

FILE___DZT / traces: 1084 / samples: 512
AMPLITUDE
TIME [ns]

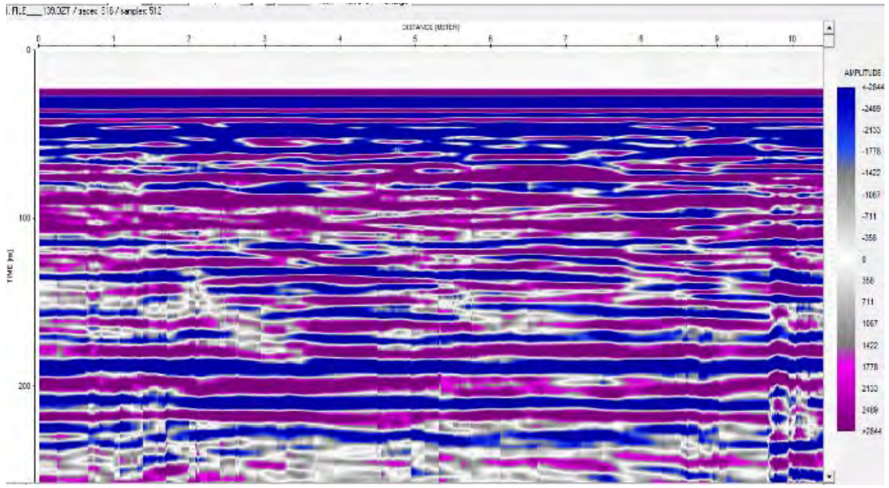

Y:\100 MHz\ERT Line (4)\FILE___101.DZT / traces: 1084 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]

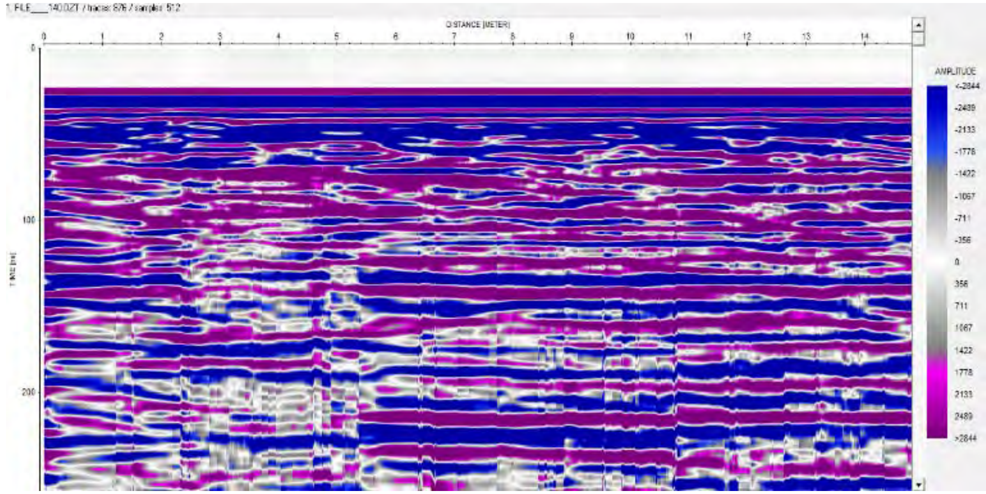
IMAGES OF GPR PROFILE SCANNED ALONG ERT-5

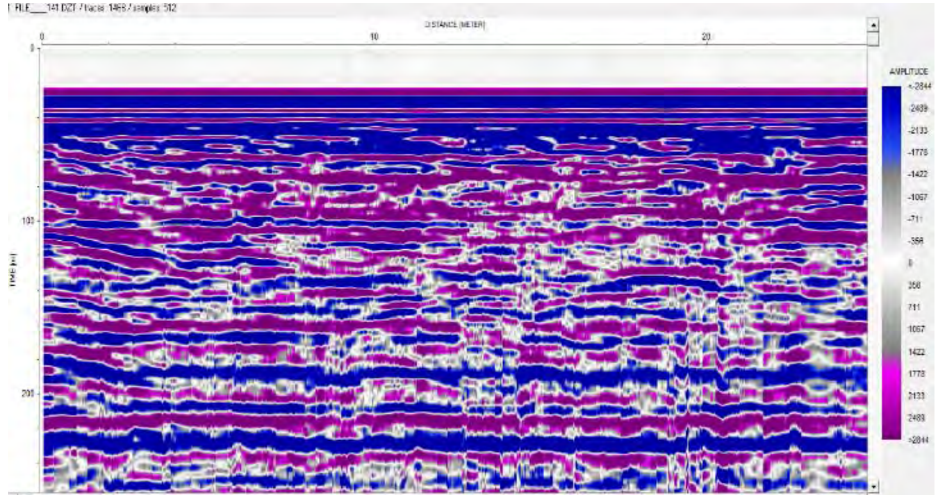


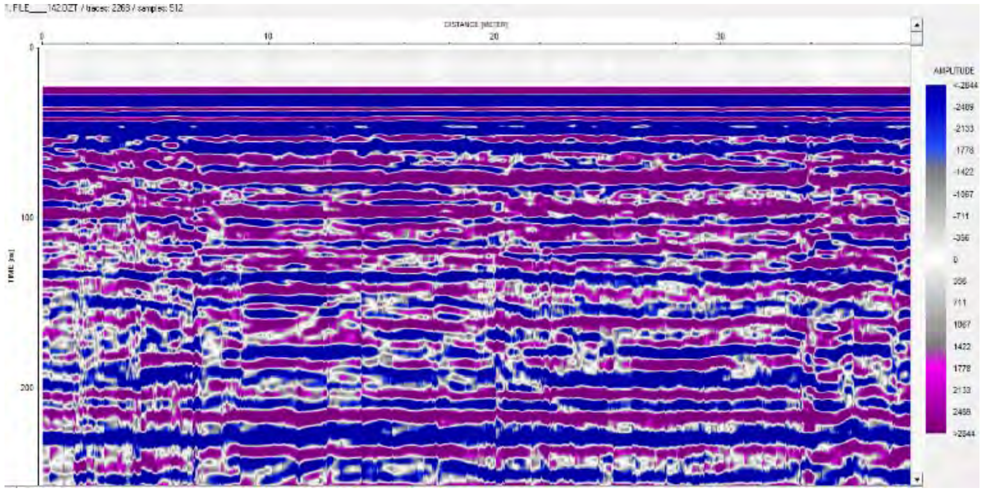


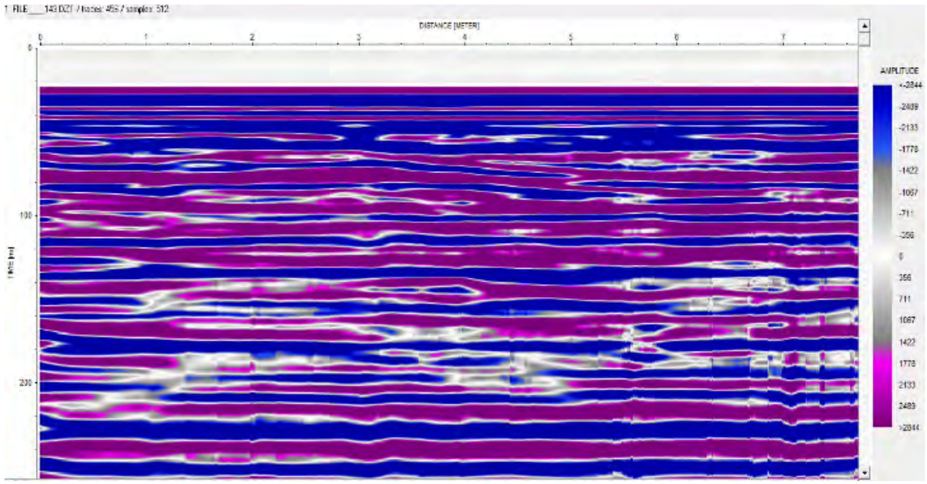




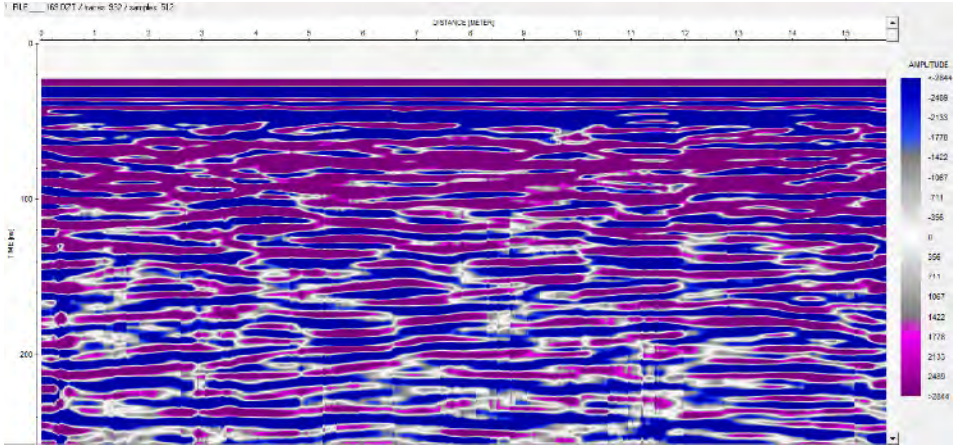

1. FILE___140.DZT / traces: 876 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]

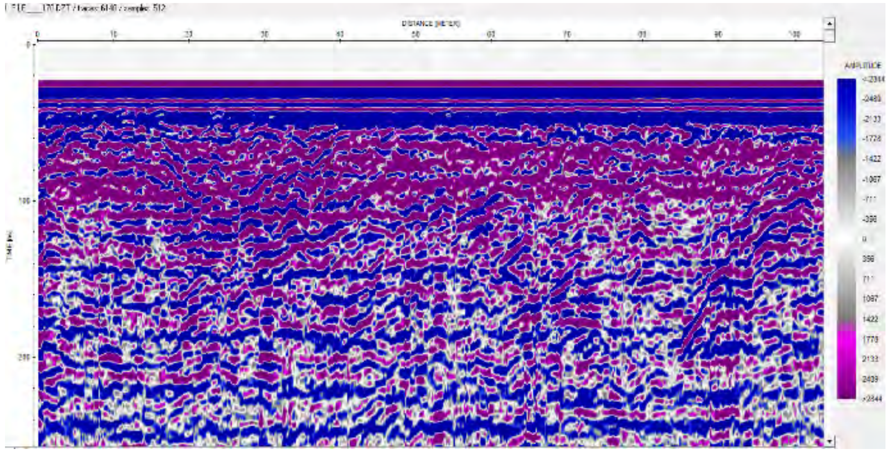

1. FILE___141.DZT / traces: 1468 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]


1. FILE___142.DZT / traces: 2263 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]

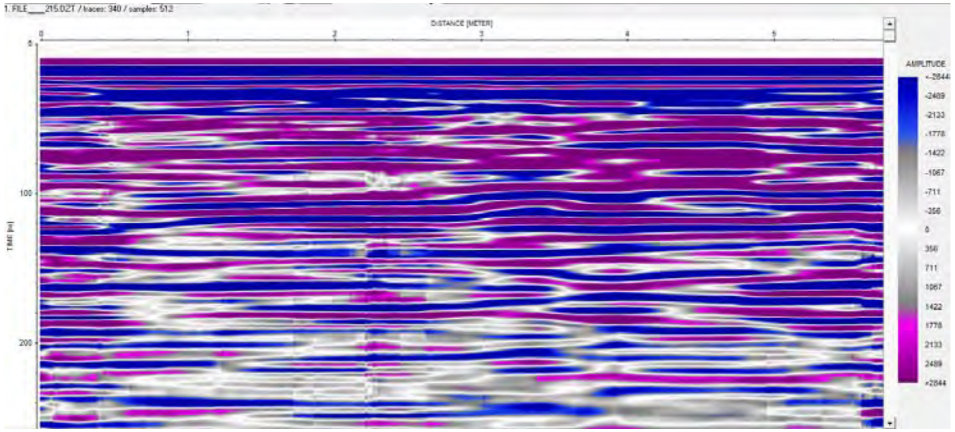

1. FILE___143.DZT / traces: 456 / samples: 512
DISTANCE [METER]
AMPLITUDE
TIME [ns]

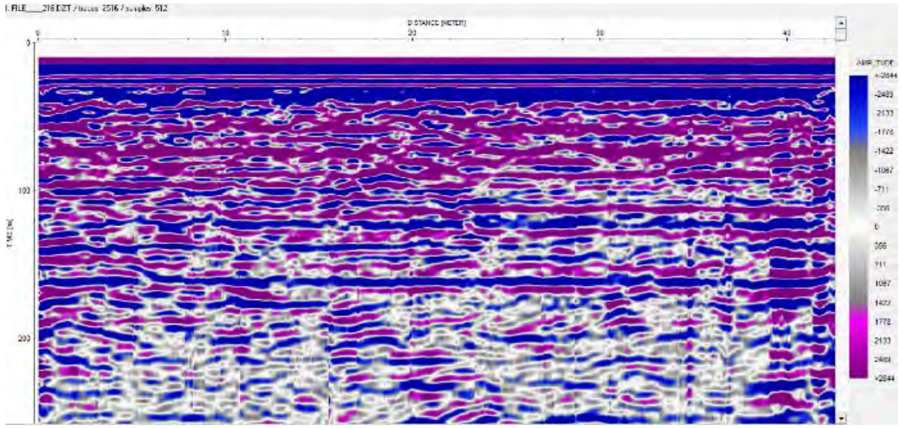
IMAGES OF GPR PROFILE SCANNED ALONG ERT-6

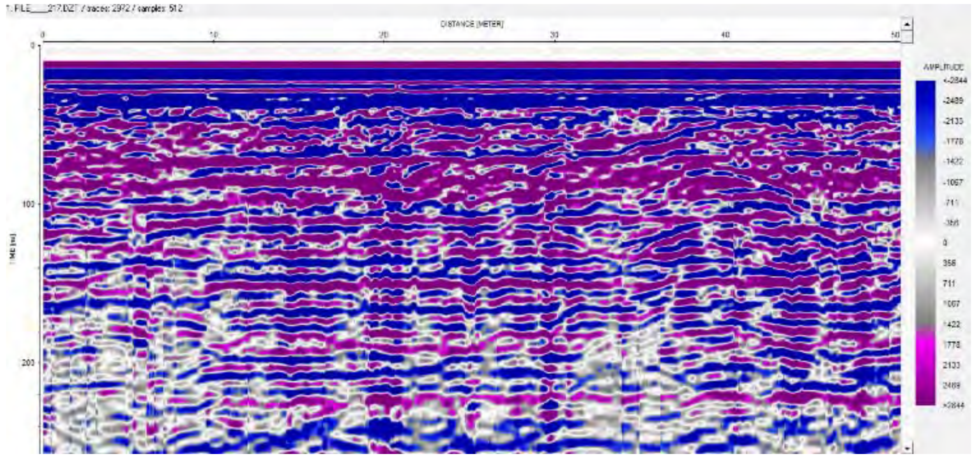


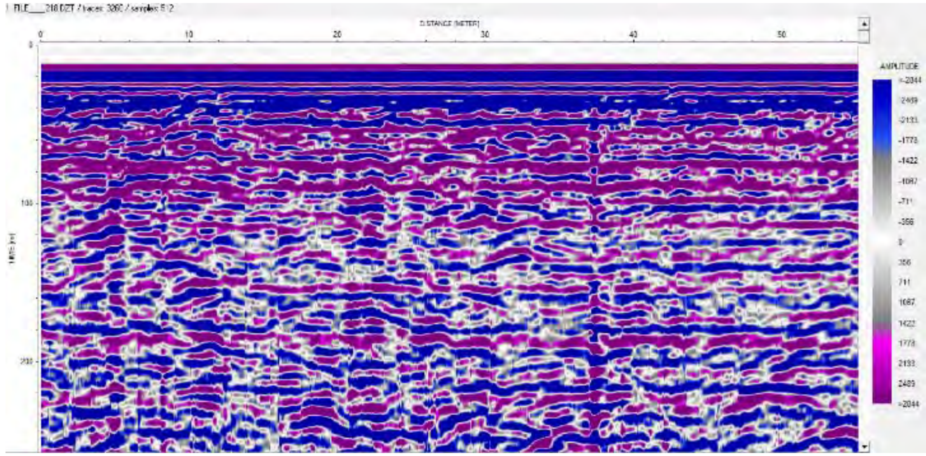


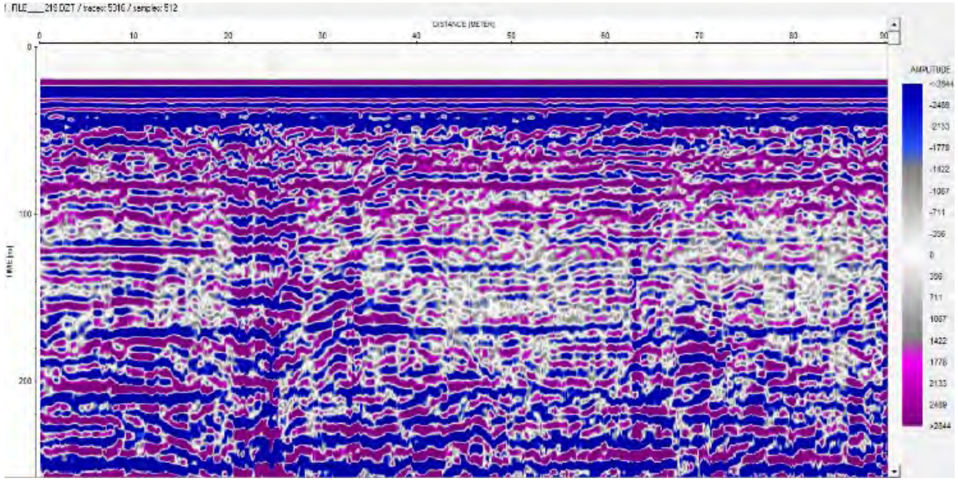
IMAGES OF GPR PROFILE SCANNED ALONG ERT-7

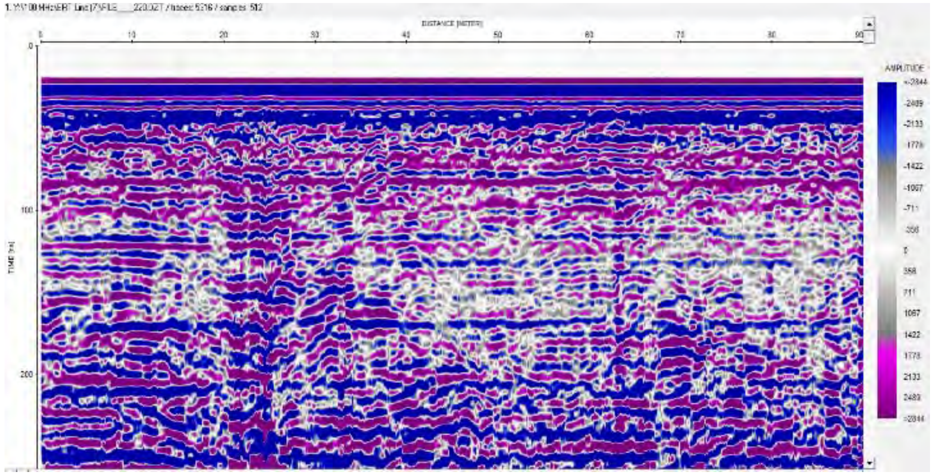


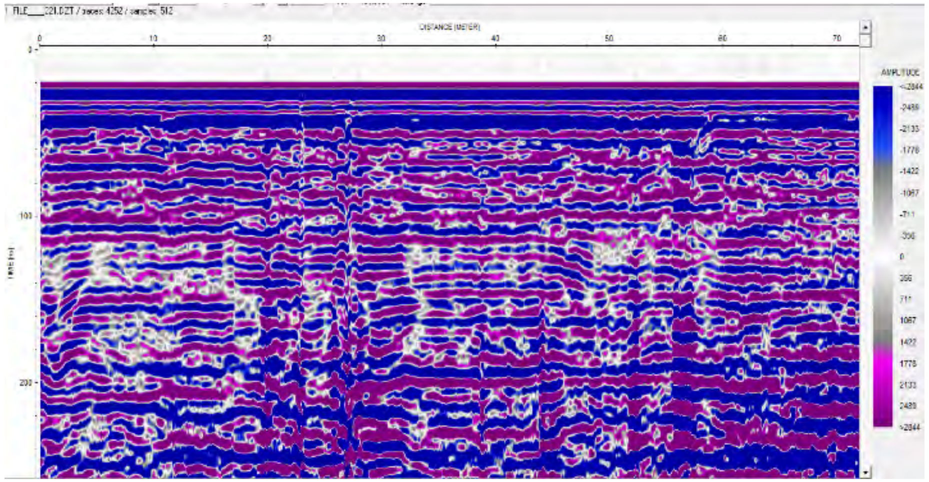


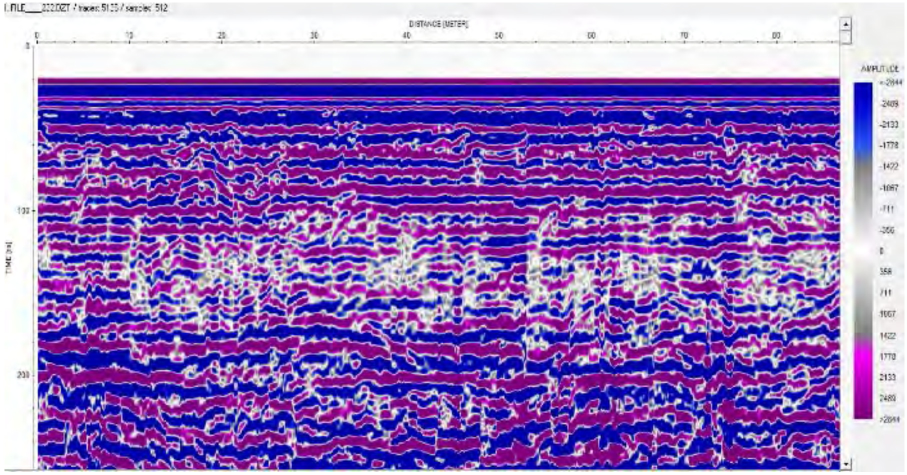




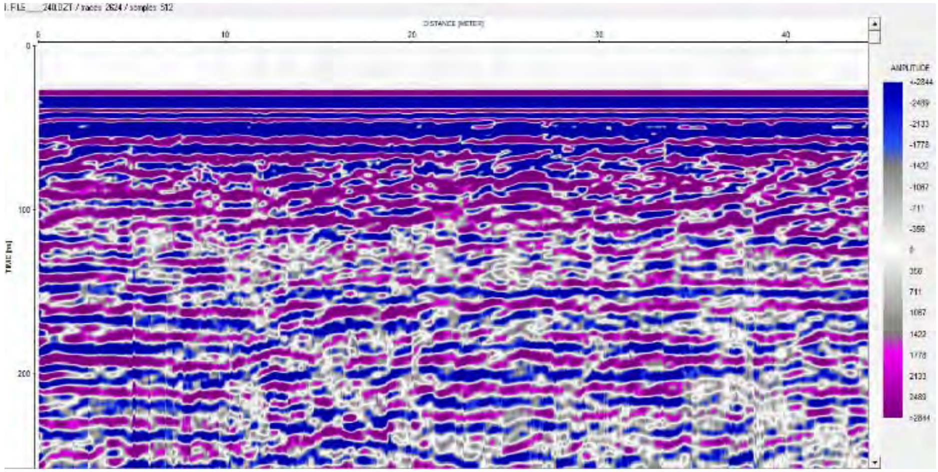


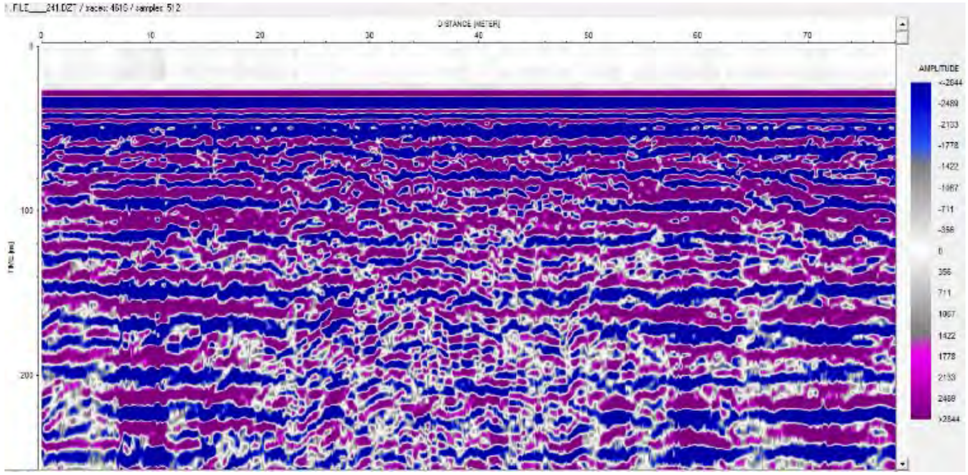


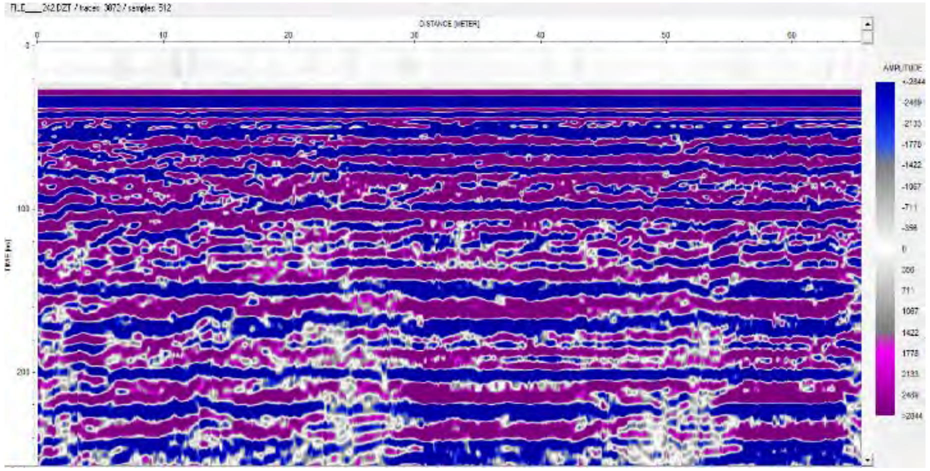


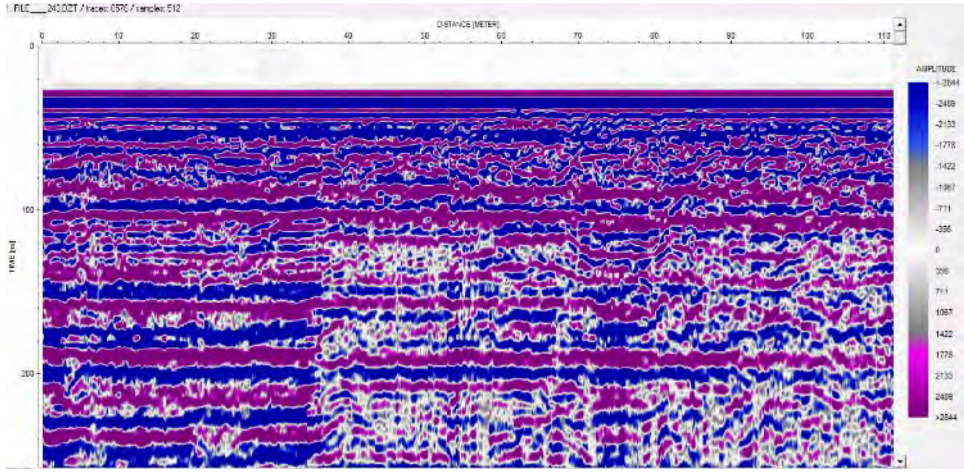


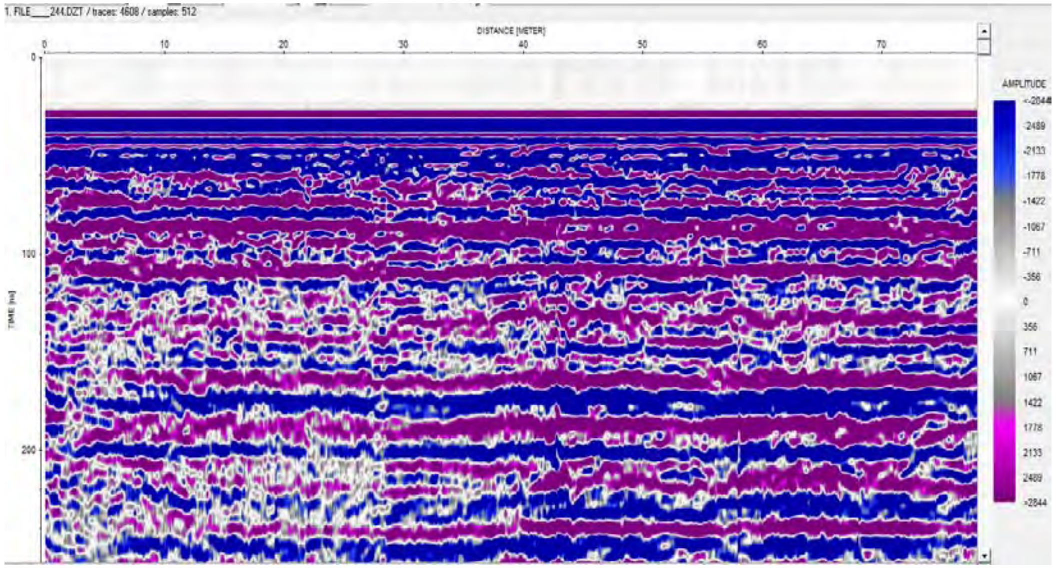
<u>IMAGES OF GPR PROFILE SCANNED ALONG ERT-8</u>



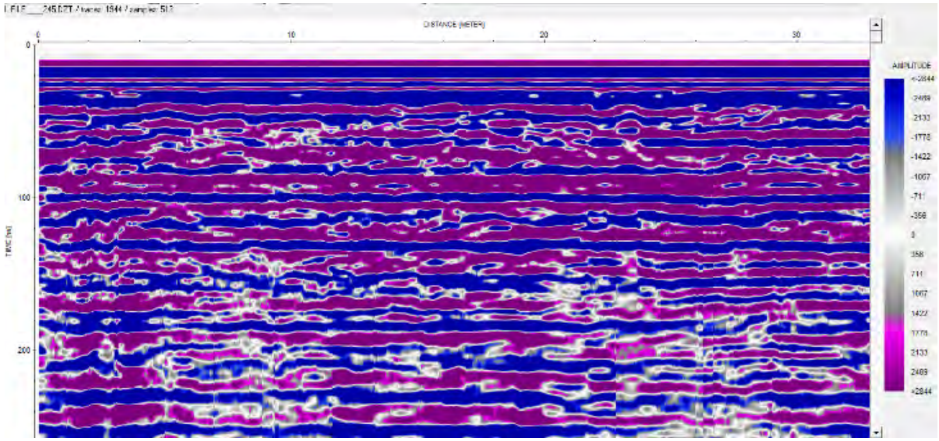


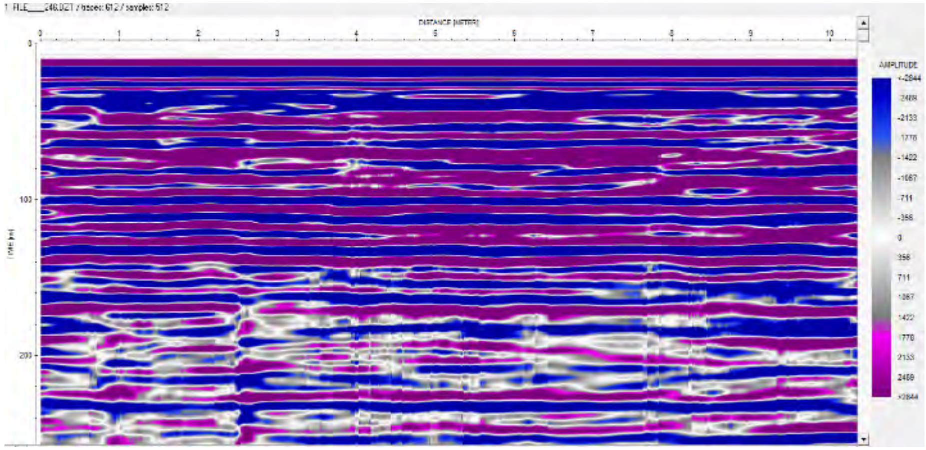


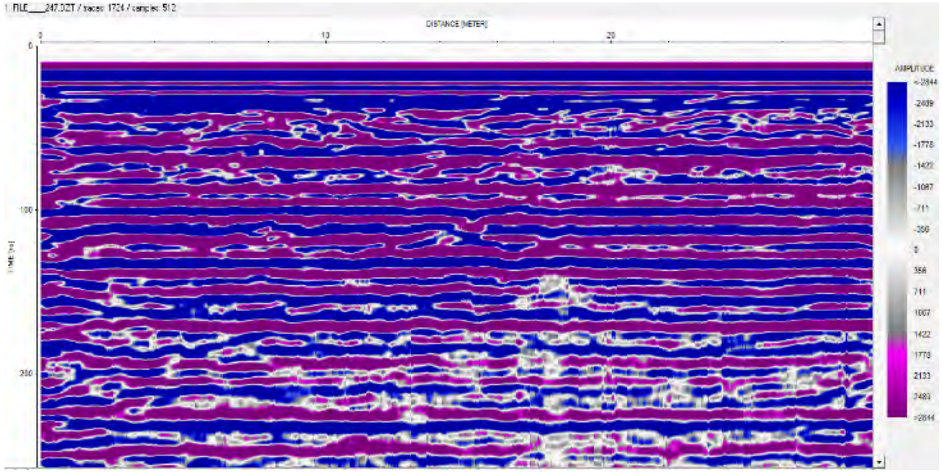


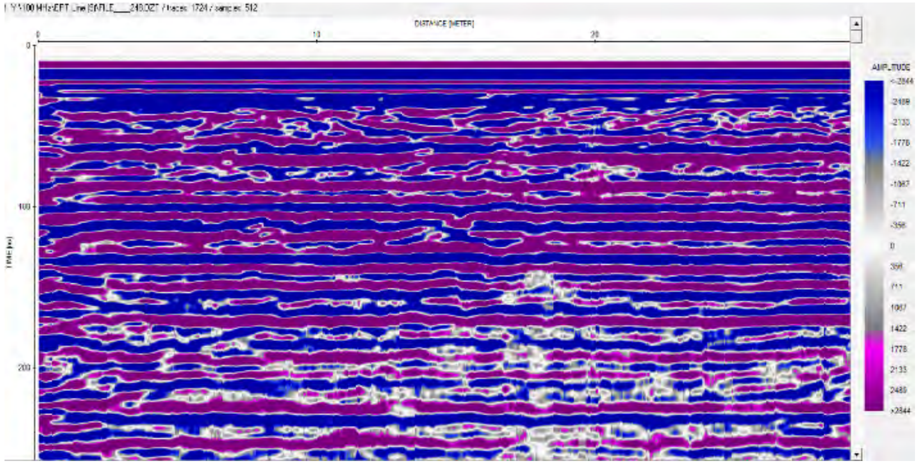

1. FILE____244.DZT / traces: 4608 / samples: 512
DISTANCE [METER]
0
10
20
30
40
50
60
70
0
100
200
TIME [ns]
AMPLITUDE
2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

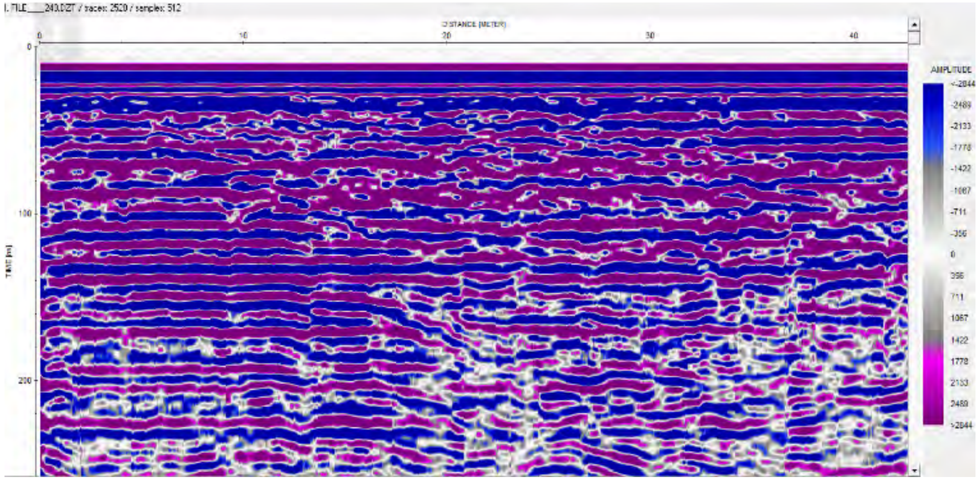
IMAGES OF GPR PROFILE SCANNED ALONG ERT-9

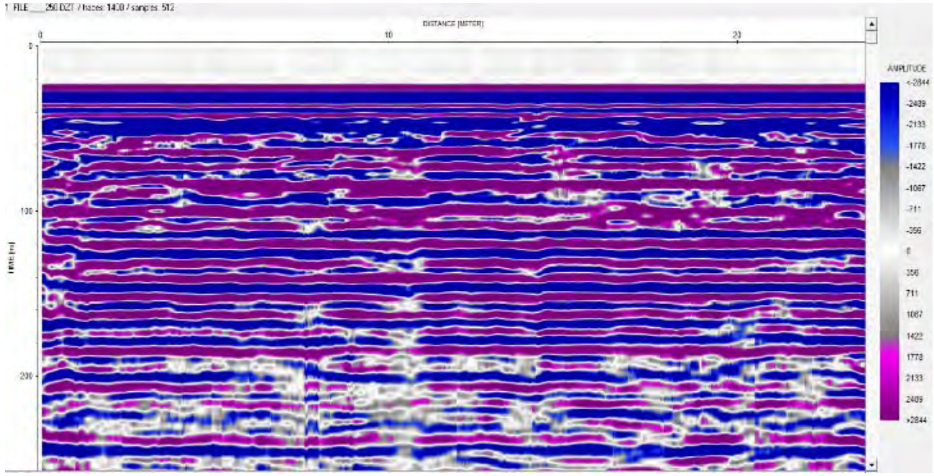


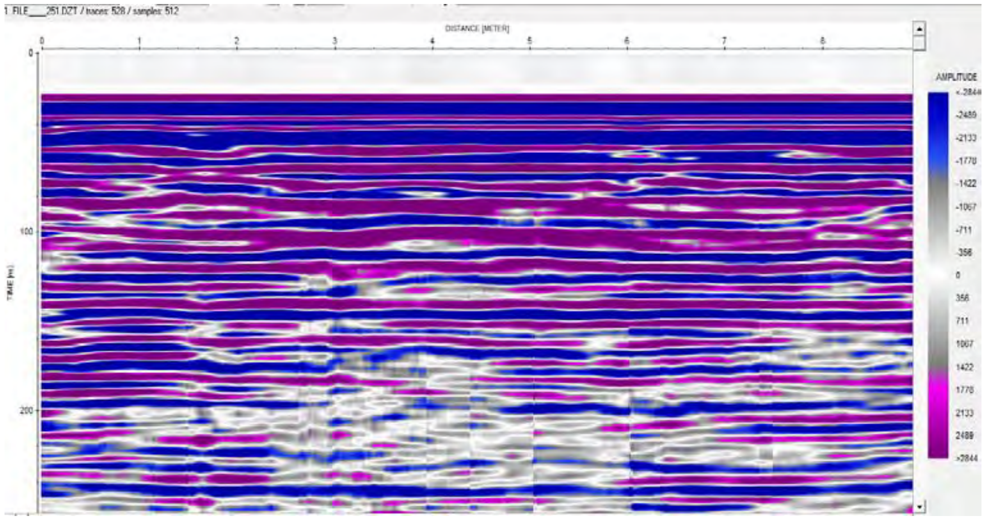


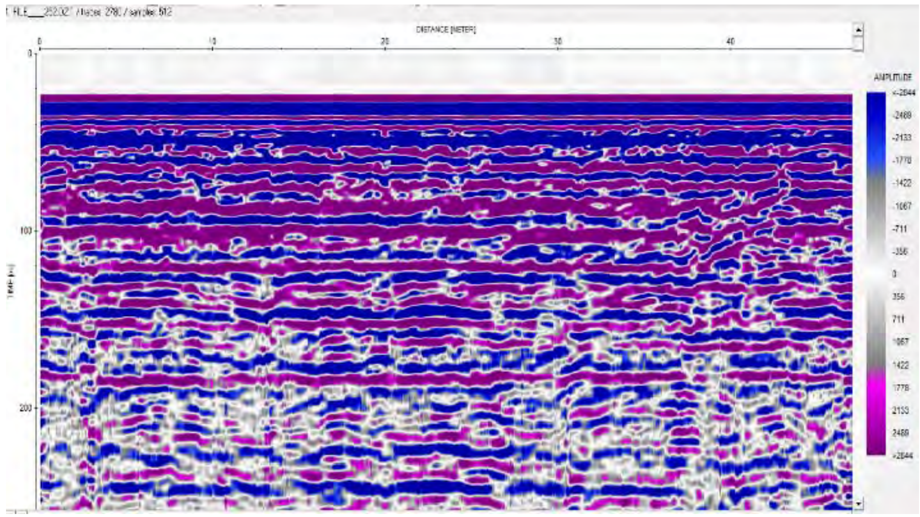


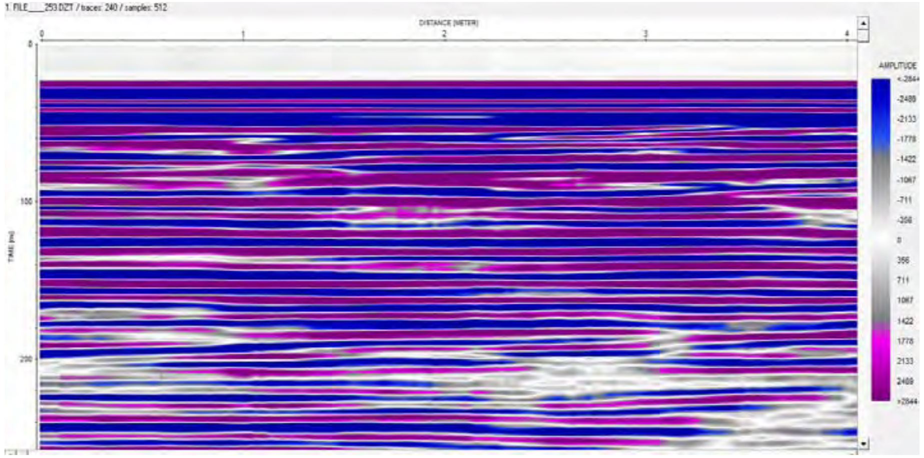


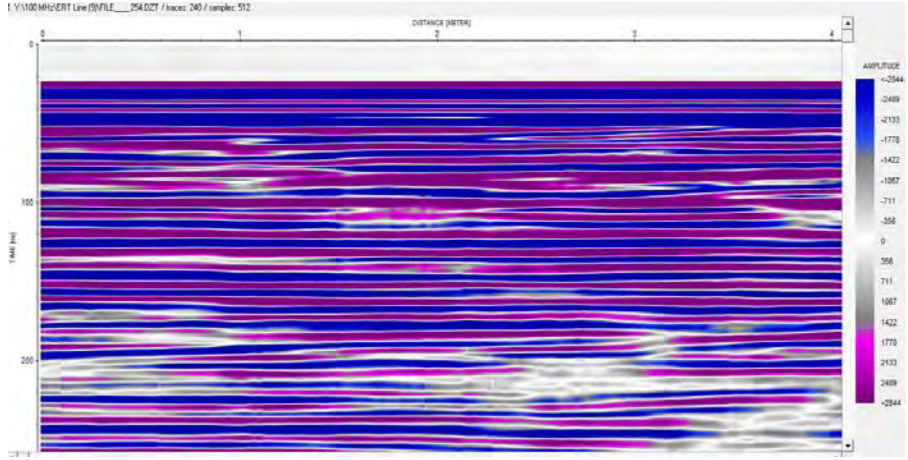

DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE

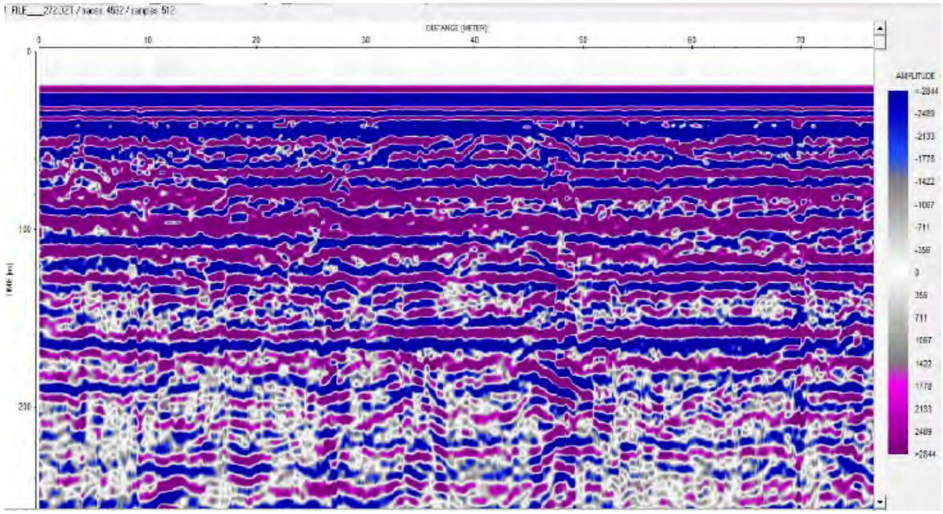

DISTANCE [METER]
AMPLITUDE

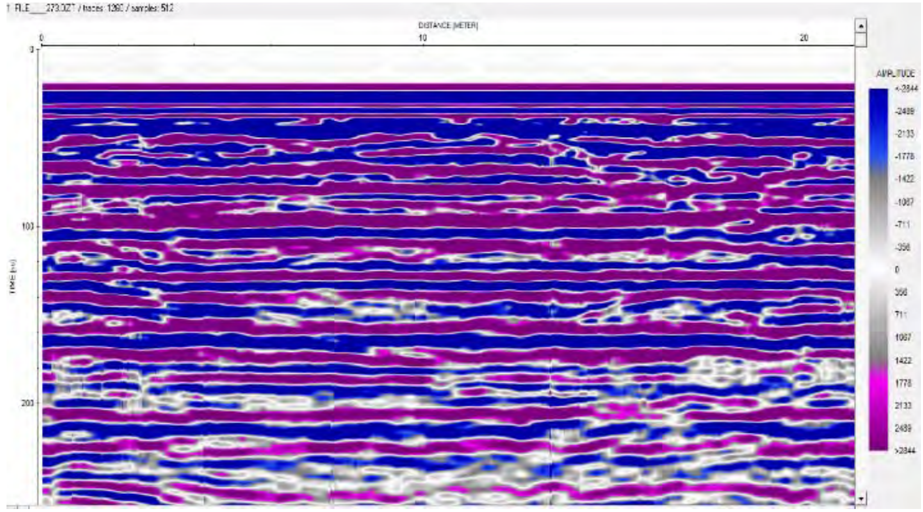

DISTANCE [METER]
AMPLITUDE

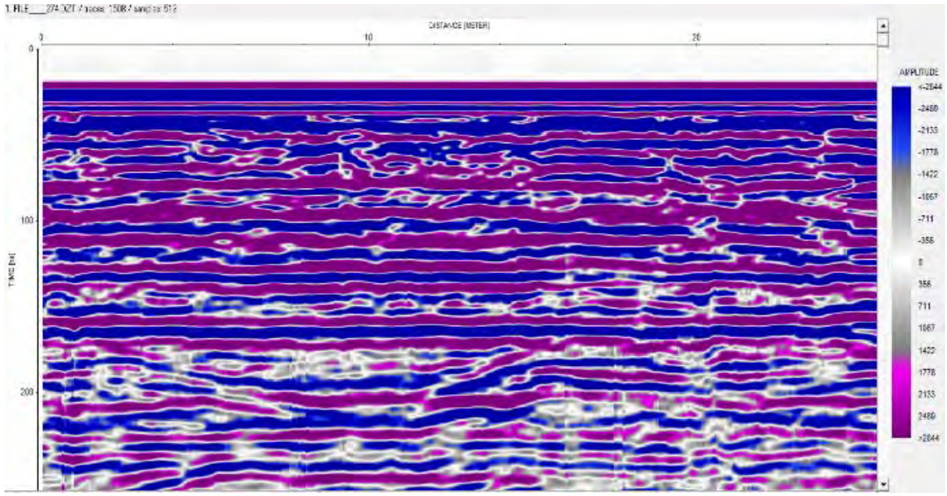

1. FILE____253.DZT / traces: 240 / samples: 512
DISTANCE [METER]
0
1
2
3
4
0
100
200
TIME [ns]
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

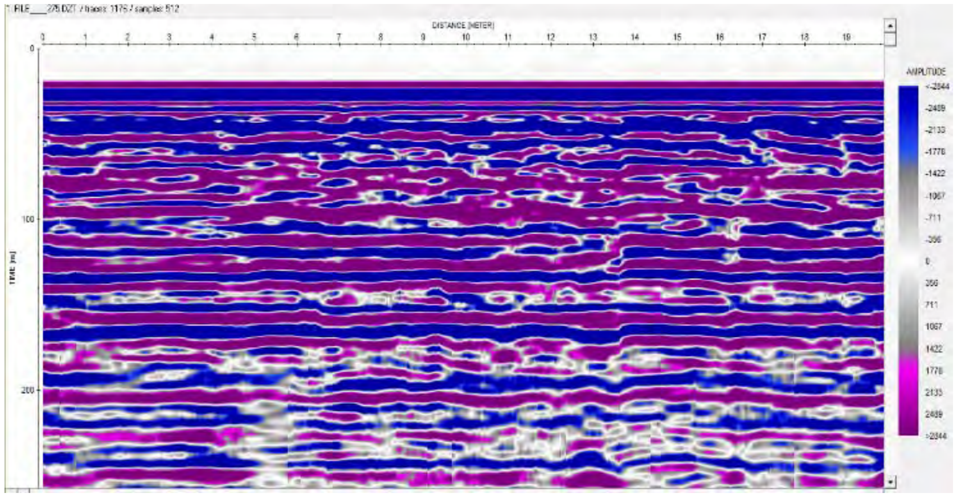

1. Y:\100 MHz\ERT Line (5)\FILE____254.DZT / traces: 240 / samples: 512
DISTANCE [METER]
0
1
2
3
4
0
100
200
TIME [ns]
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

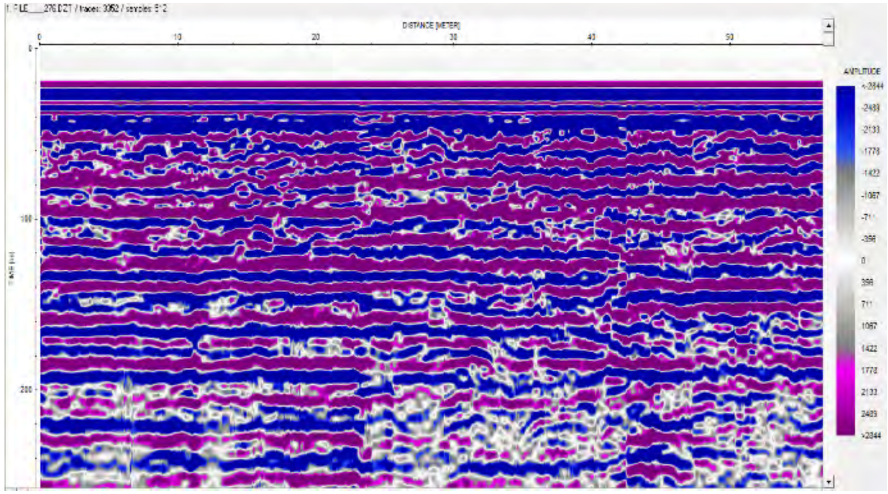
<u>IMAGES OF GPR PROFILE SCANNED ALONG ERT-10</u>

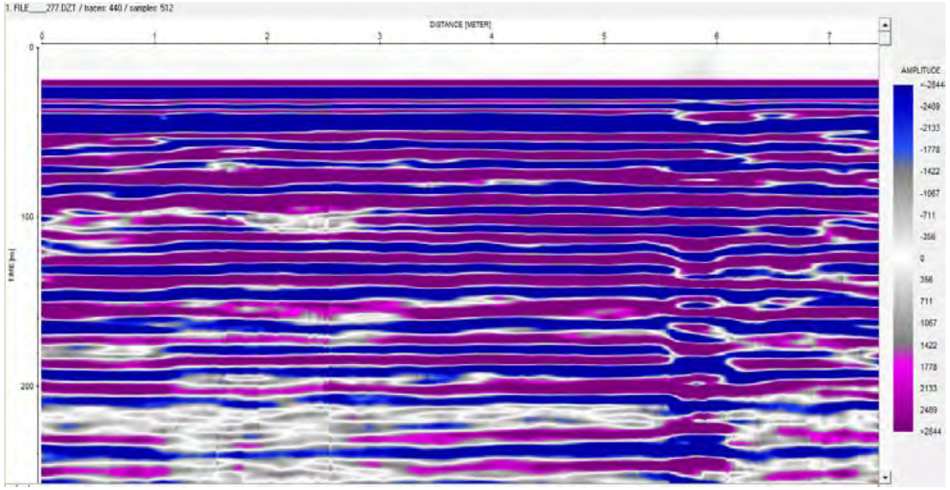


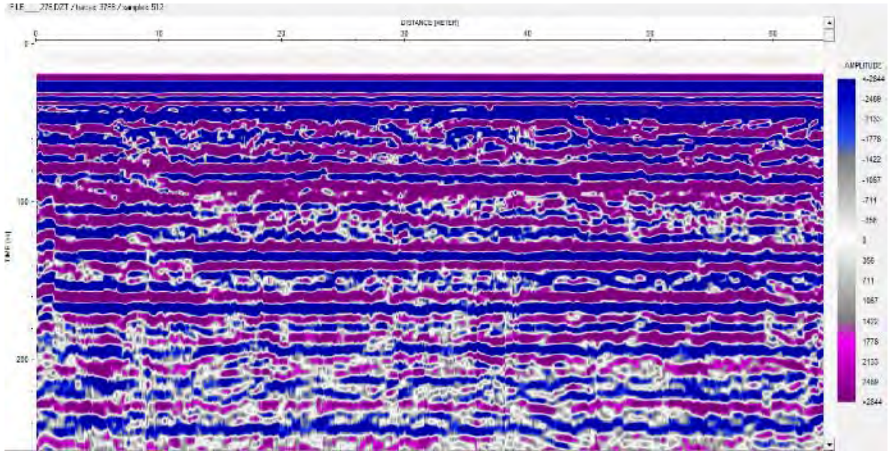


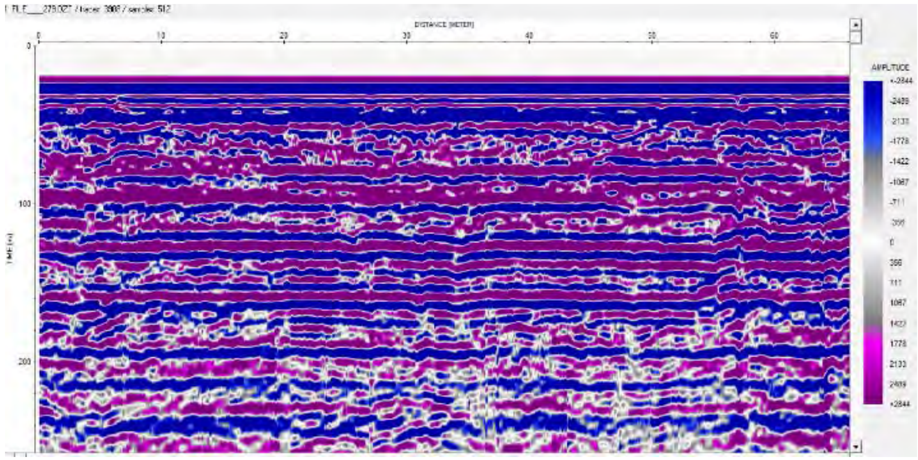


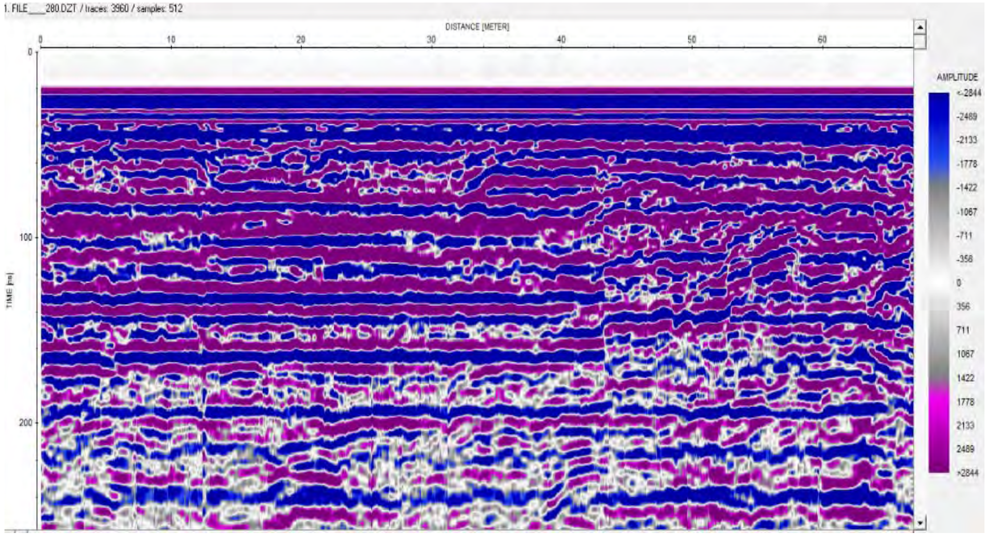




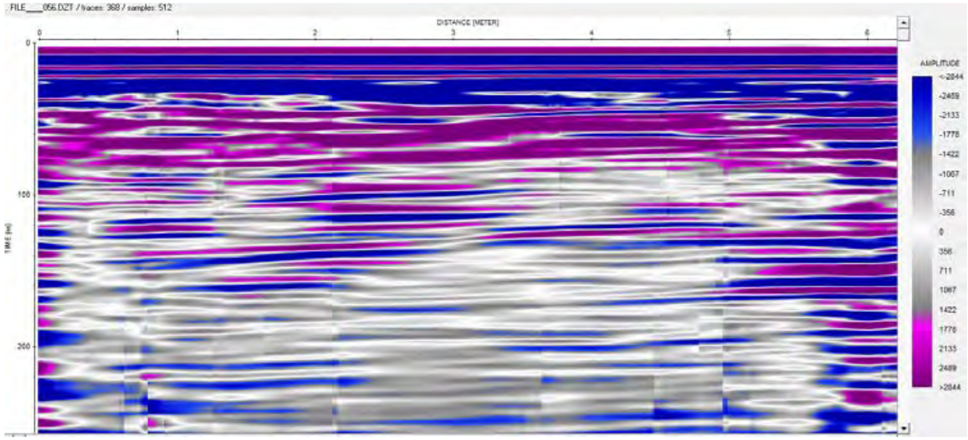


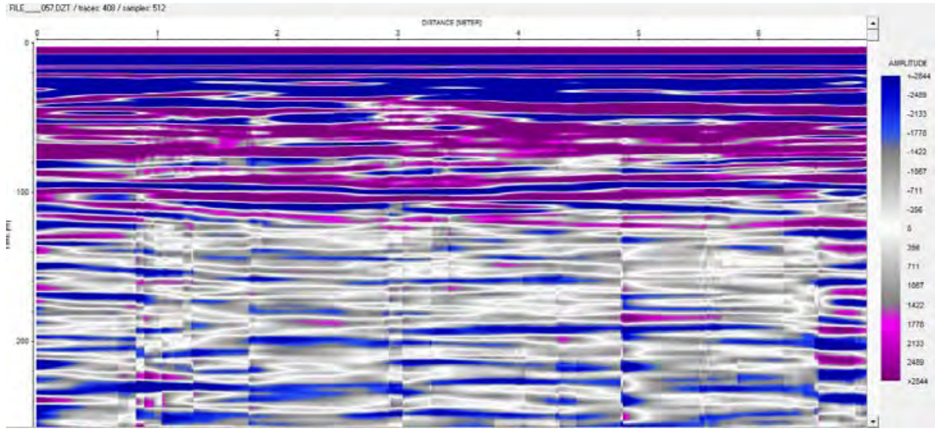


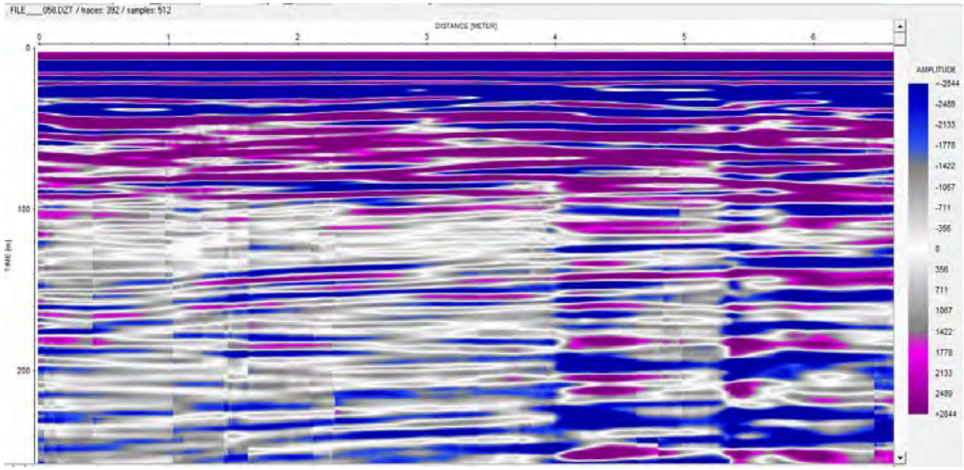


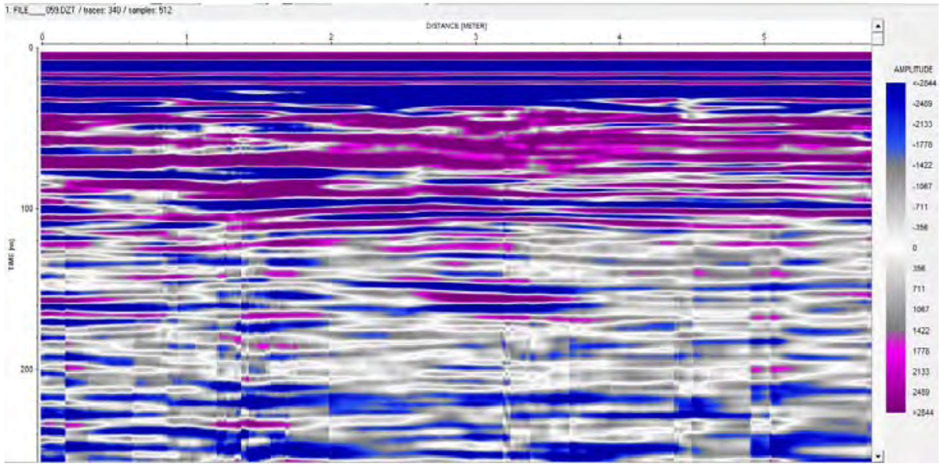

1. FILE___280.DZT / traces: 3960 / samples: 512
DISTANCE [METER]
0
10
20
30
40
50
60
0
100
200
TIME [ns]
AMPLITUDE
<-2844
-2489
-2133
-1778
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

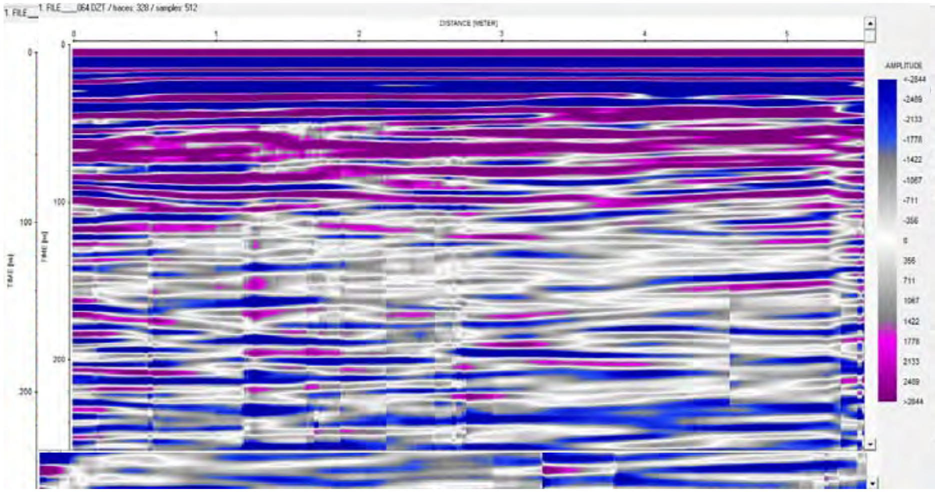
IMAGES OF GPR PROFILE SCANNED ACROSS ERT-1

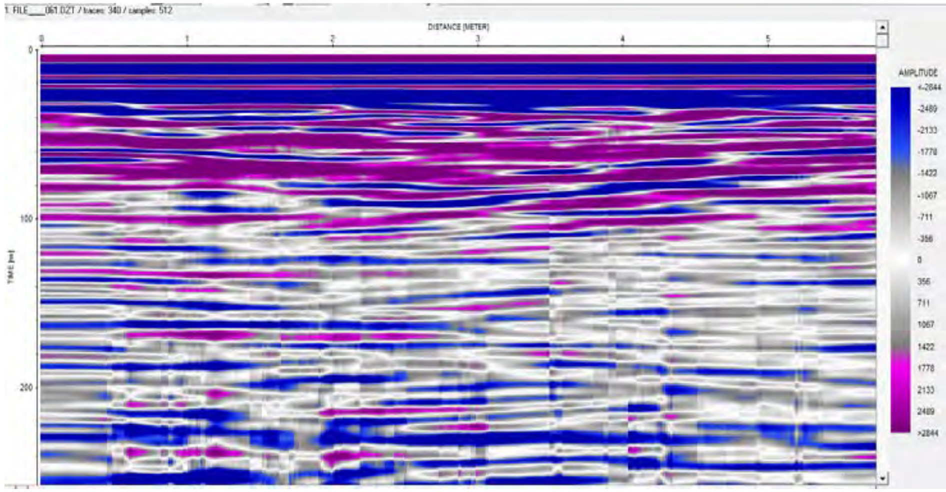


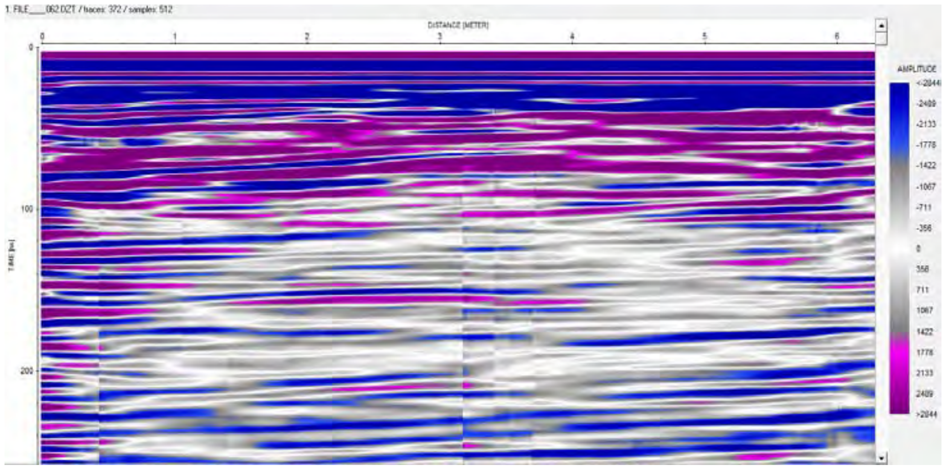


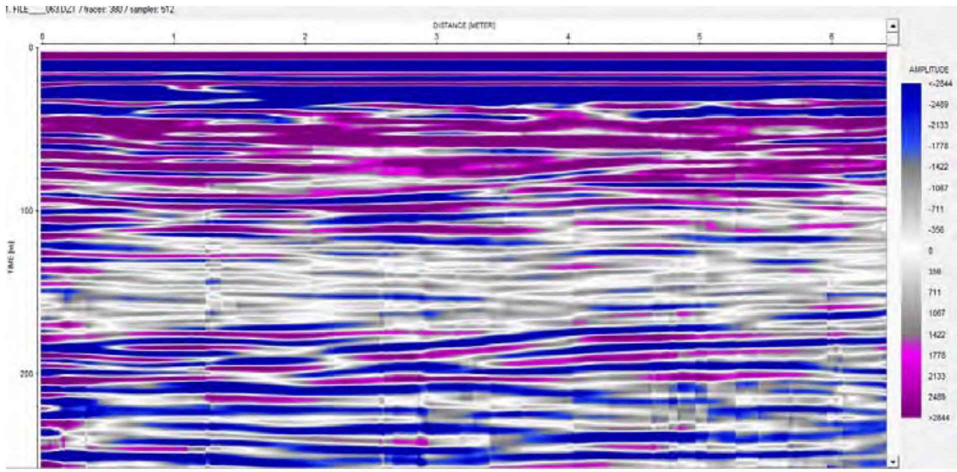


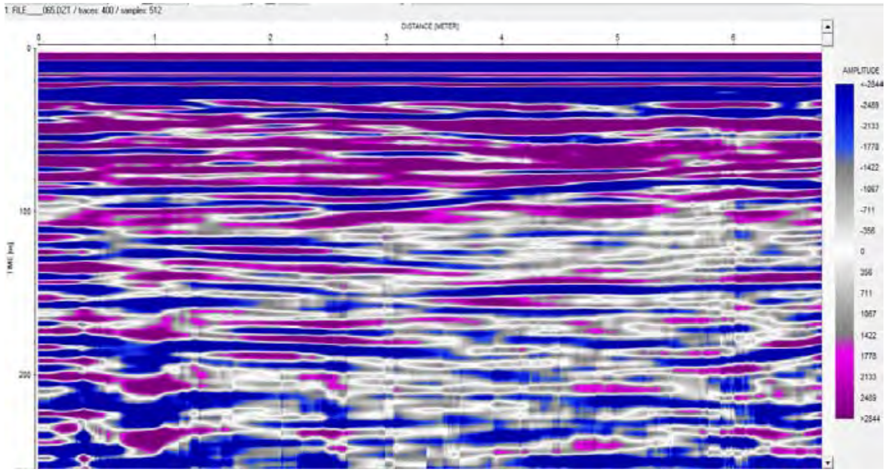


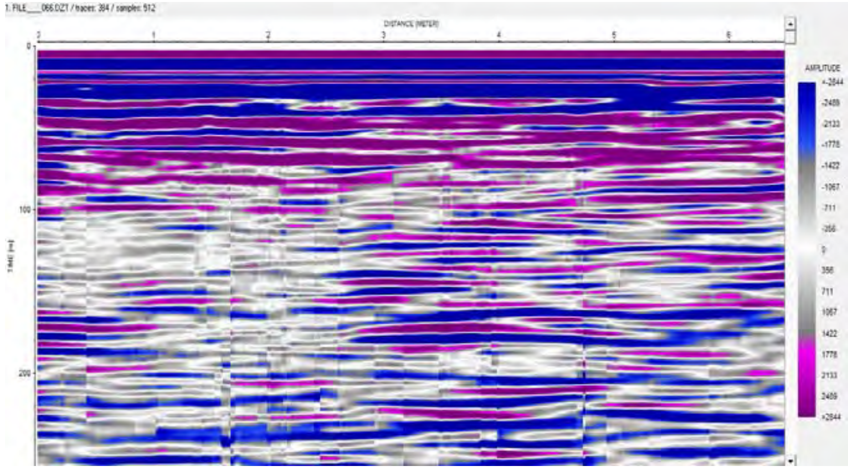

1. FILE___064.DZT / traces: 328 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

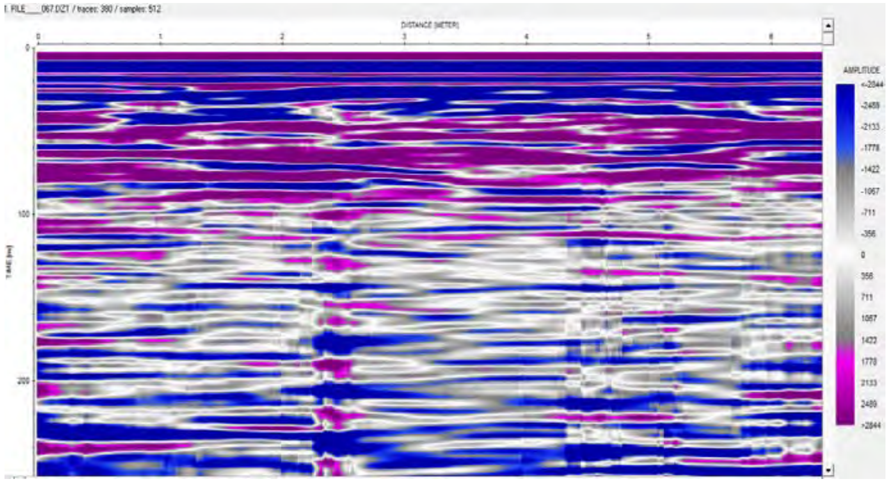

1. FILE___061.DZT / traces: 340 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

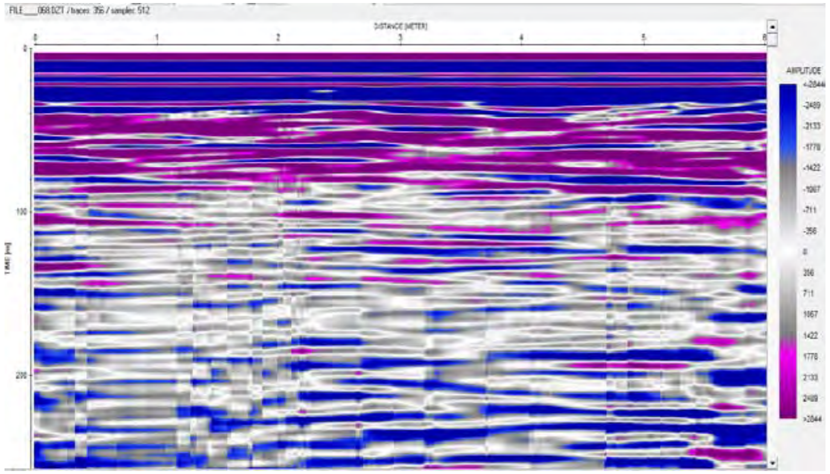

1. FILE___062.DZT / traces: 372 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

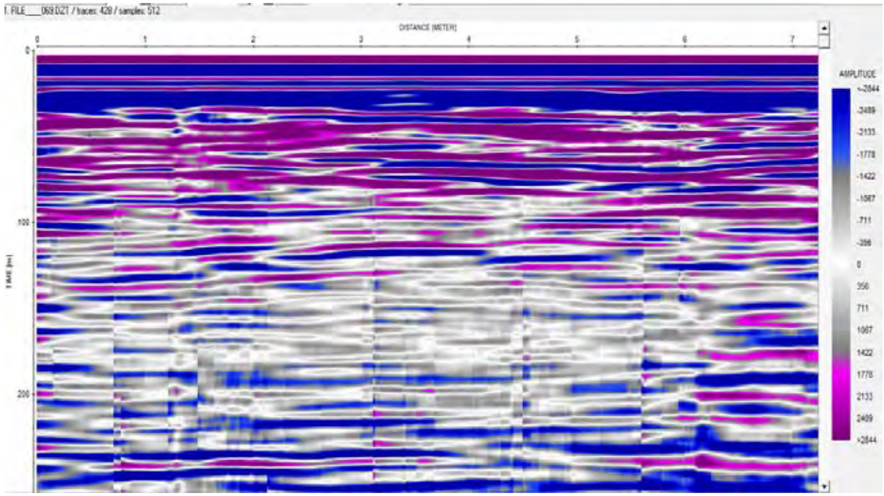

1. FILE___063.DZT / traces: 380 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

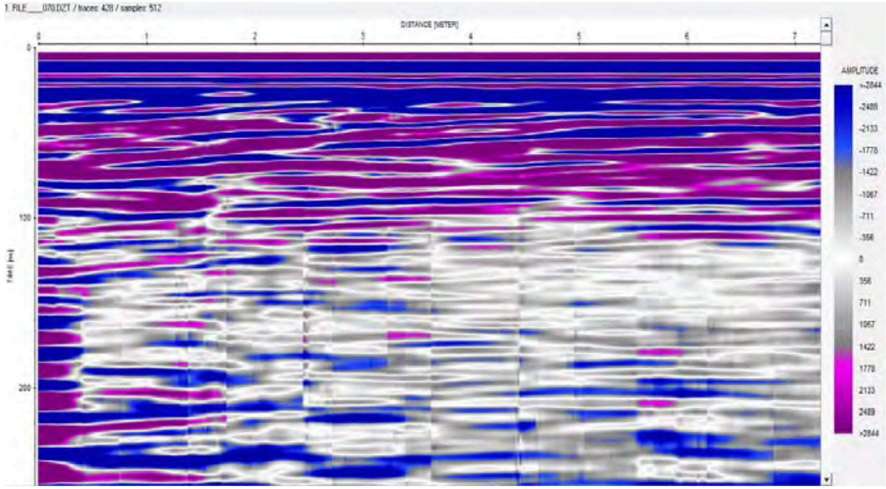

1. FILE____065.DZT / traces: 400 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

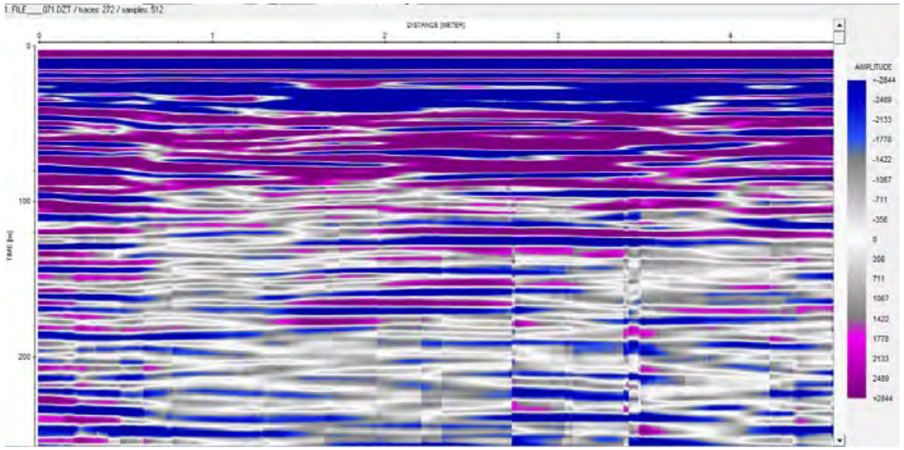

1. FILE____066.DZT / traces: 384 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

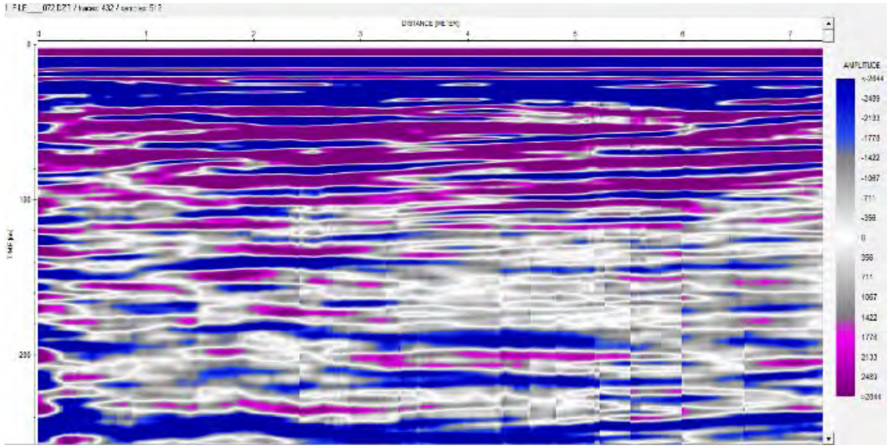

1. FILE____067.DZT / traces: 380 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

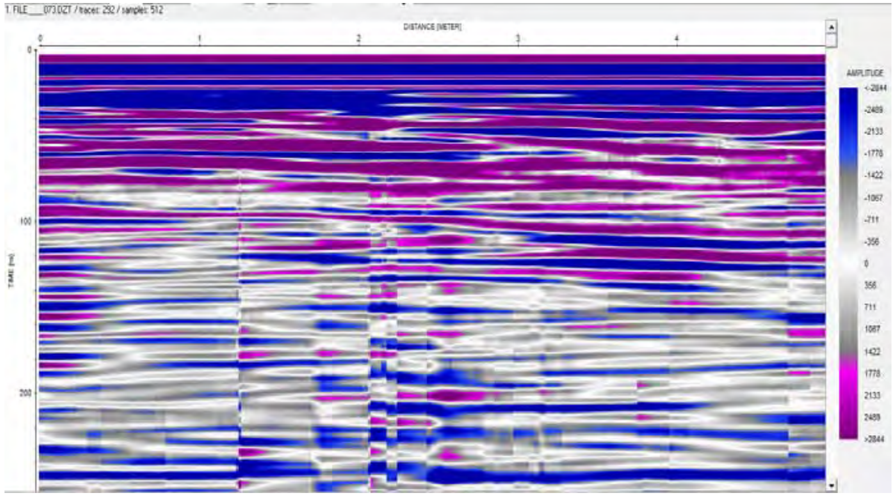

FILE____068.DZT / traces: 356 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

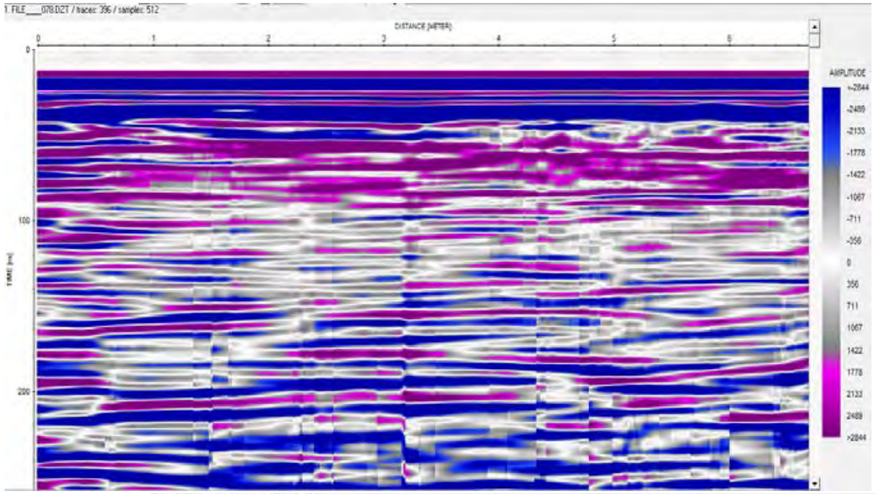


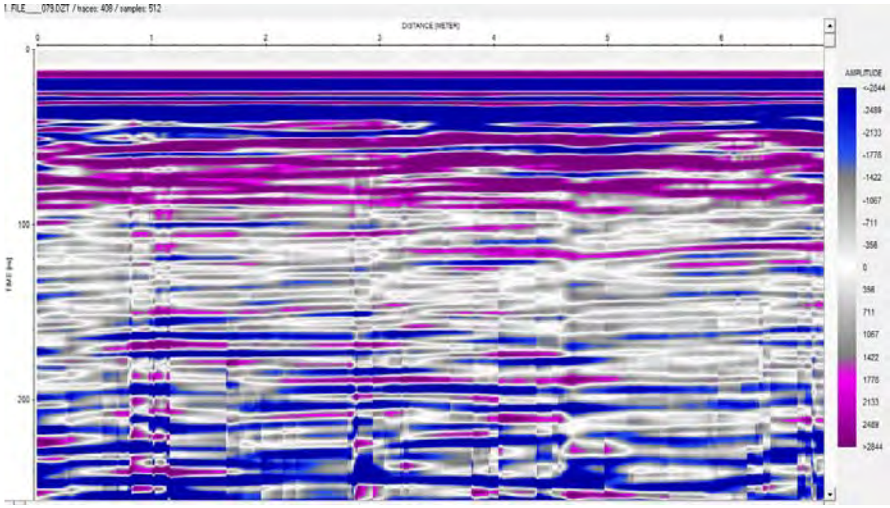


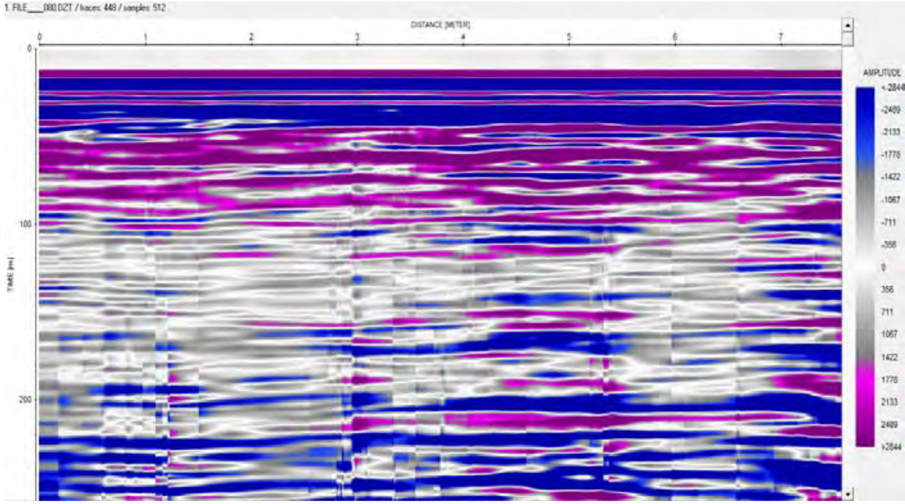


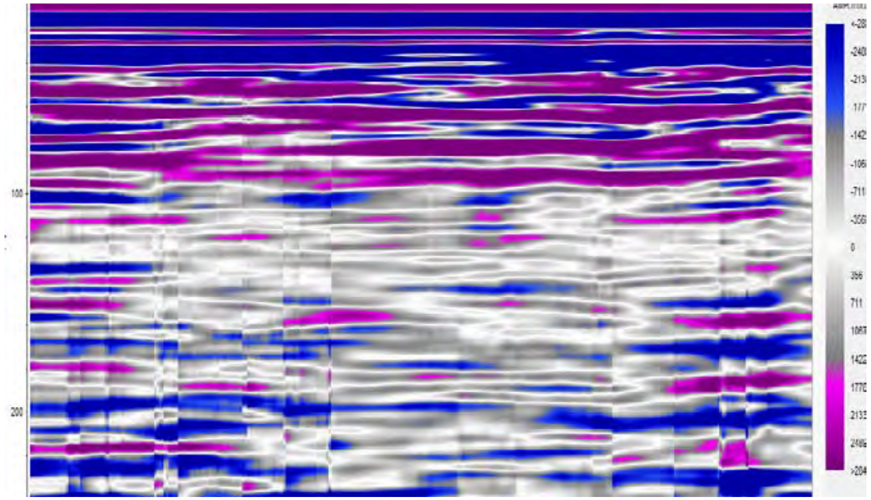


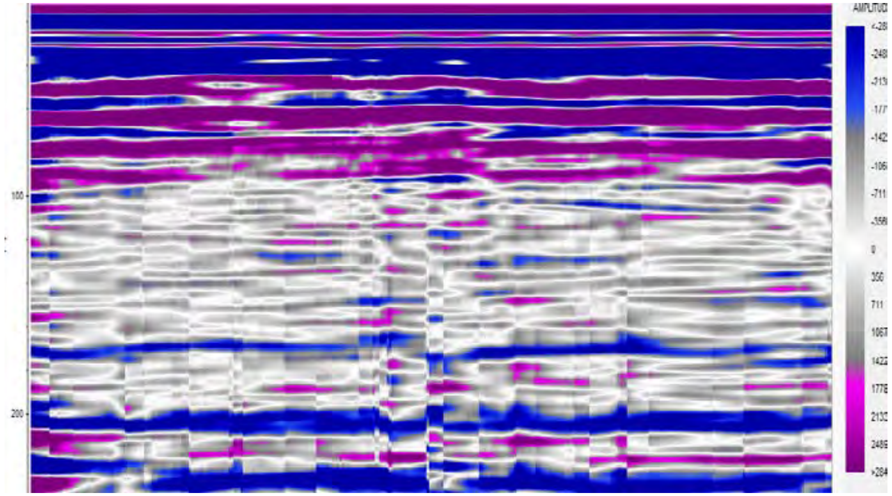

1. FILE___073.DZT / traces: 292 / samples: 512
DISTANCE [METER]
AMPLITUDE

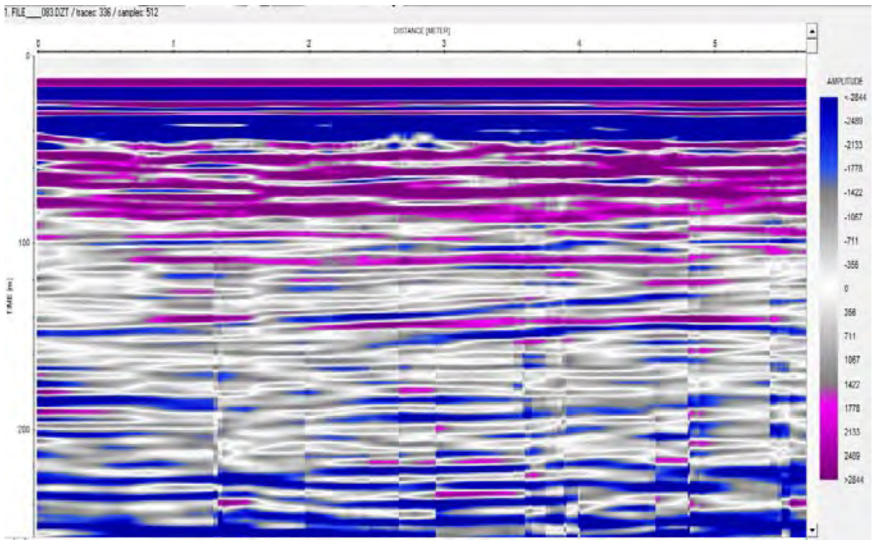

1. FILE___078.DZT / traces: 396 / samples: 512
DISTANCE [METER]
AMPLITUDE

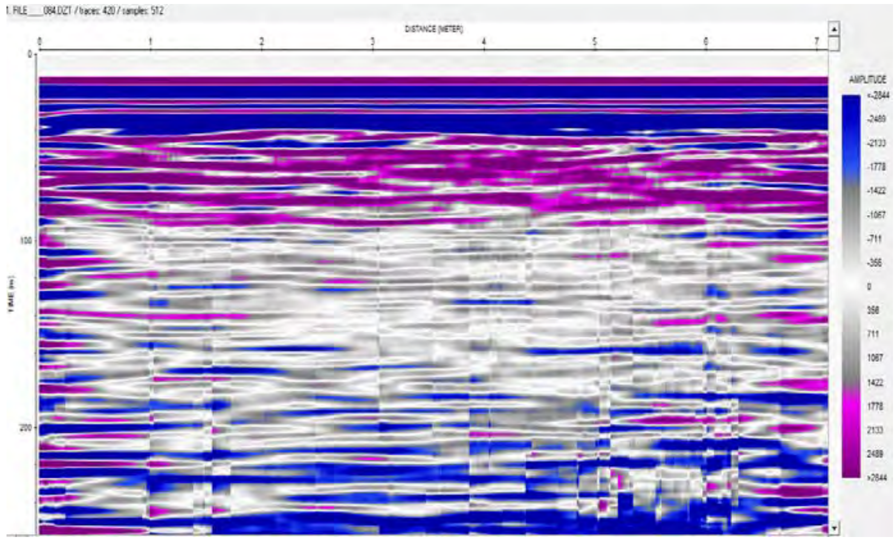

1. FILE___079.DZT / traces: 408 / samples: 512
DISTANCE [METER]
AMPLITUDE

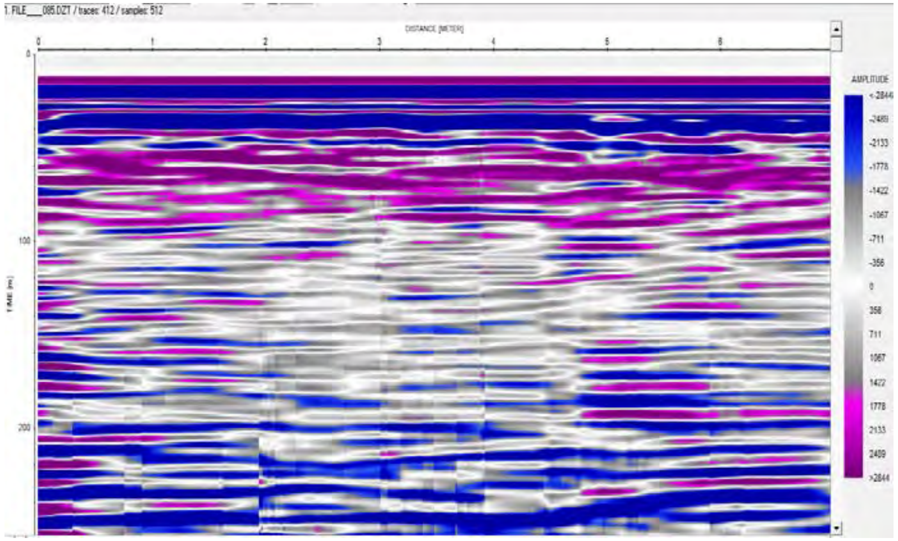

1. FILE___080.DZT / traces: 448 / samples: 512
DISTANCE [METER]
AMPLITUDE

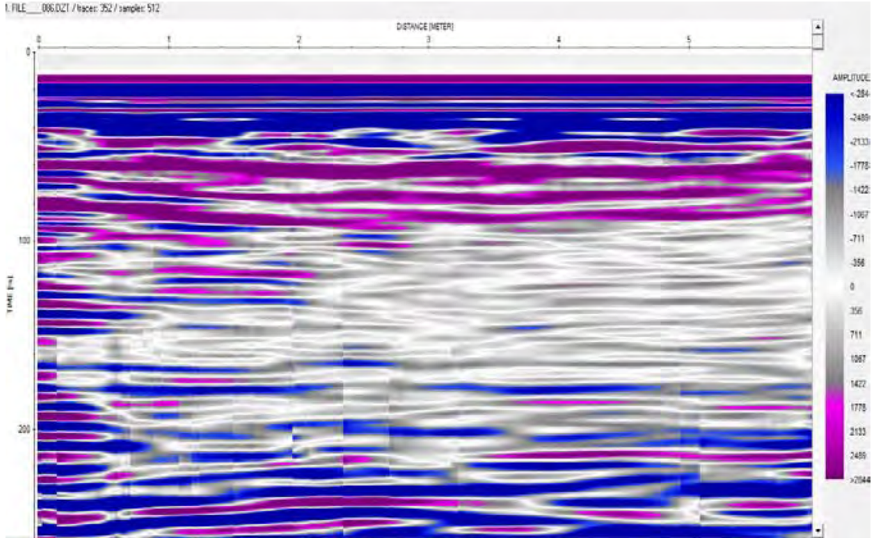


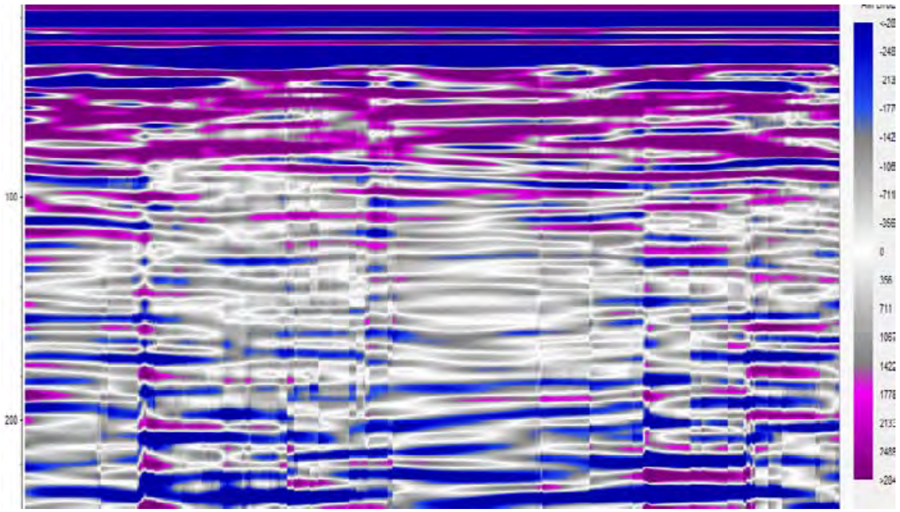


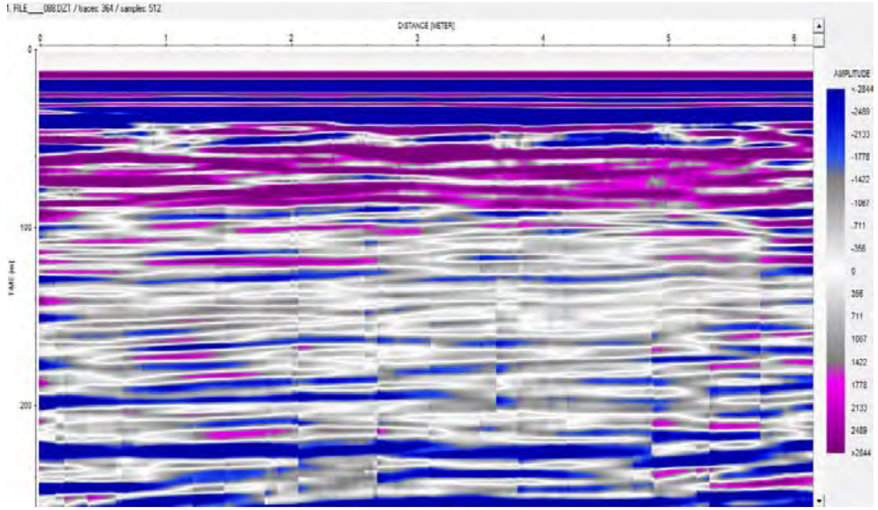

DISTANCE [METER]
AMPLITUDE

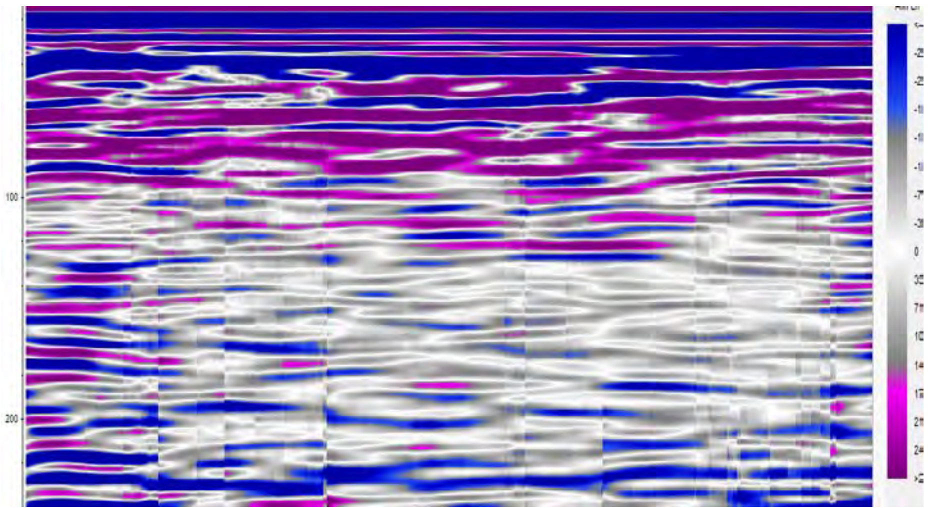

DISTANCE [METER]
AMPLITUDE

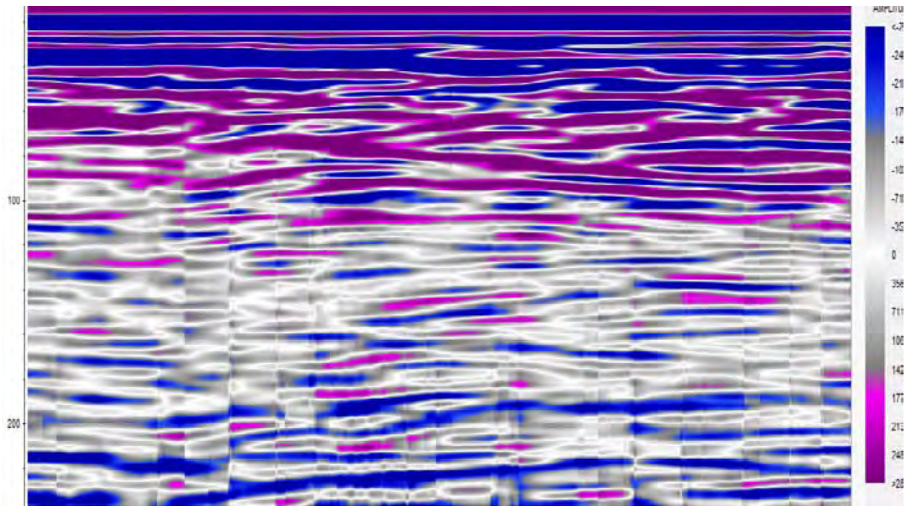


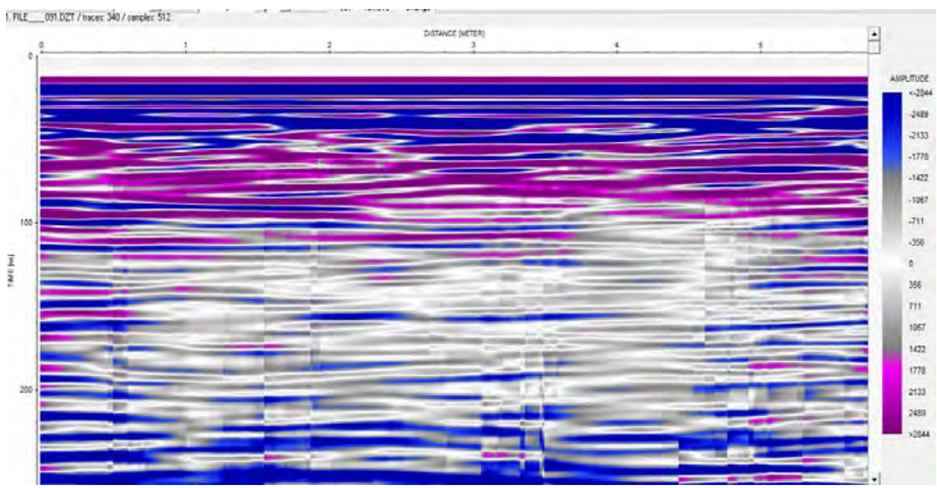


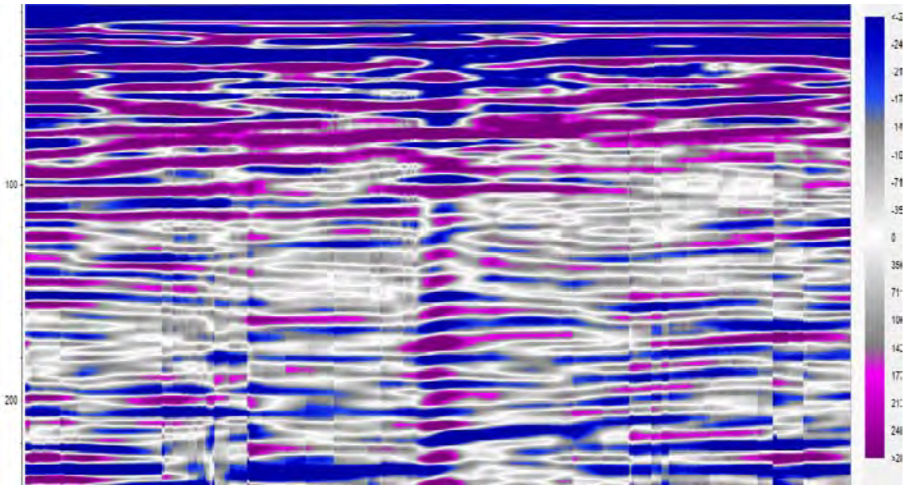


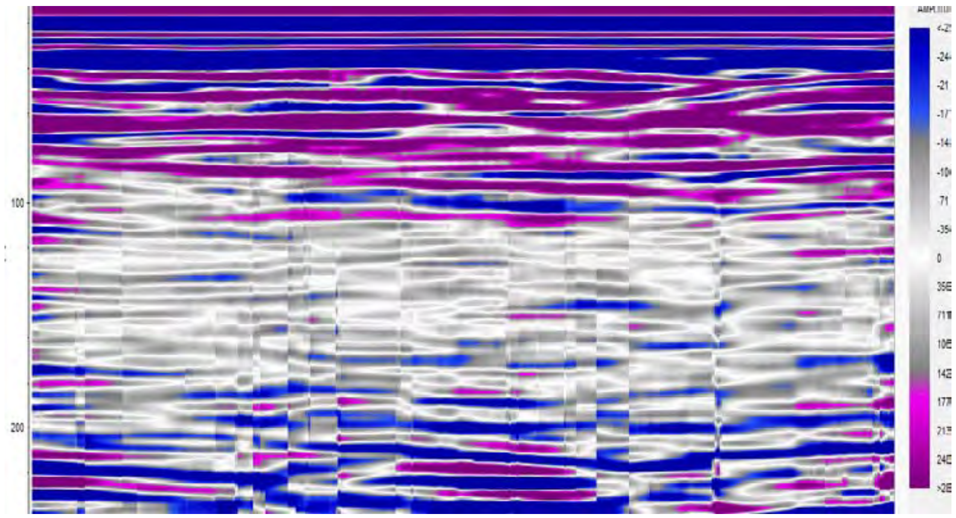


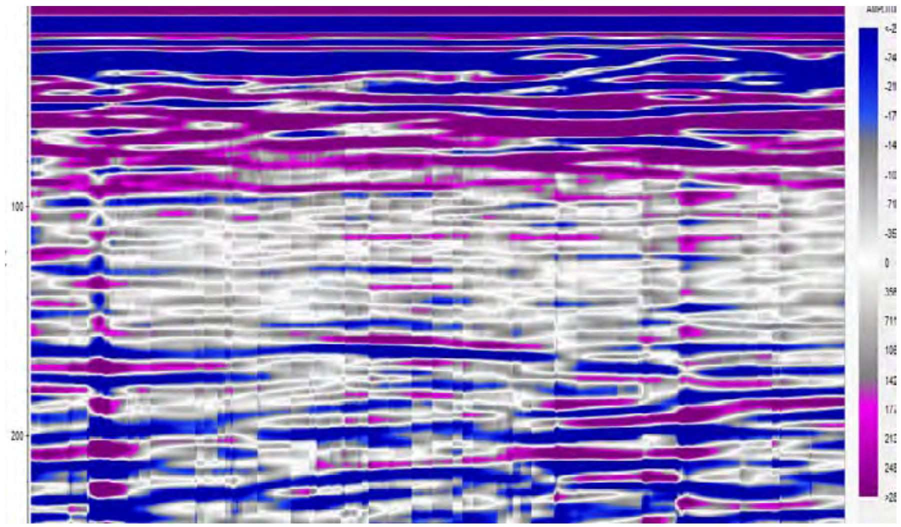


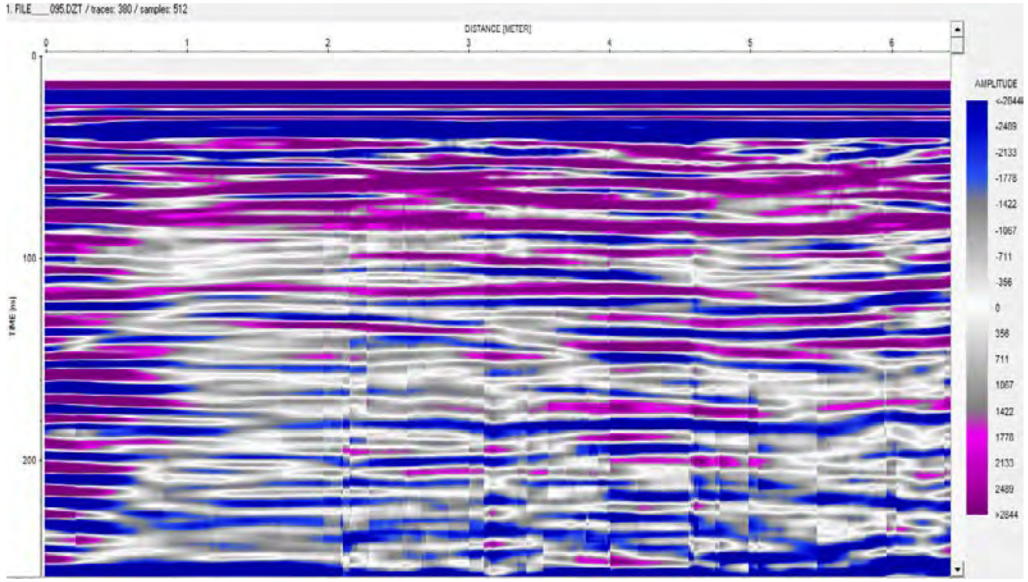








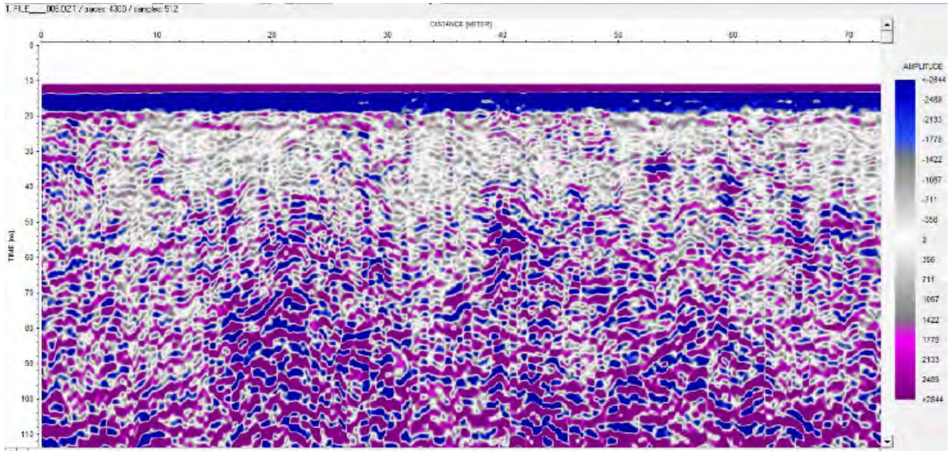


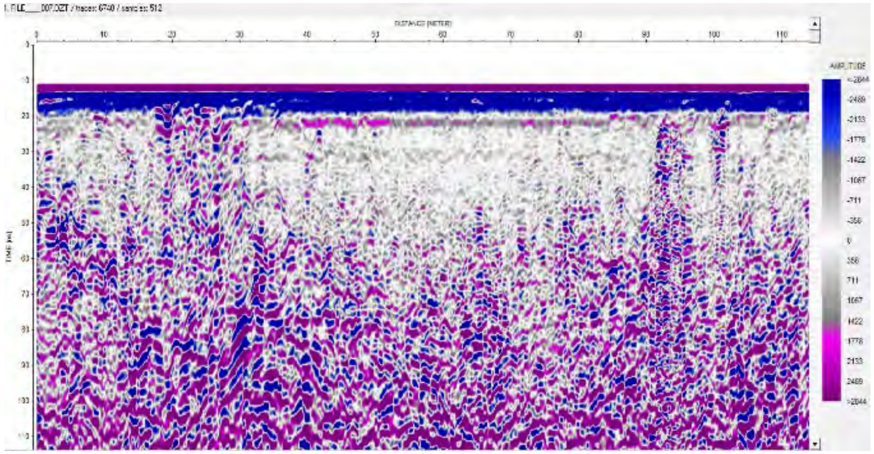

1. FILE___095.DZT / traces: 380 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

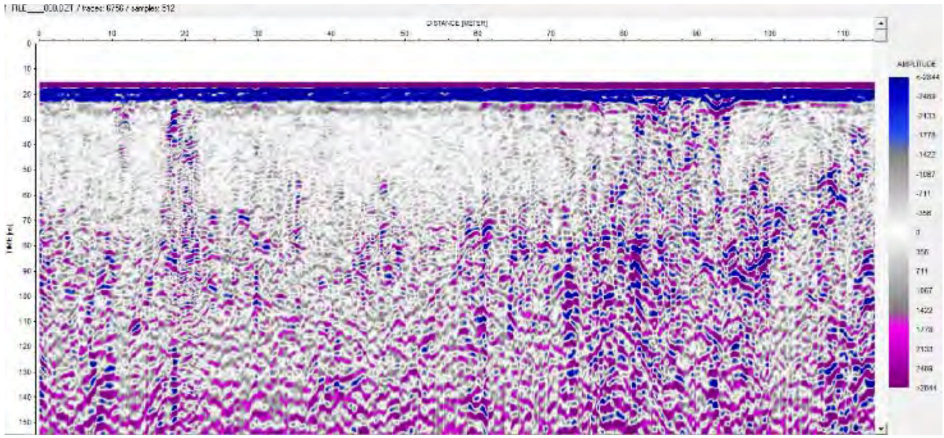
Annexure-VIII

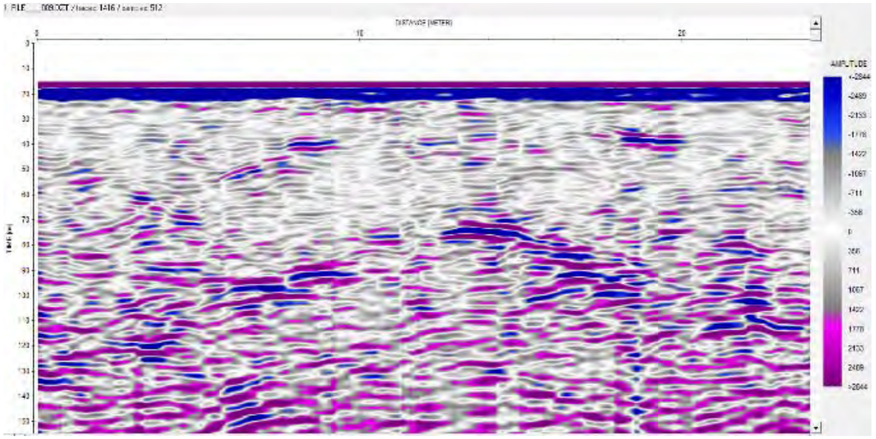
GPR PROFILES WITH 200 & 270 MHZ ANTENNA (SAVED FROM REFLEX2DQUICK SOFTWARE)

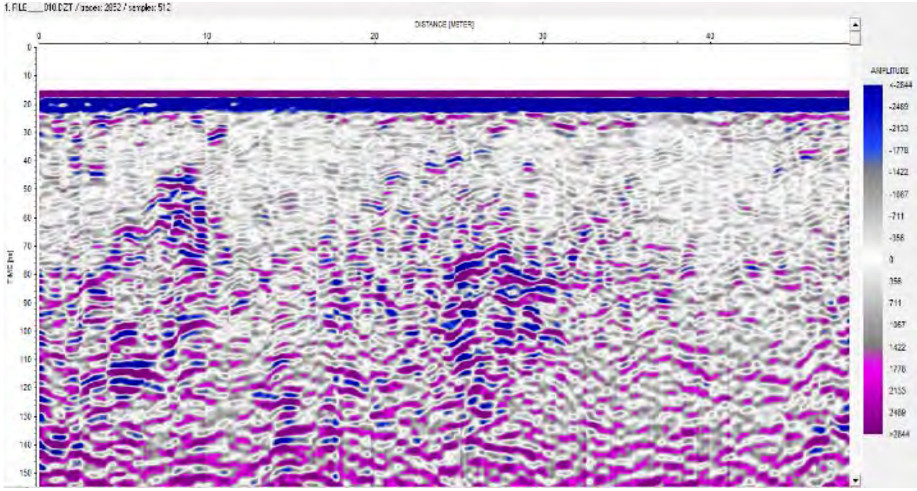
IMAGES OF GPR PROFILE SCANNED ALONG ERT-1

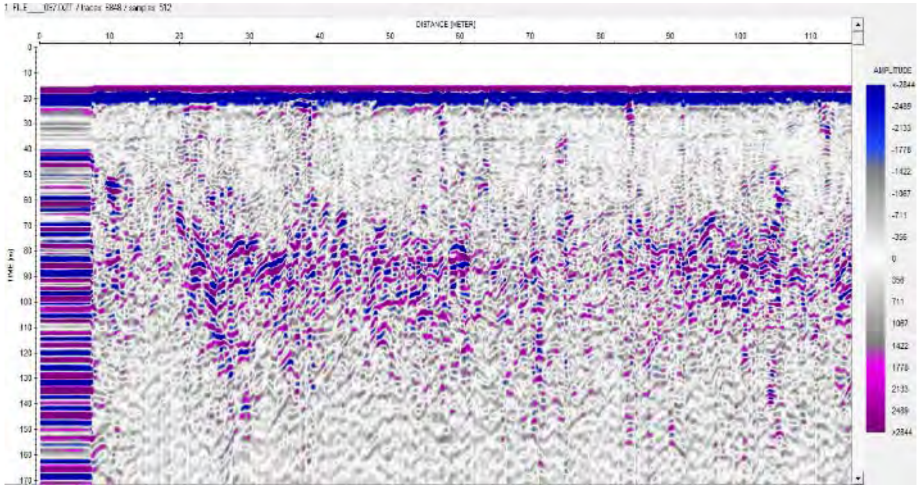


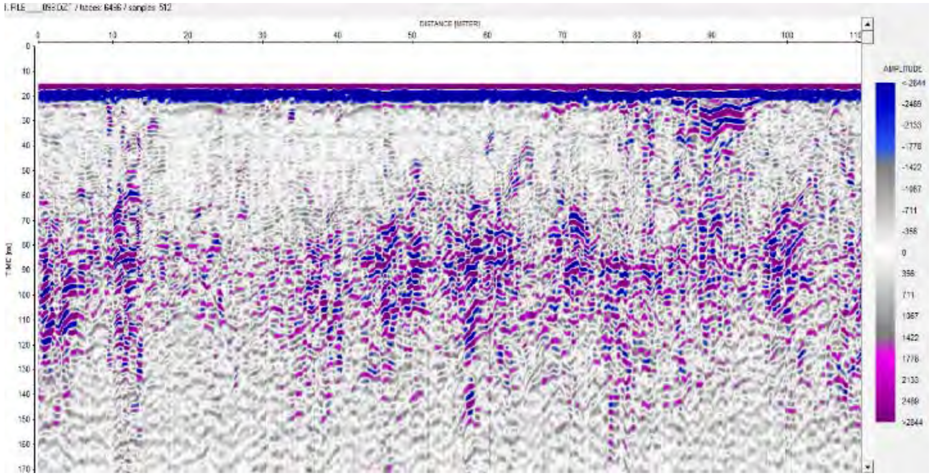


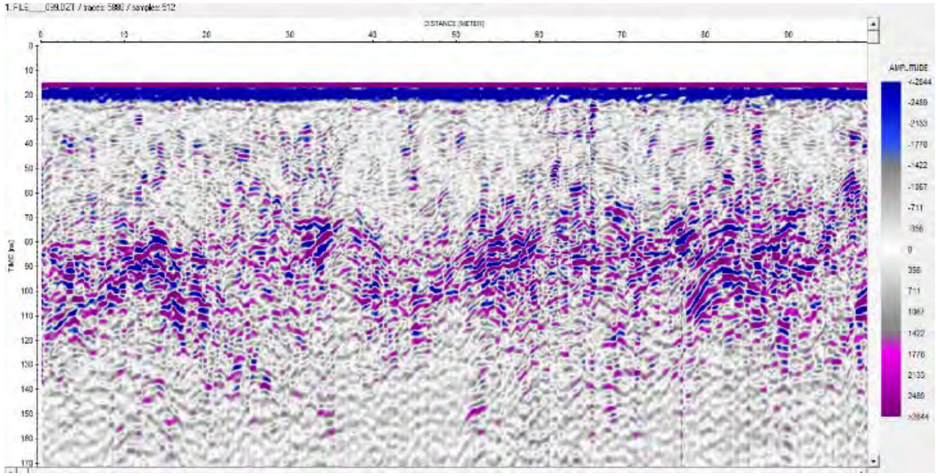


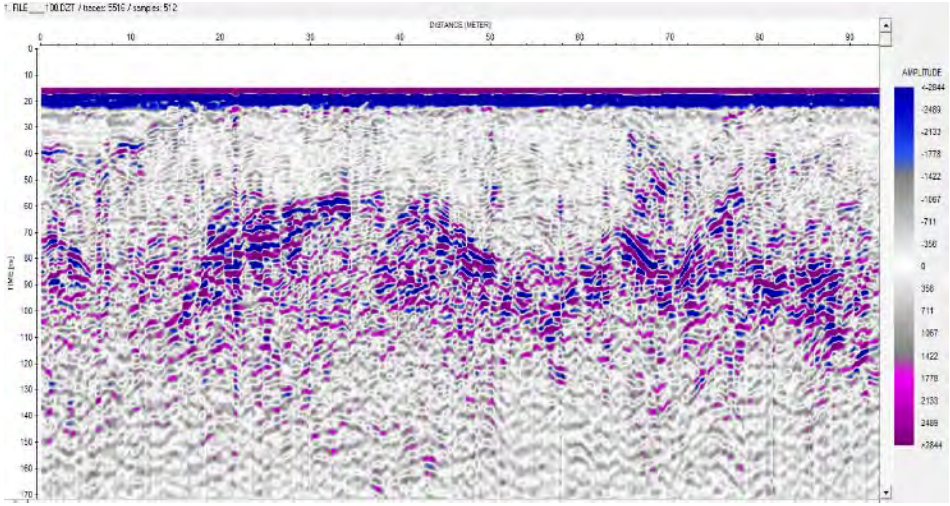








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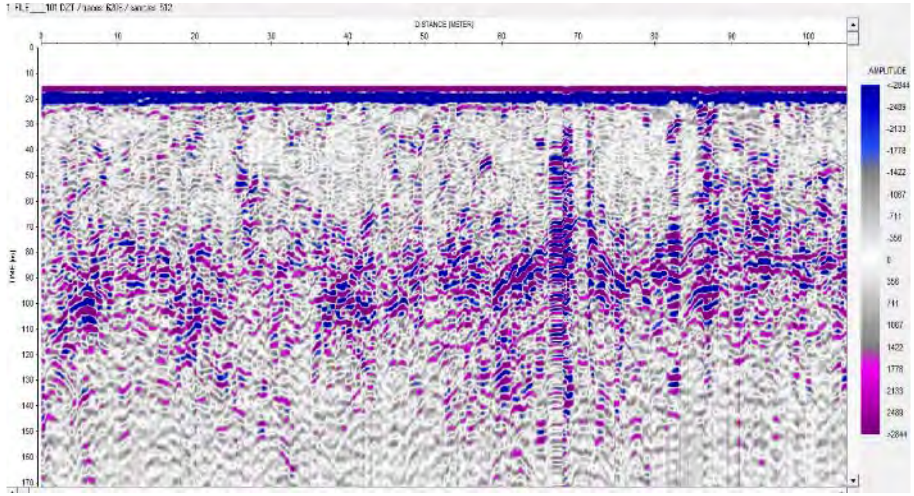
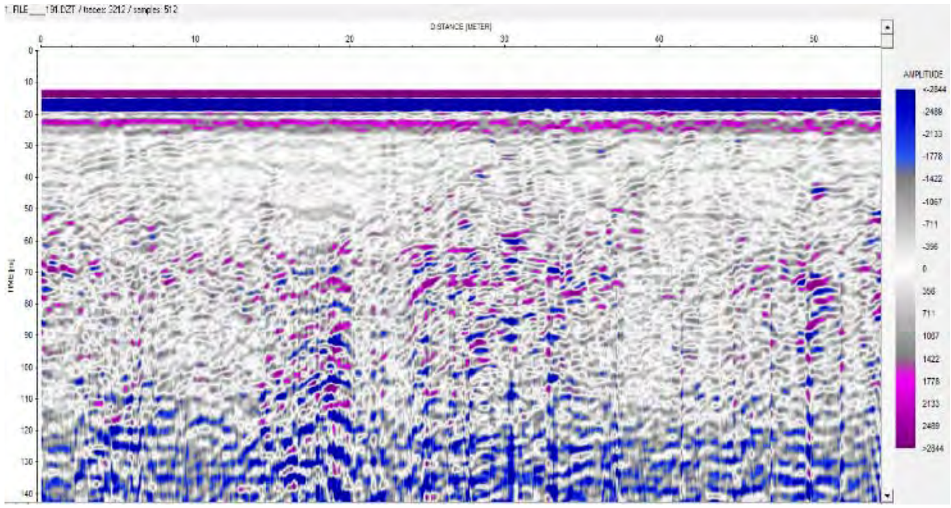
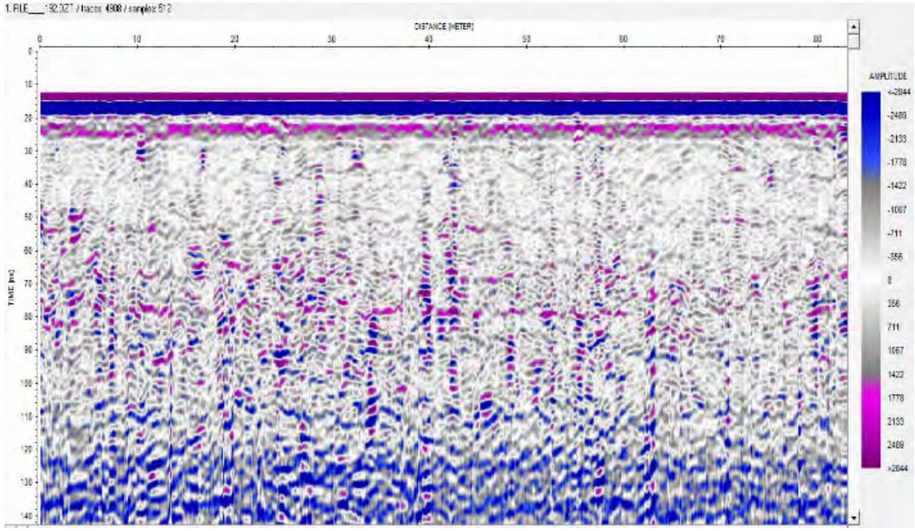
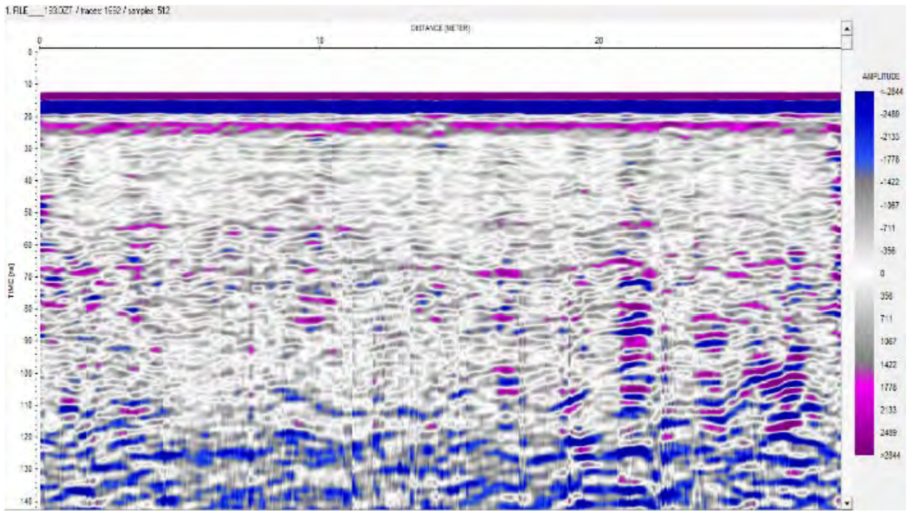
AMPLITUDE

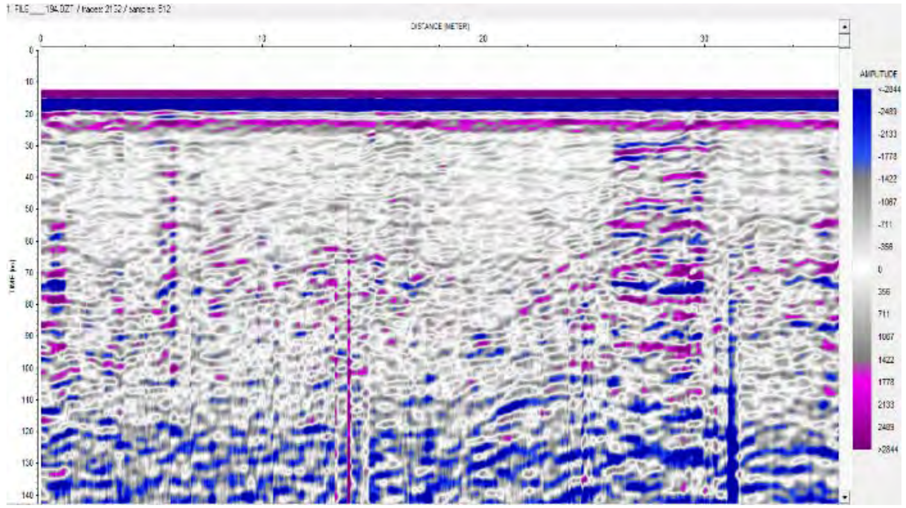

DISTANCE (METER)
AMPLITUDE

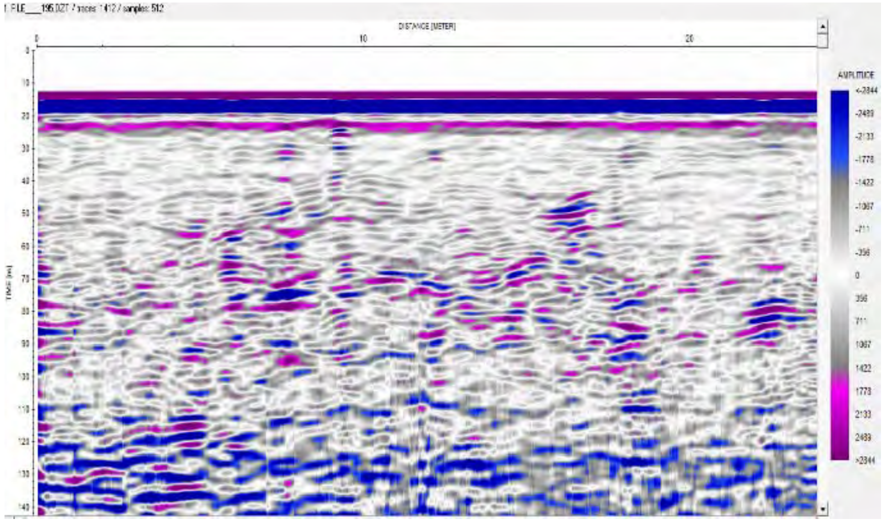
IMAGES OF GPR PROFILE SCANNED ALONG ERT-2







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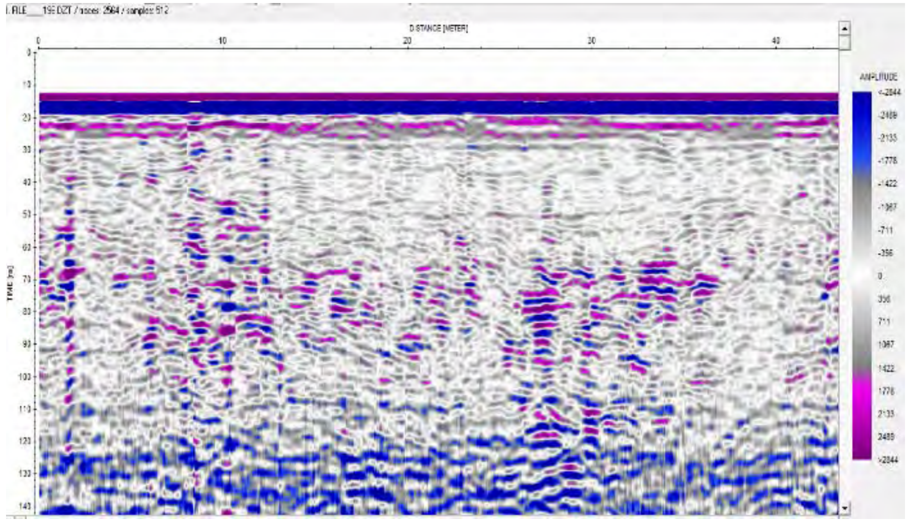
AMPLITUDE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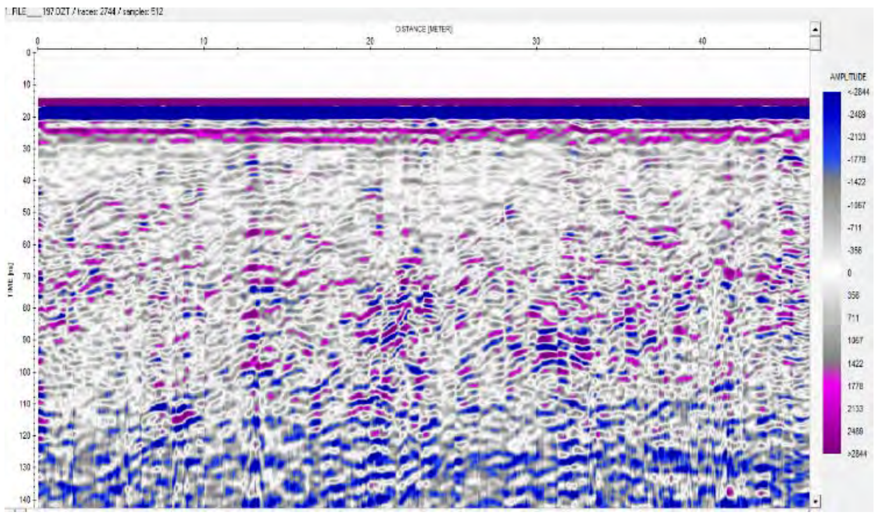
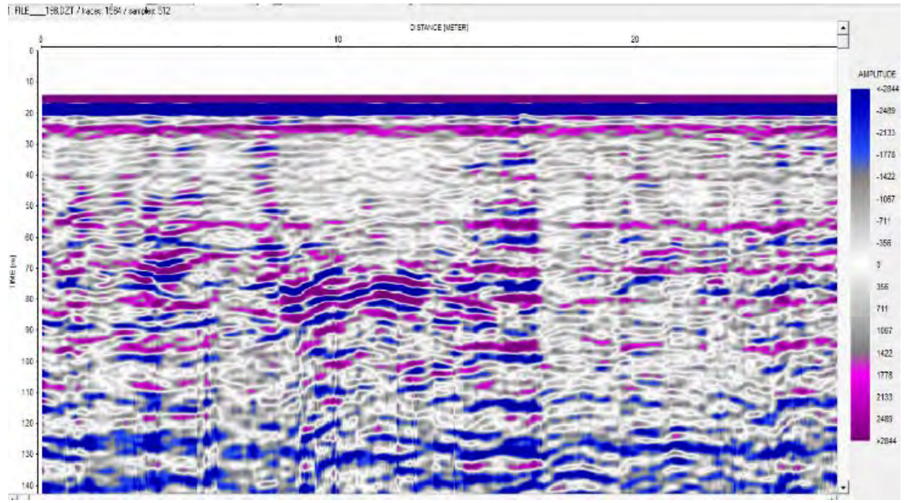
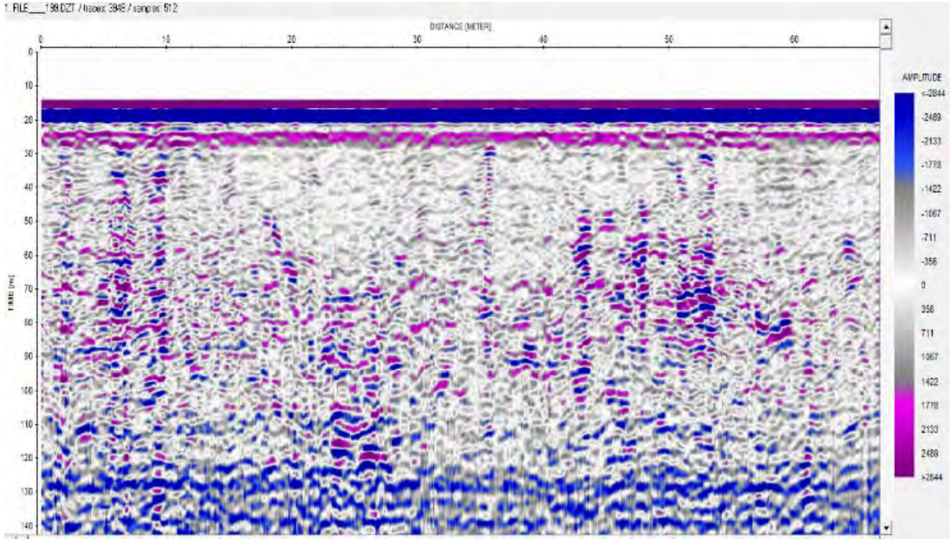
AMPLITUDE


DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE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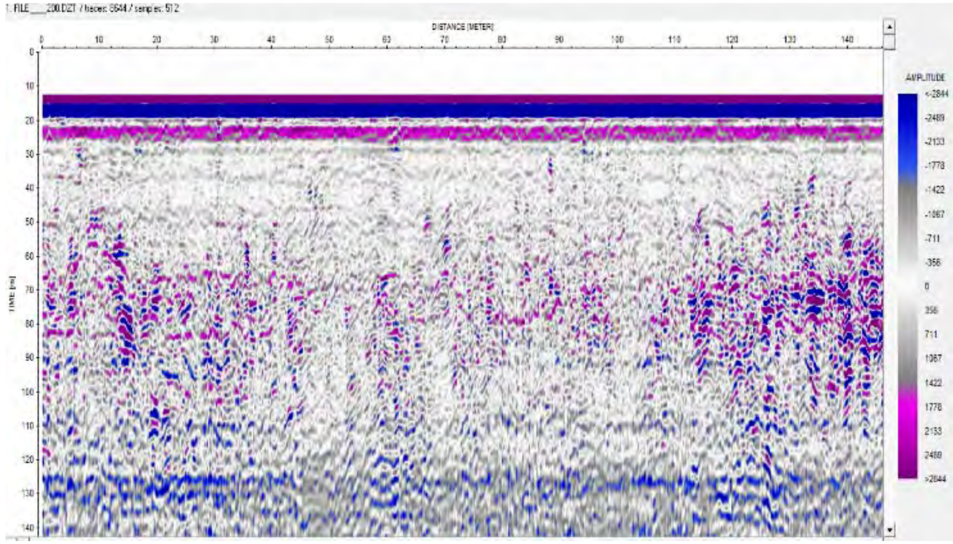
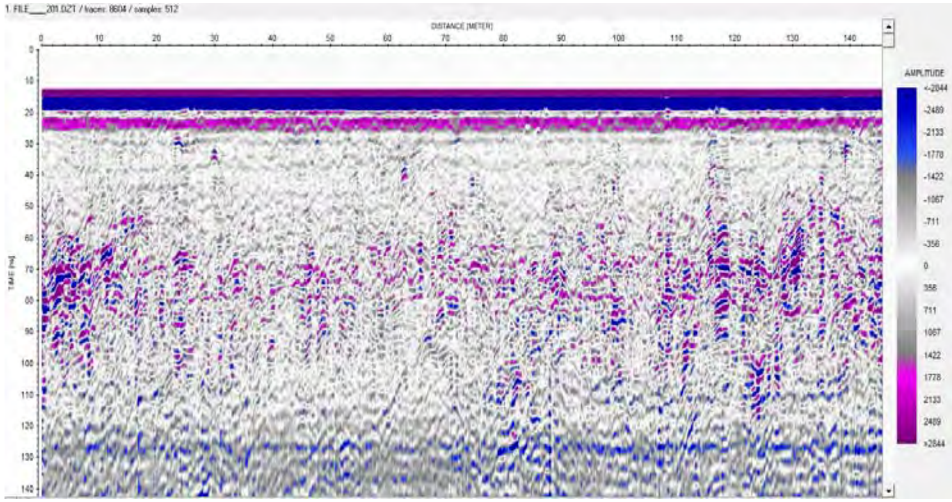
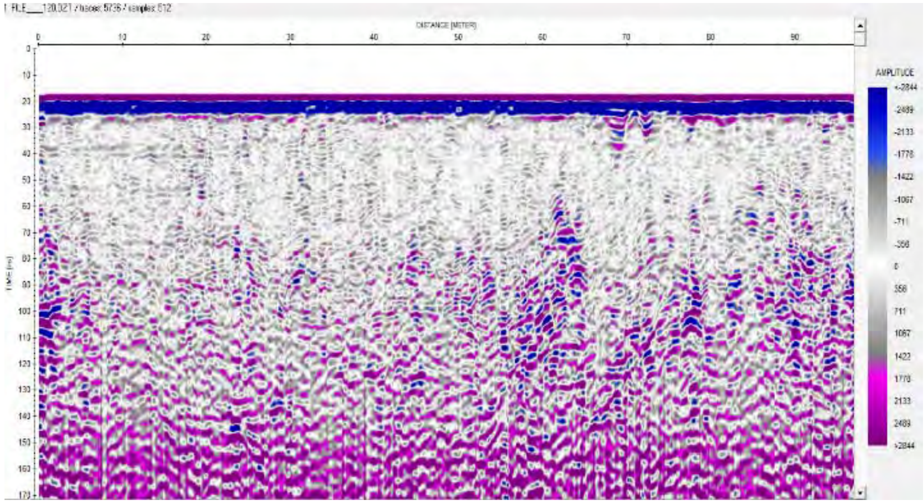
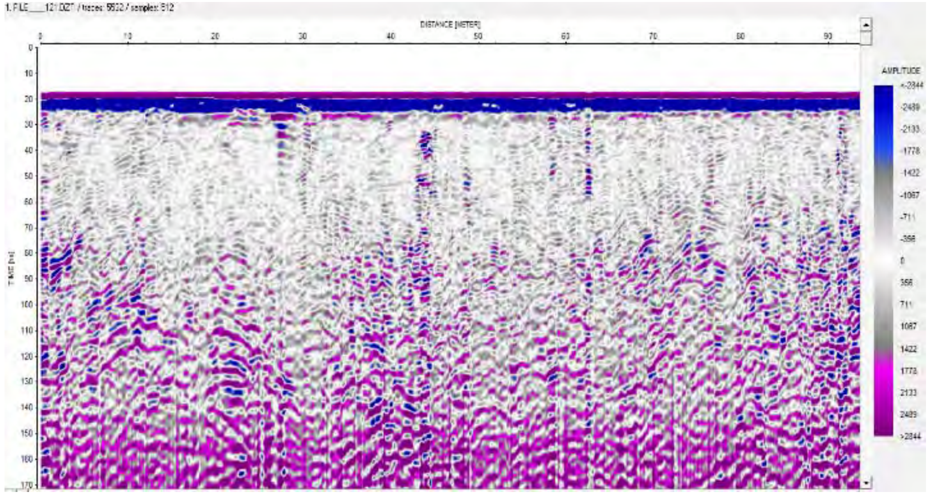
TIME [ns]
AMPLITUDE

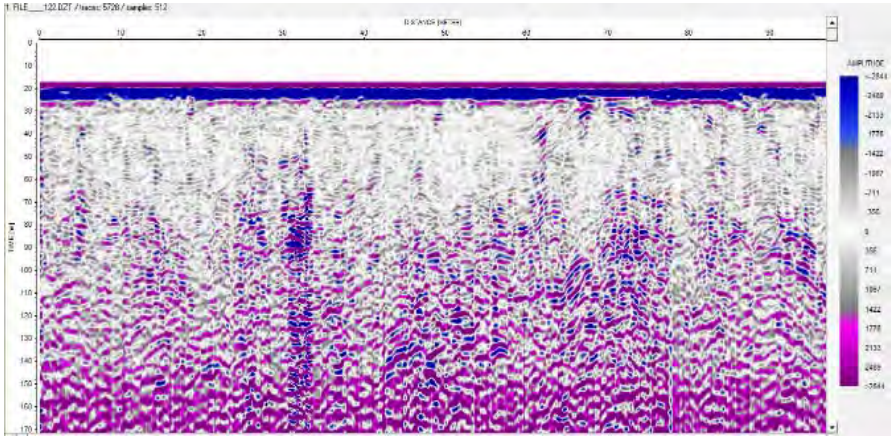

DISTANCE [METER]
TIME [ns]
AMPLITUDE

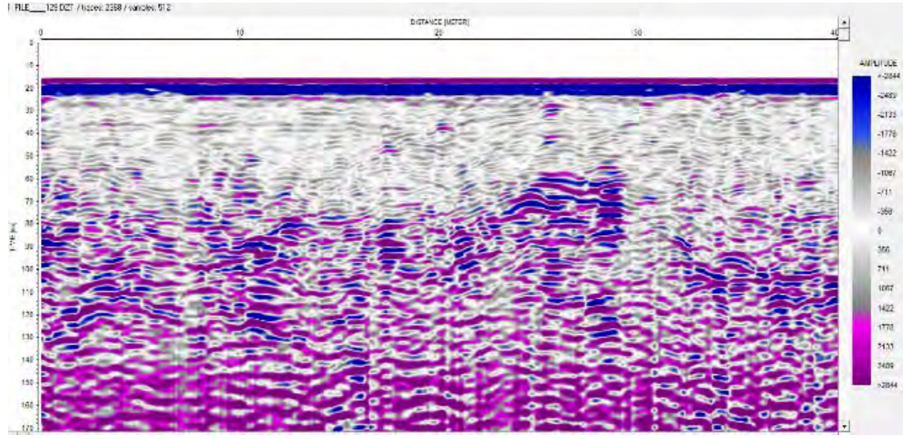

DISTANCE [METER]
TIME [ns]
AMPLITUDE

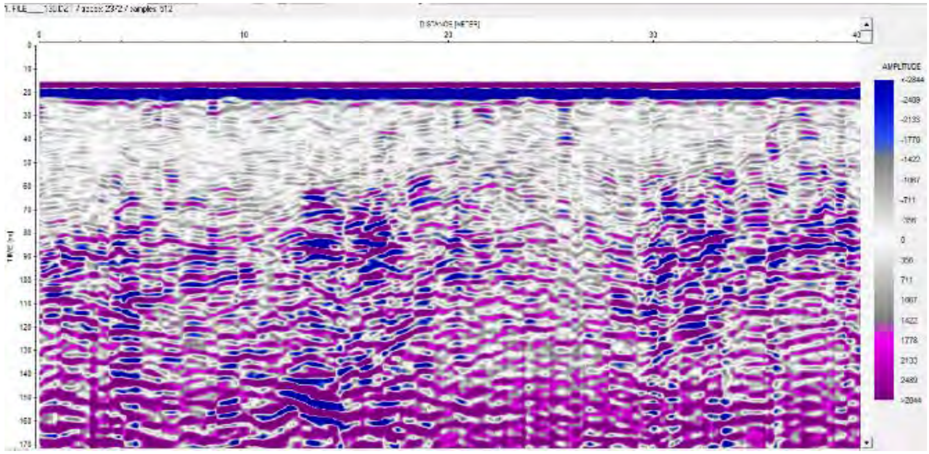
IMAGES OF GPR PROFILE SCANNED ALONG ERT-3

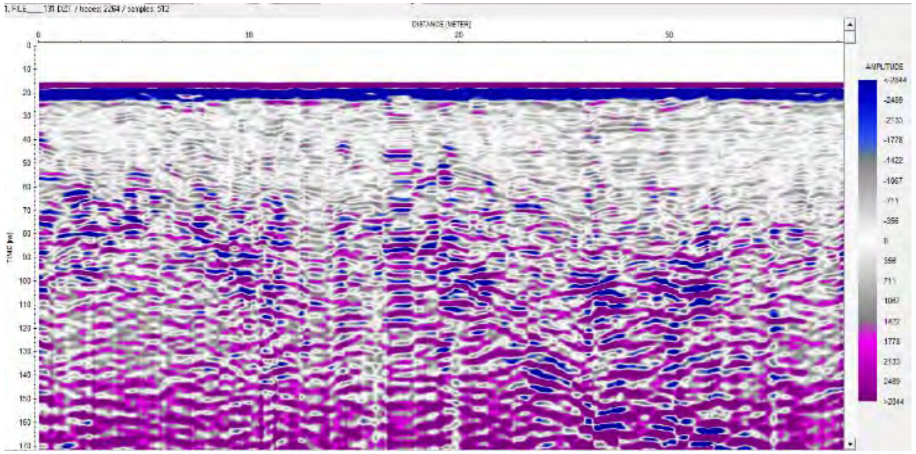


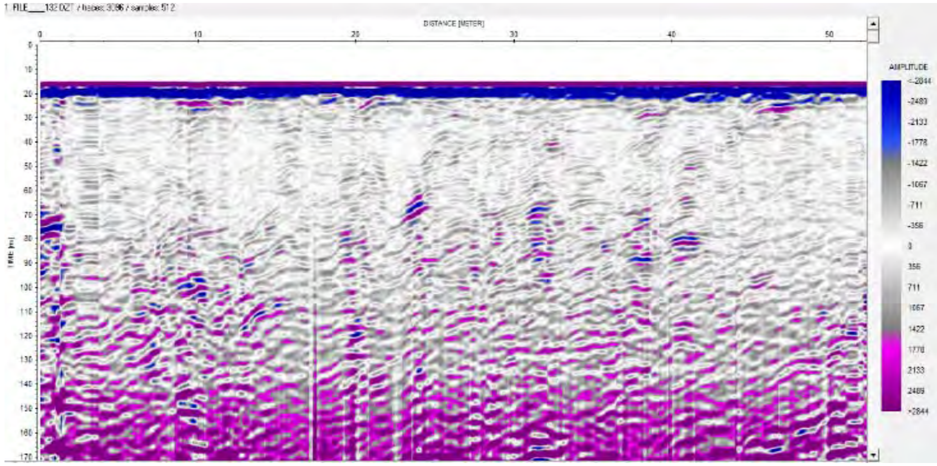


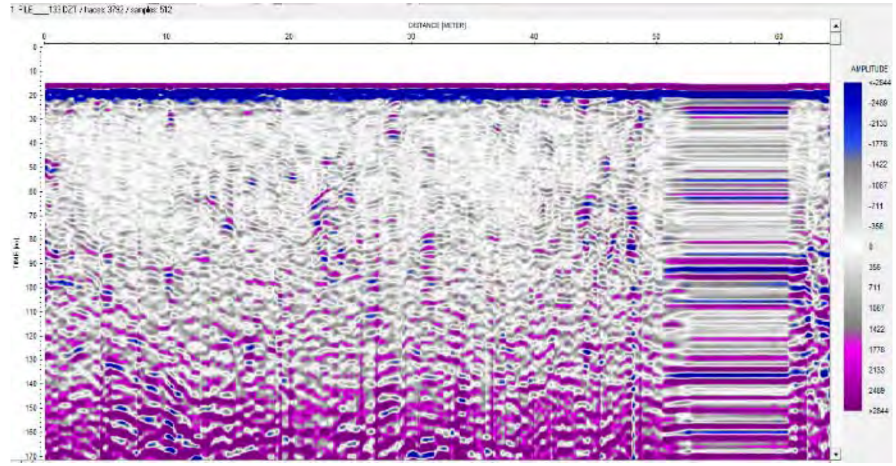




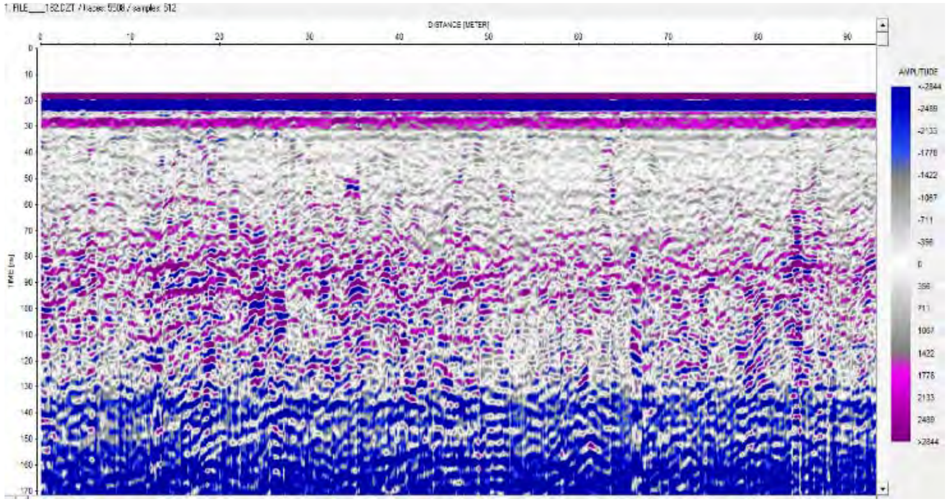


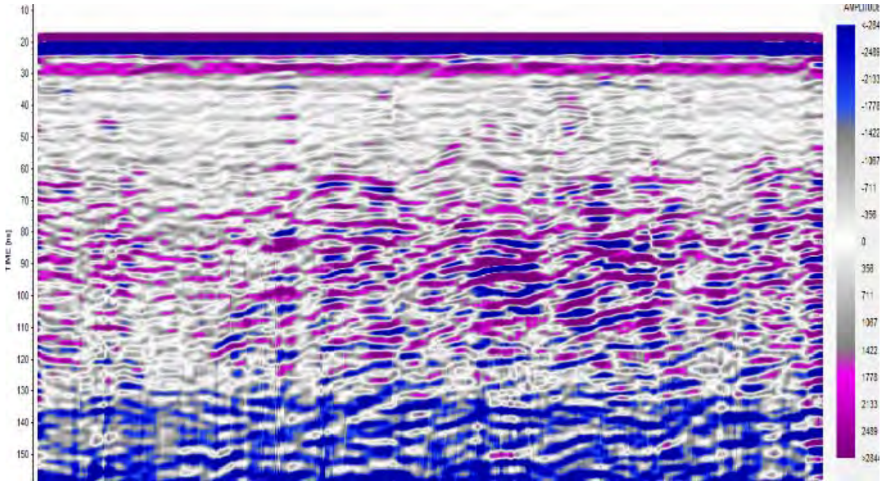


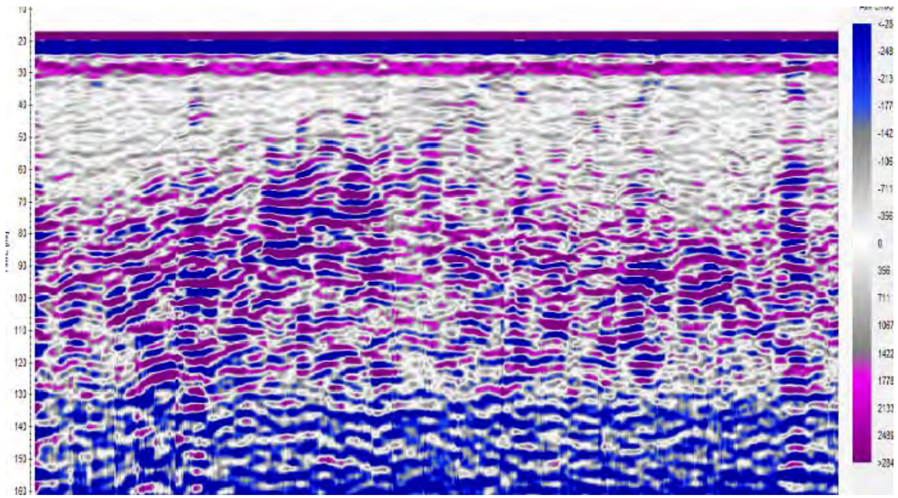


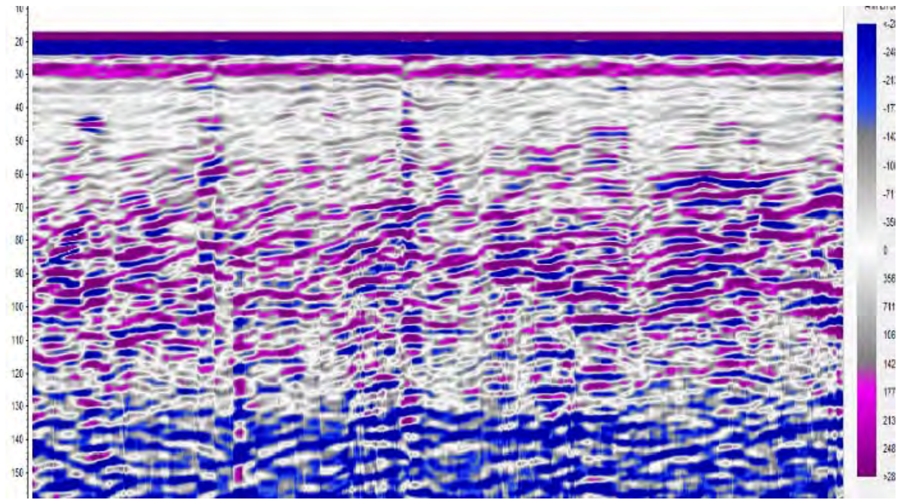


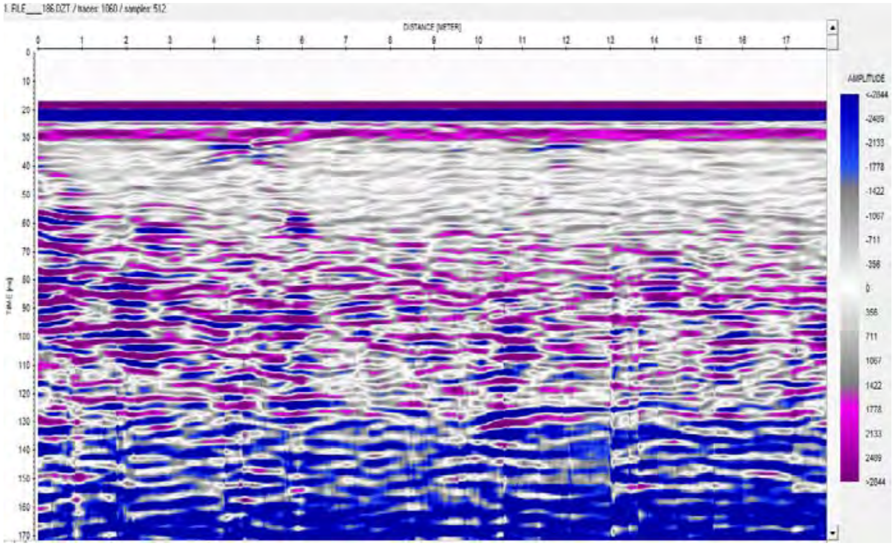
IMAGES OF GPR PROFILE SCANNED ALONG ERT-4

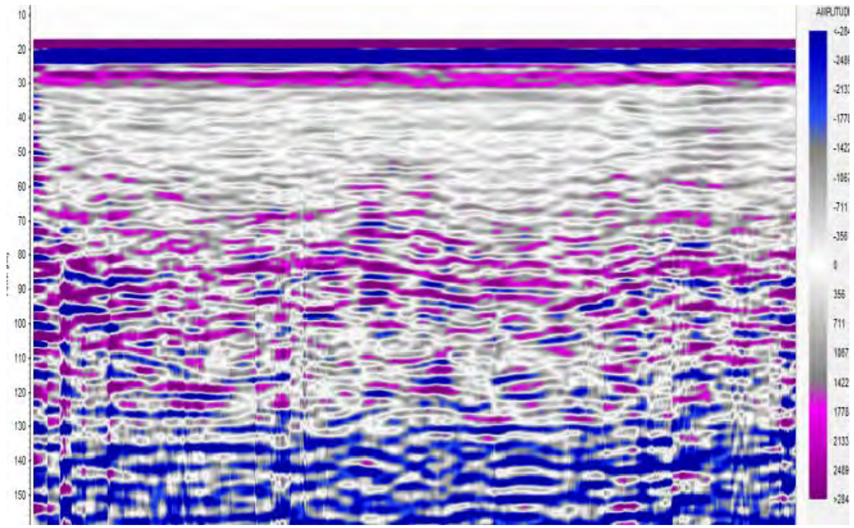


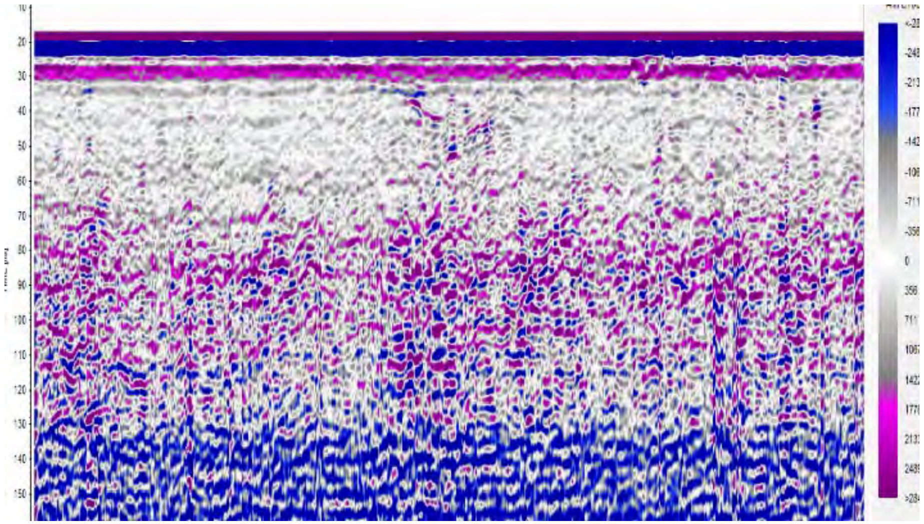


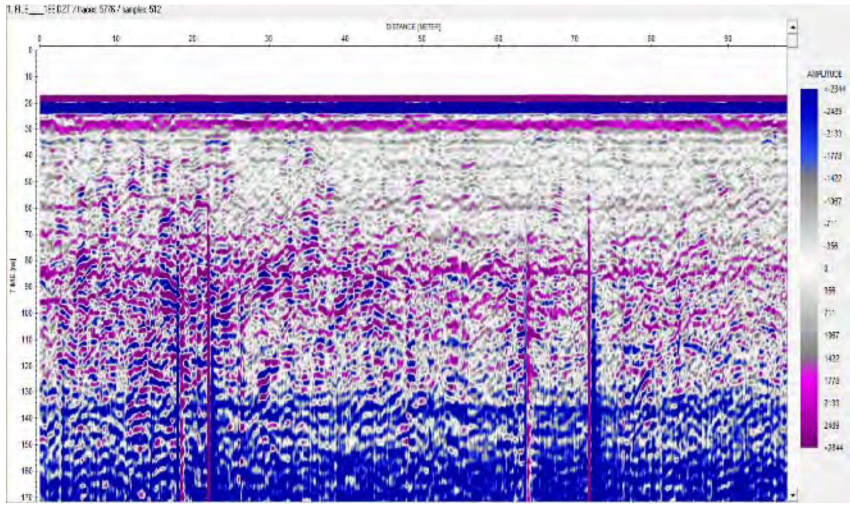





DISTANCE [METER]
AMPLITUDE



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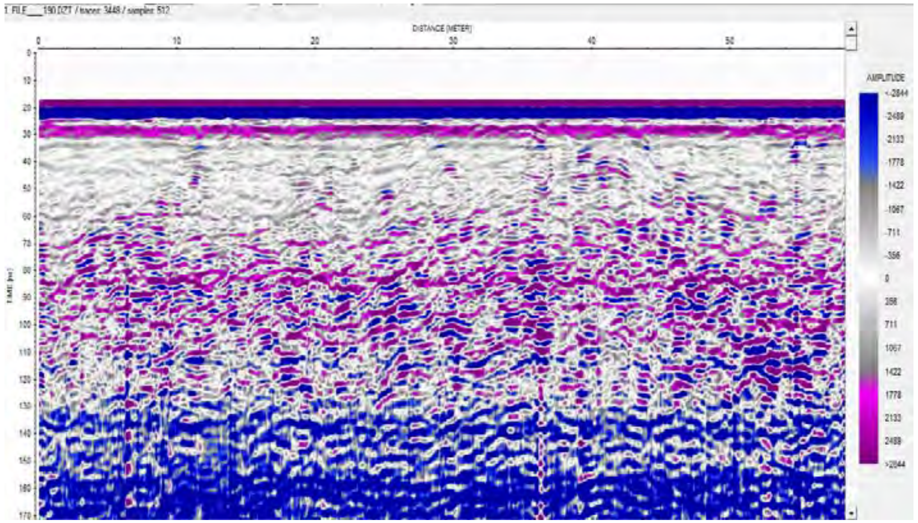
AMPLITUDE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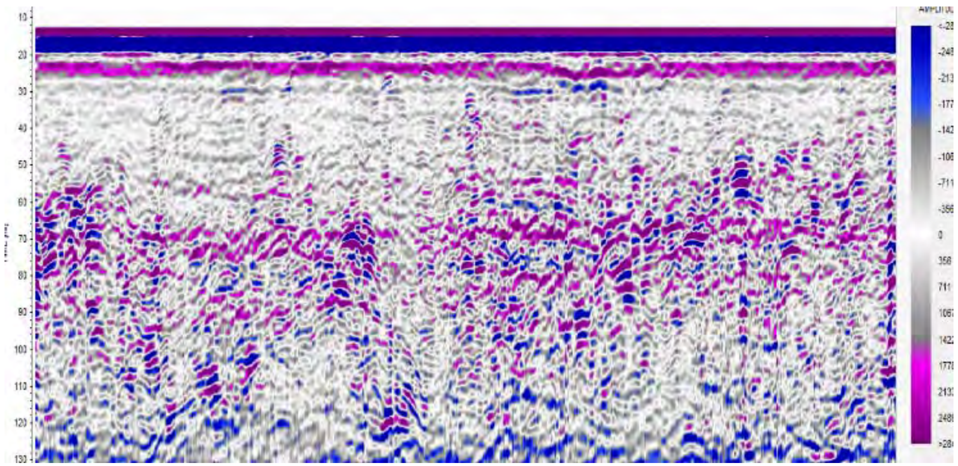
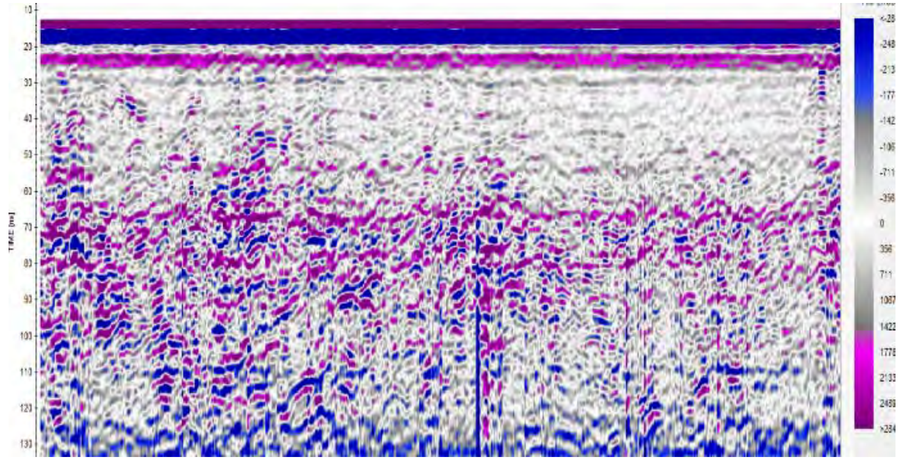
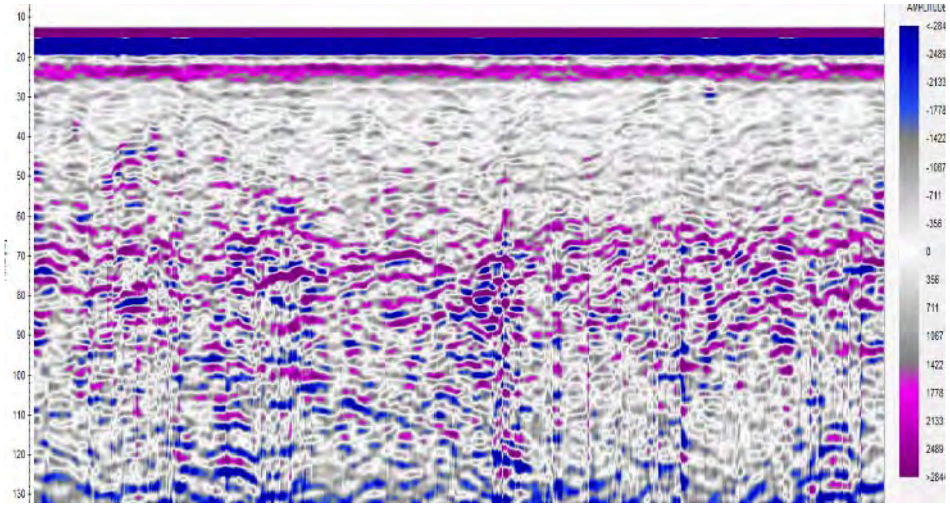
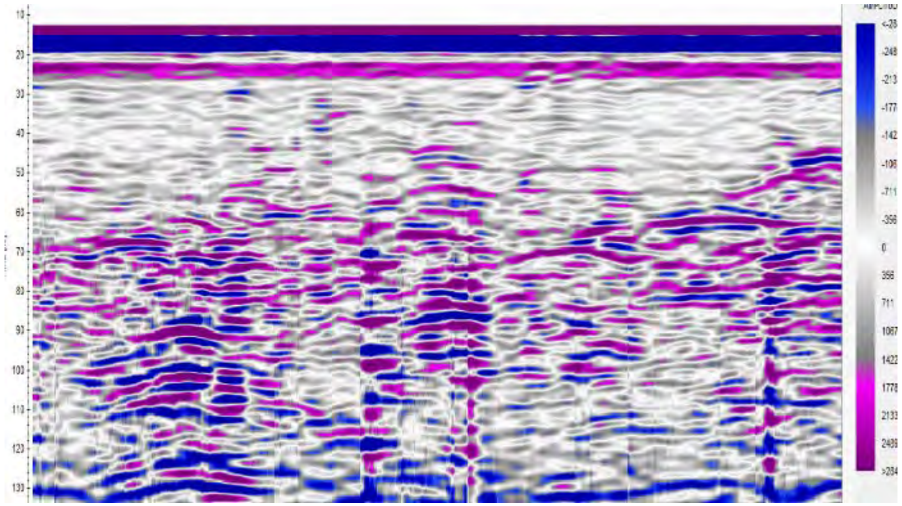
50
AMPLITUDE

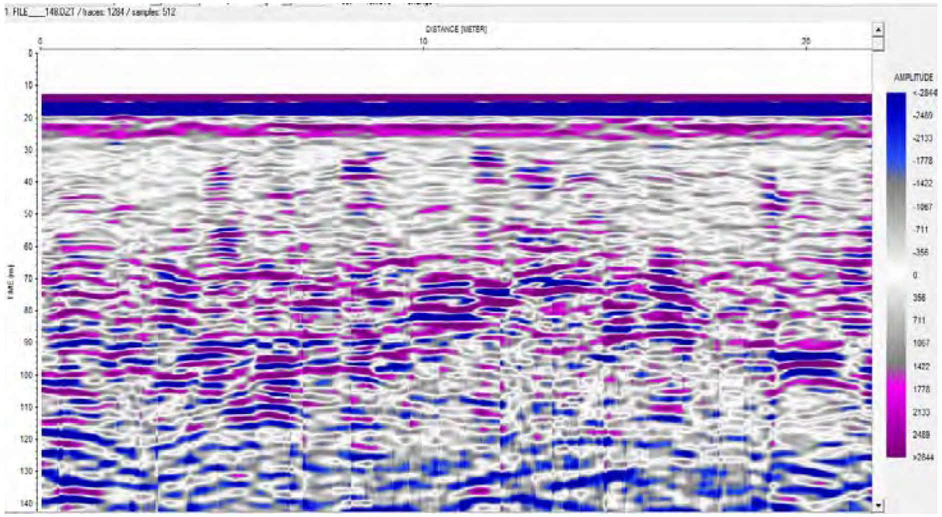
IMAGES OF GPR PROFILE SCANNED ALONG ERT-5

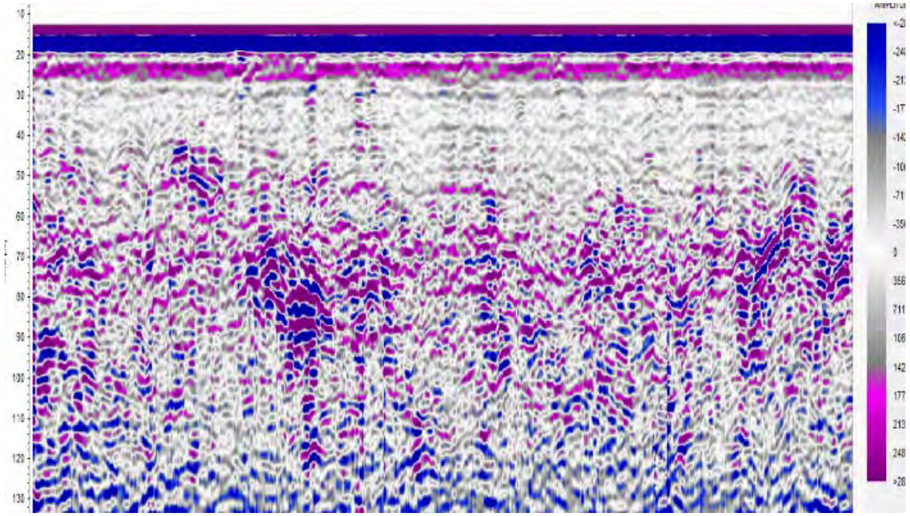




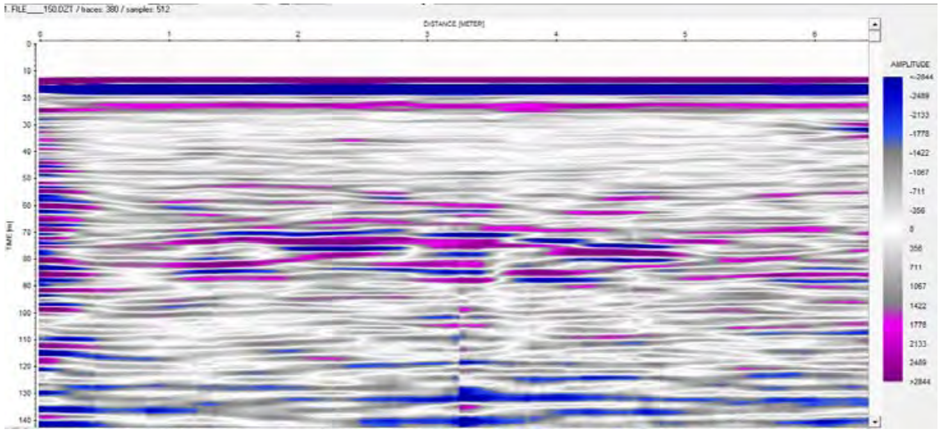


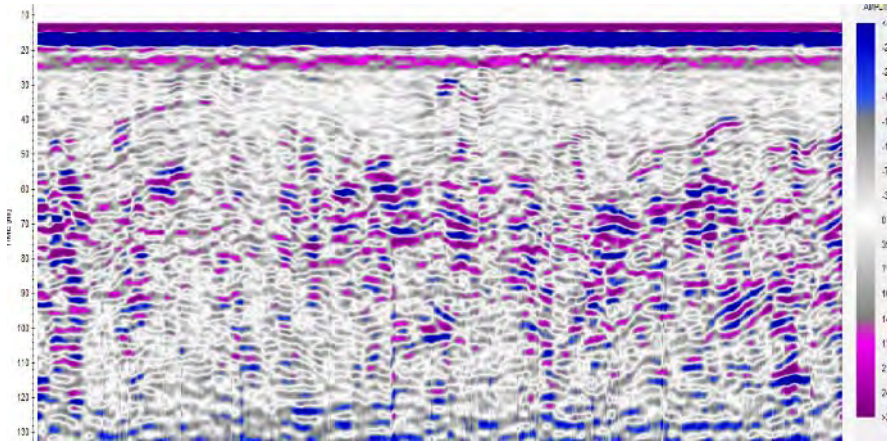


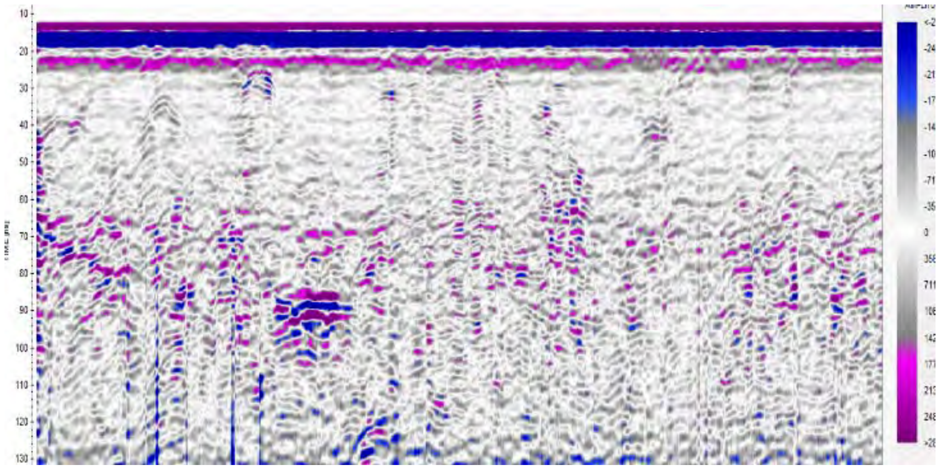


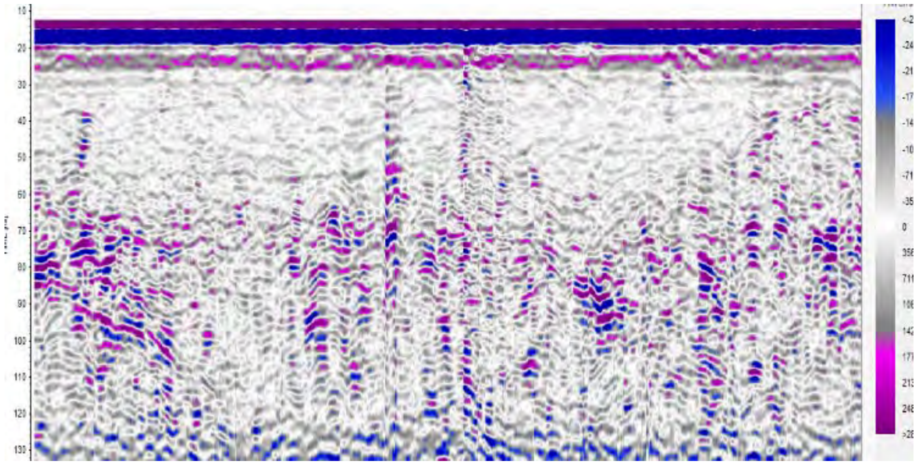


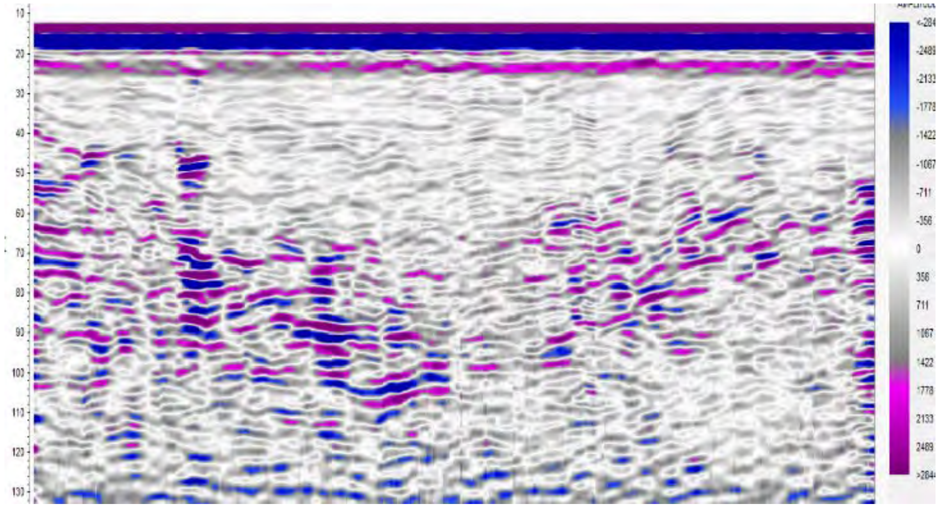
IMAGES OF GPR PROFILE SCANNED ALONG ERT-6

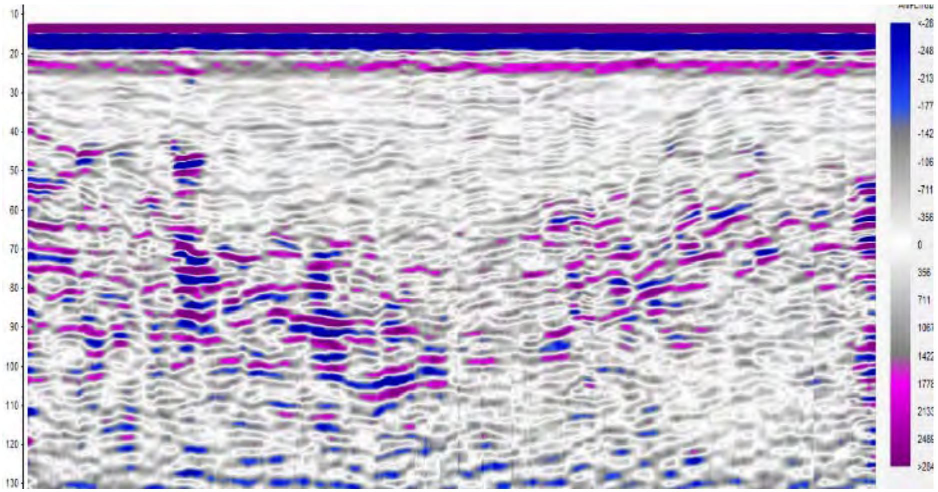


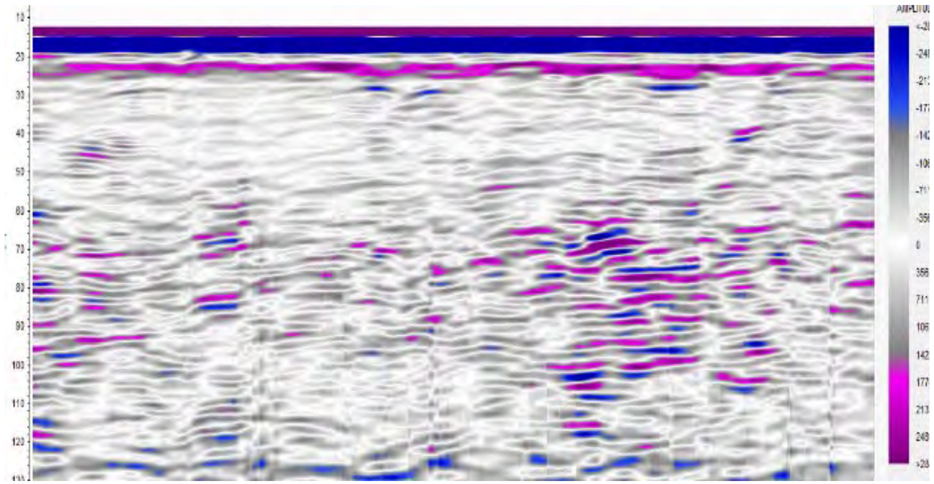


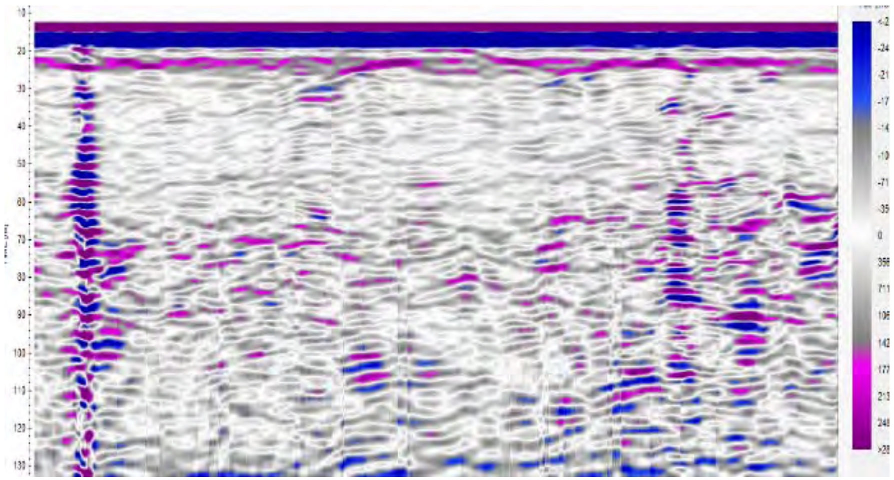


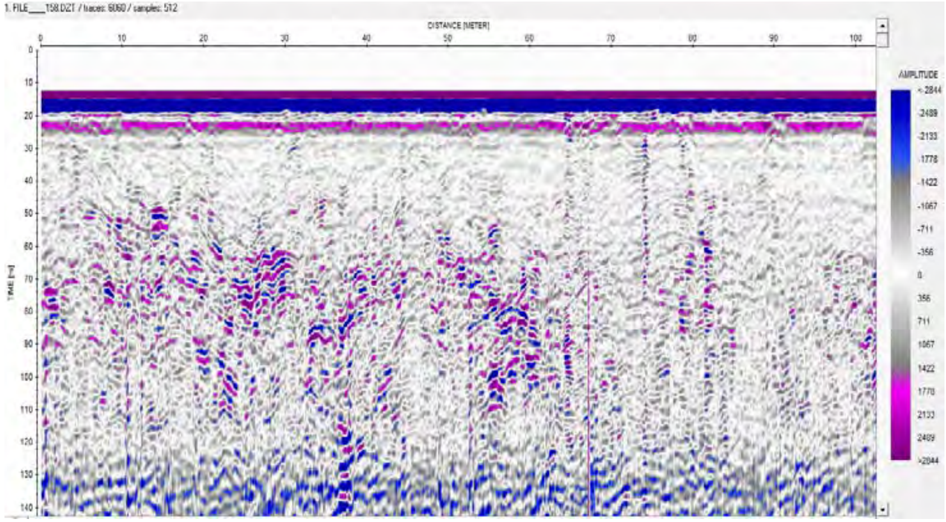




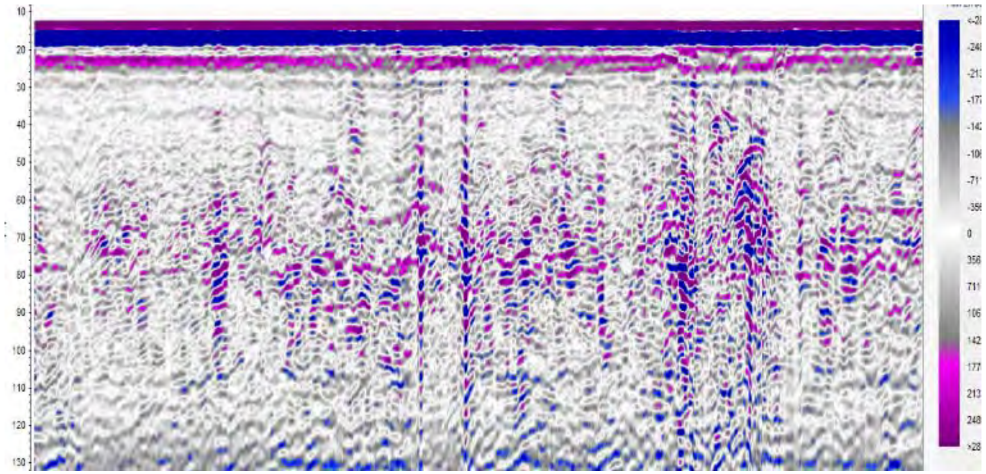


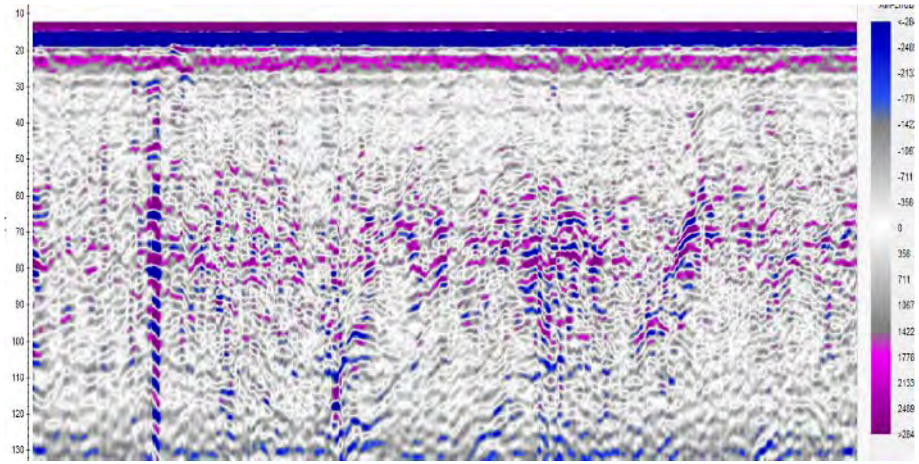


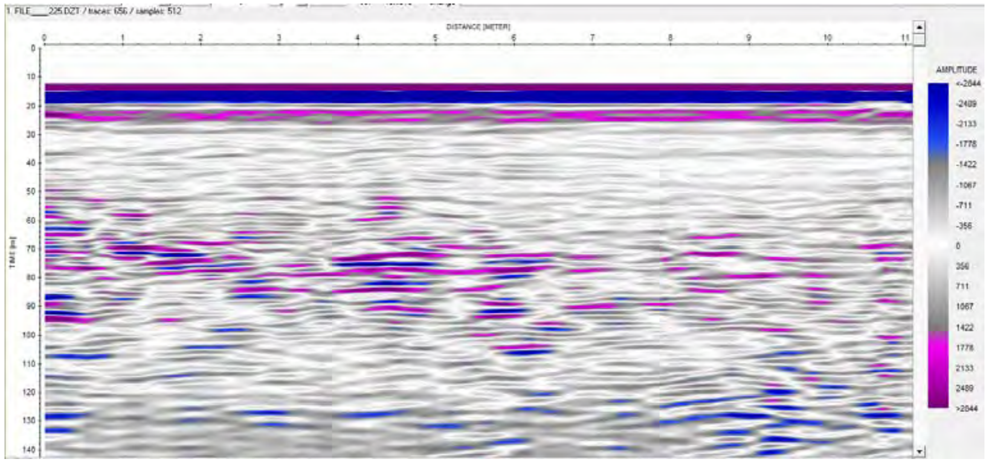


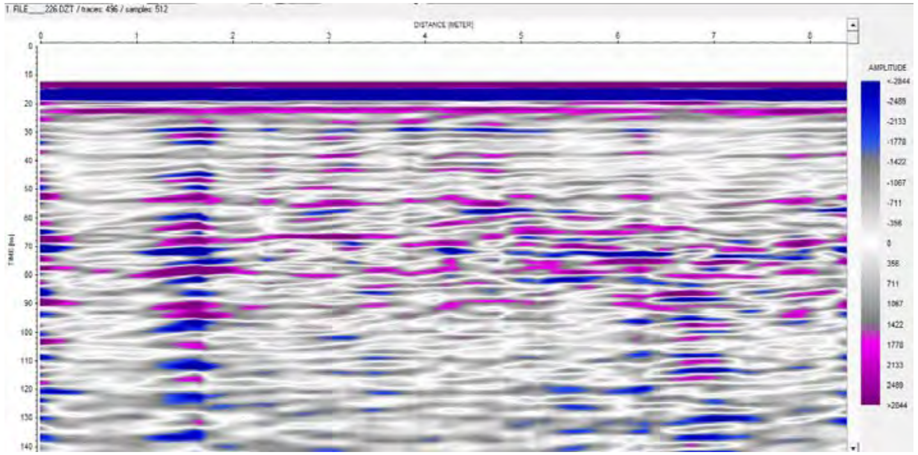


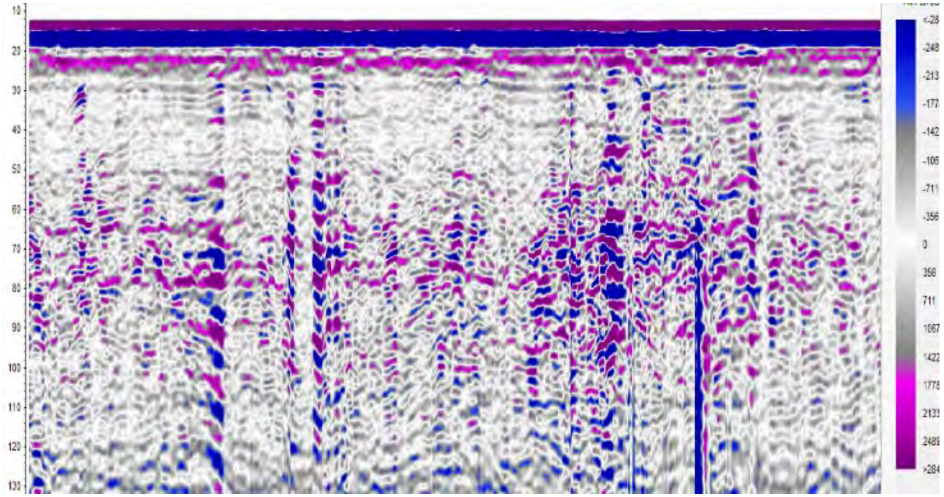
IMAGES OF GPR PROFILE SCANNED ALONG ERT-7

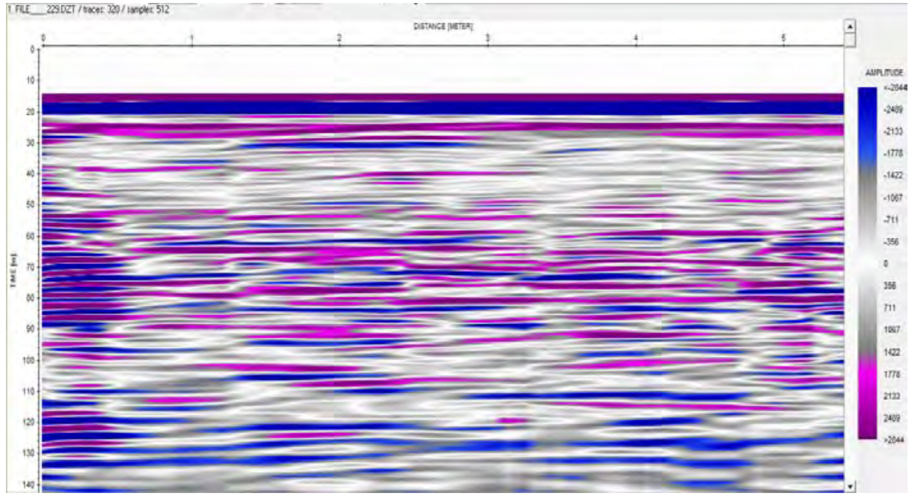


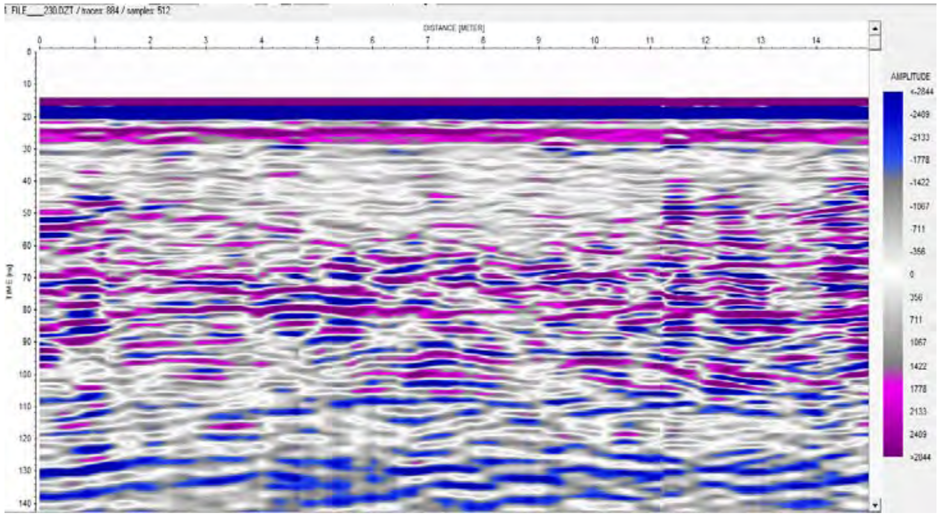


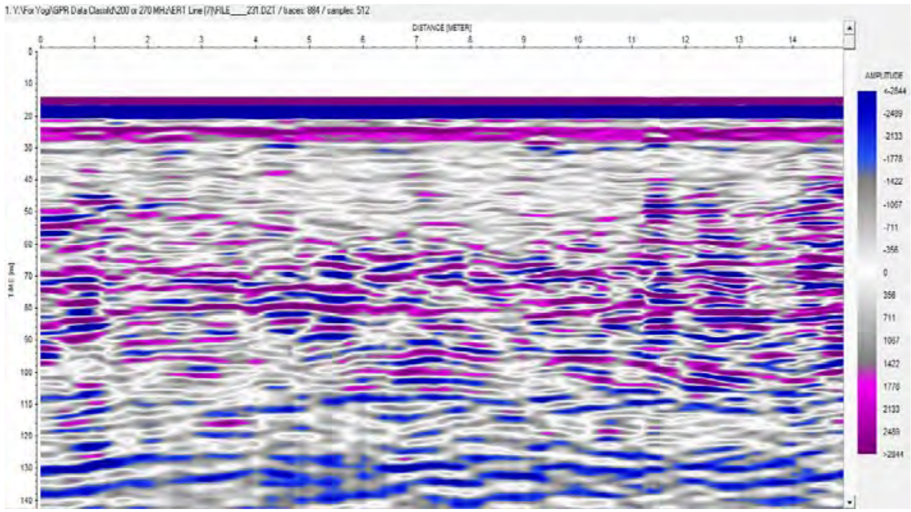


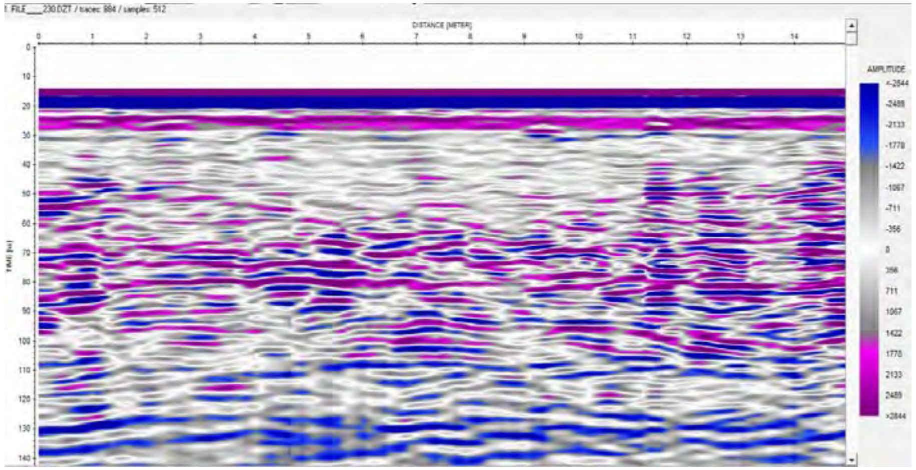


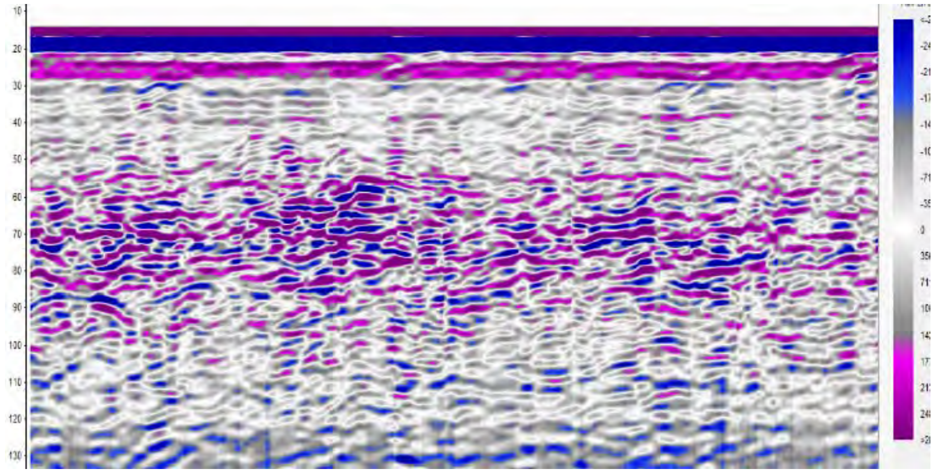


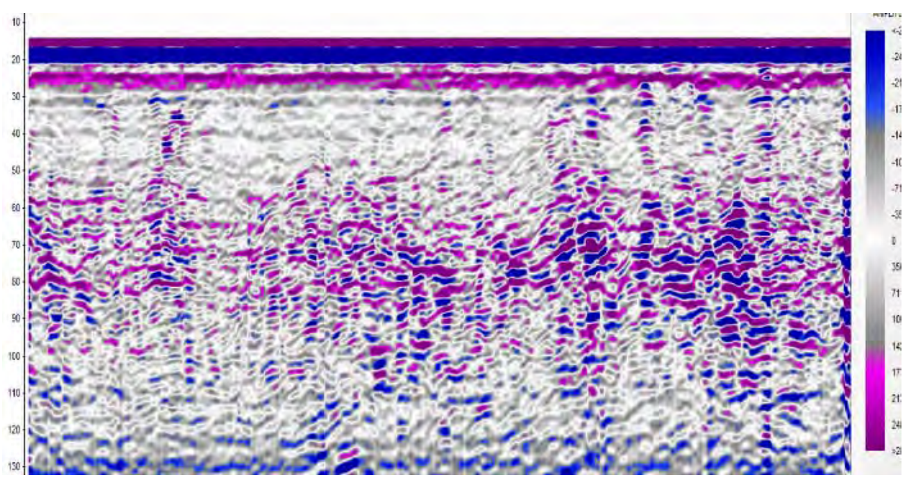


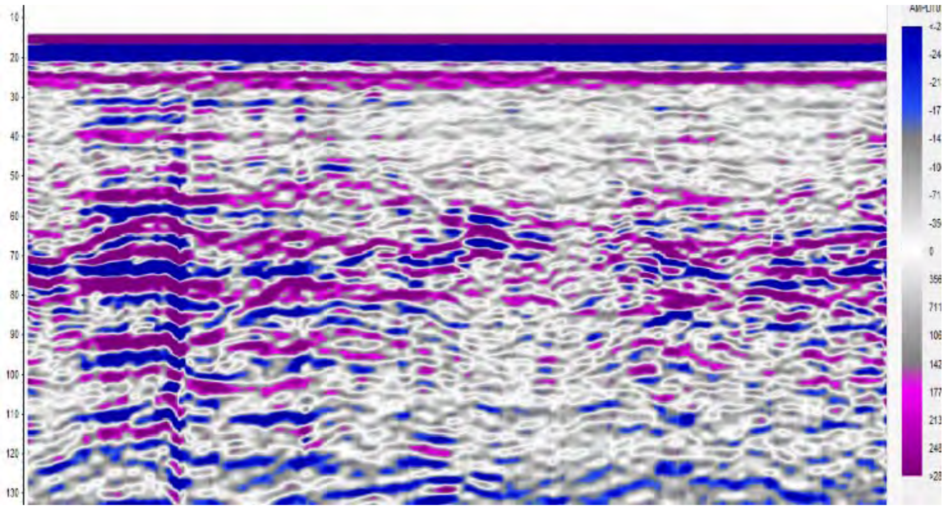


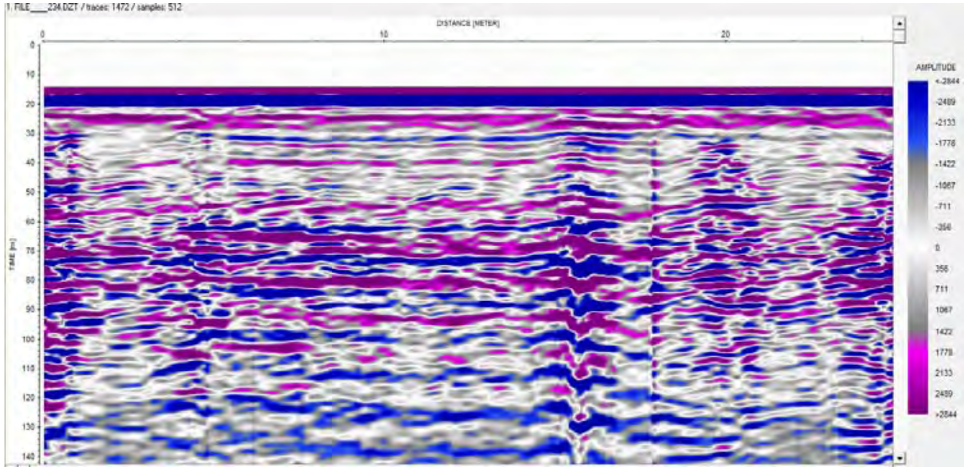








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20
TIME [ns]
AMPLITUDE
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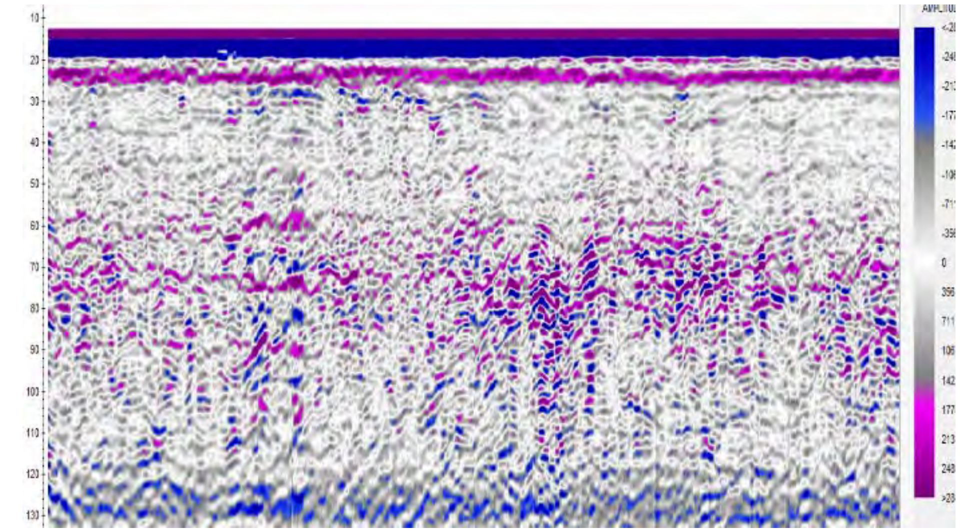
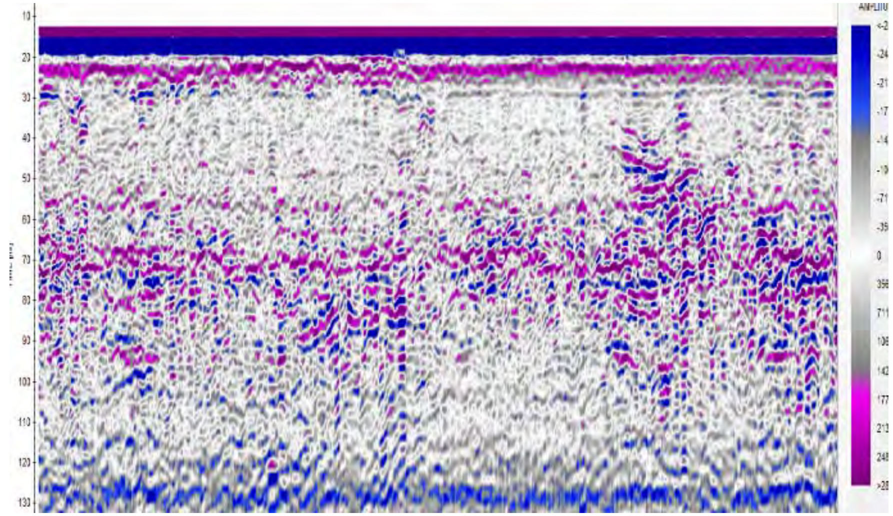
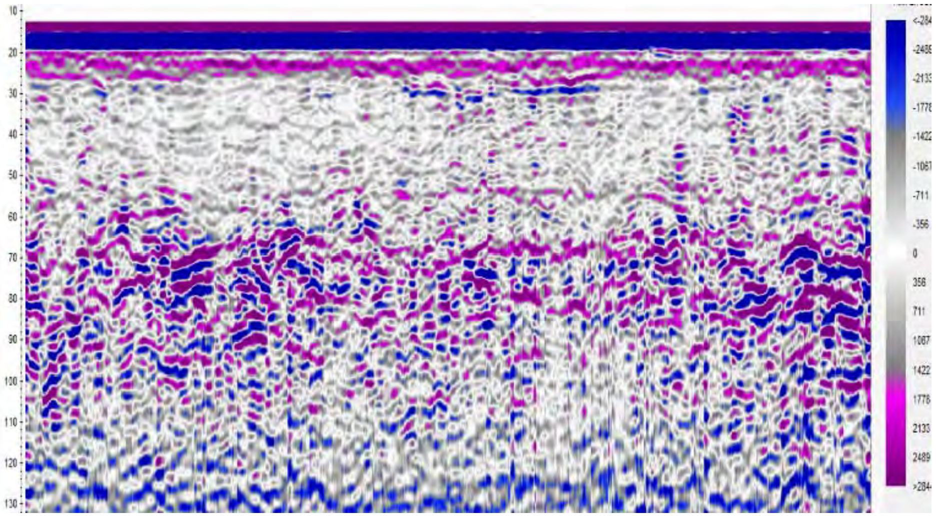
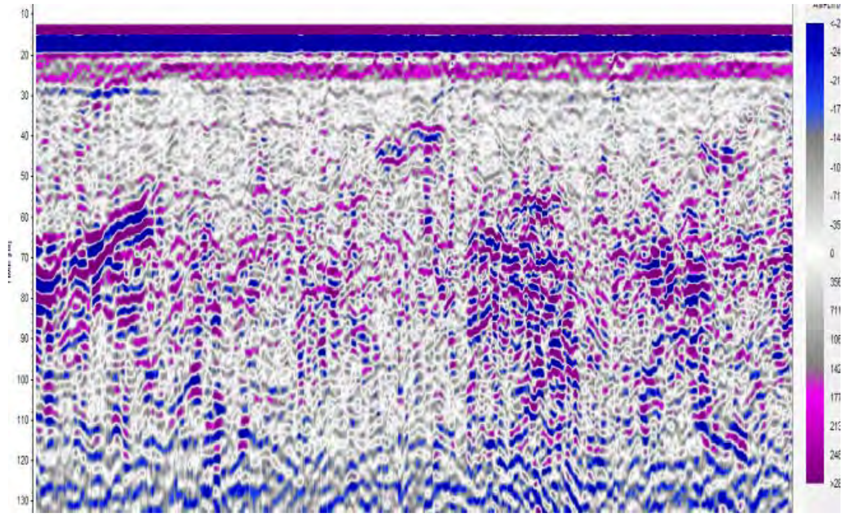
-1422
-1067
-711
-356
0
356
711
1067
1422
1778
2133
2489
>2844

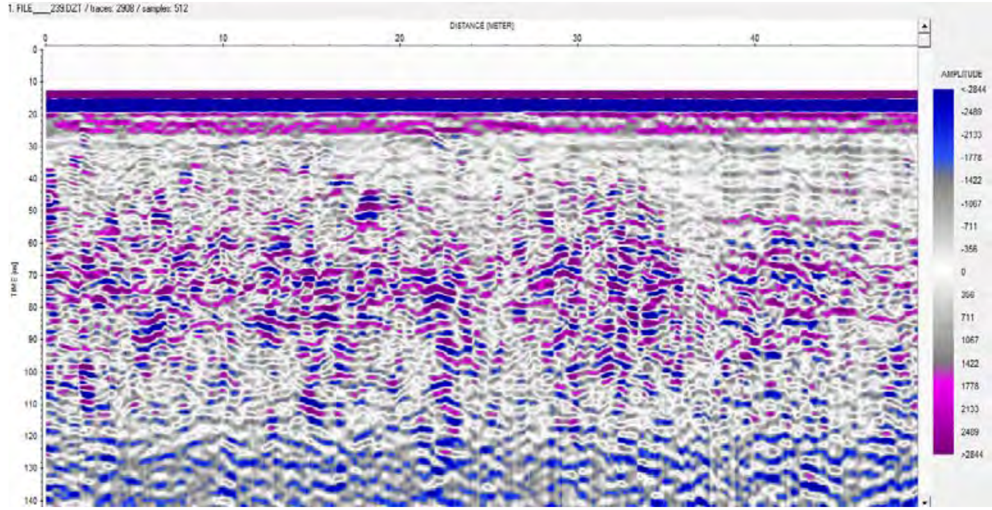
IMAGES OF GPR PROFILE SCANNED ALONG ERT-8







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20
30
40
TIME [ns]
AMPLITUDE
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-1422
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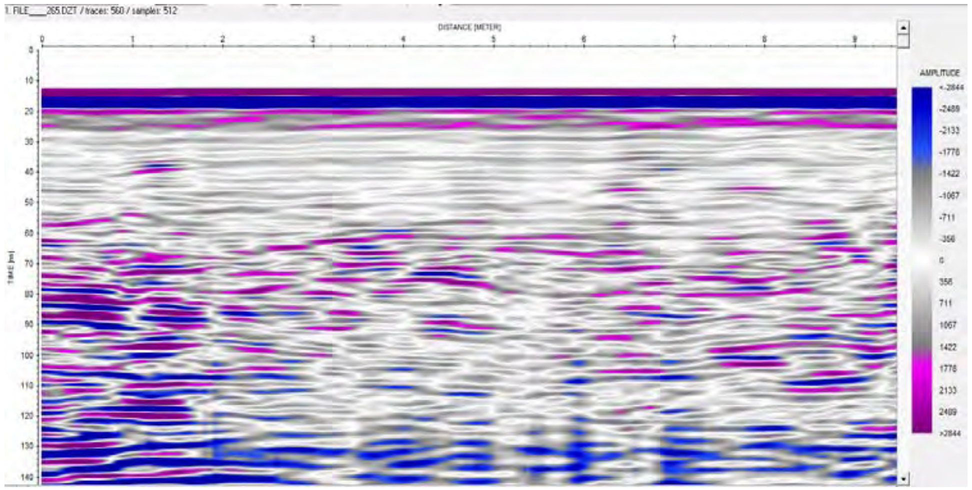
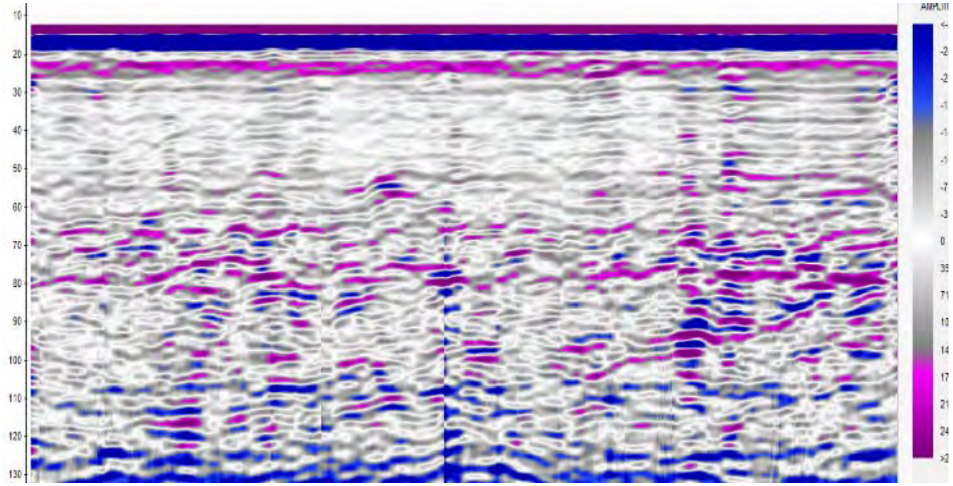
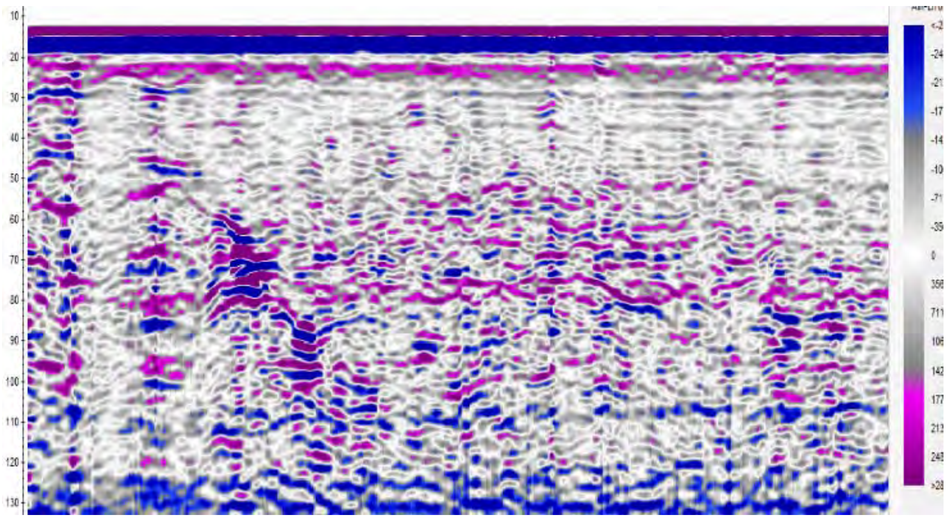
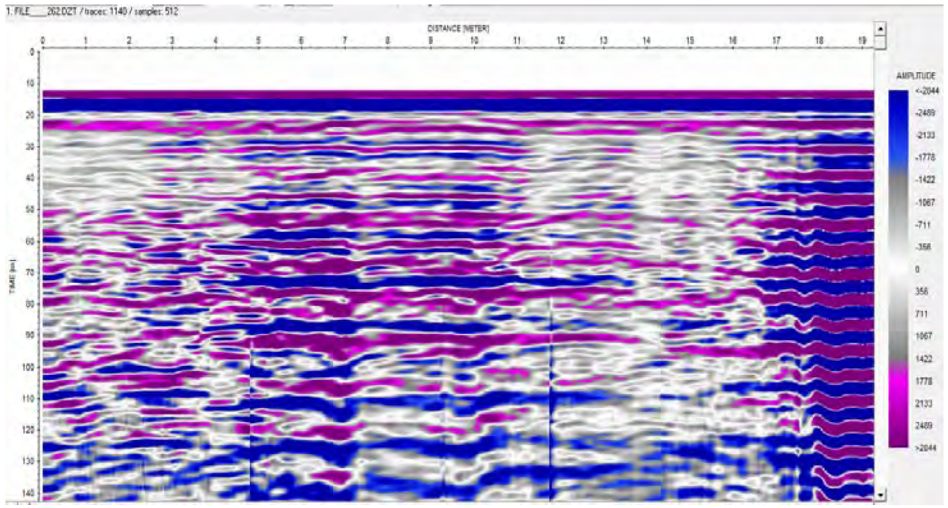
711
1067
1422
1778
2133
2489
>2844

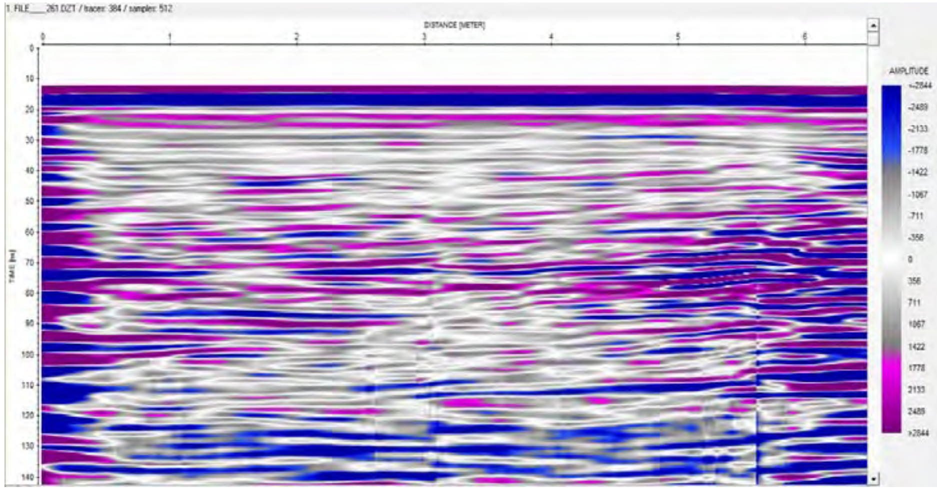
IMAGES OF GPR PROFILE SCANNED ALONG ERT-9

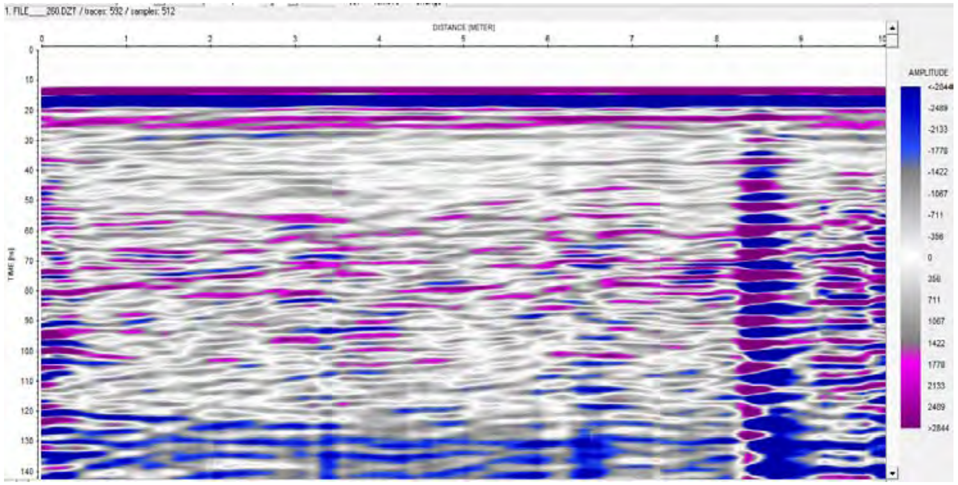


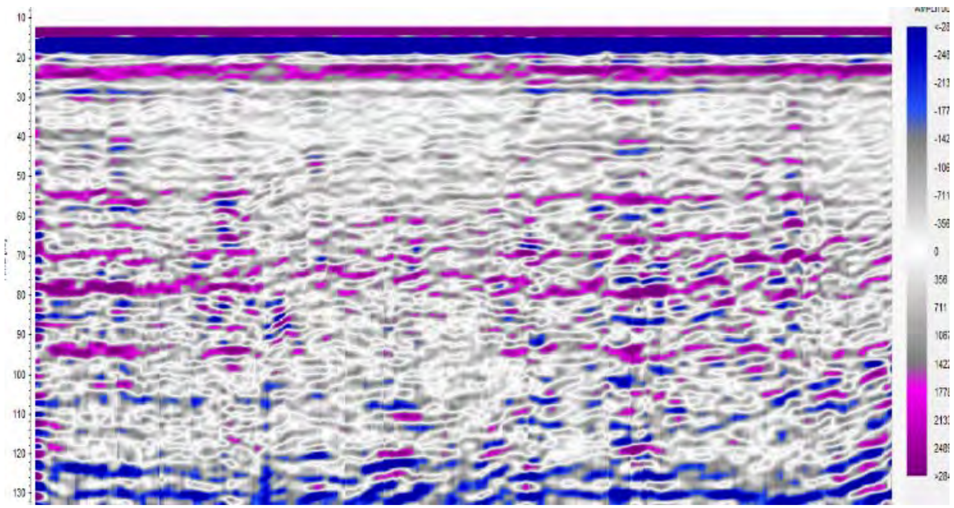


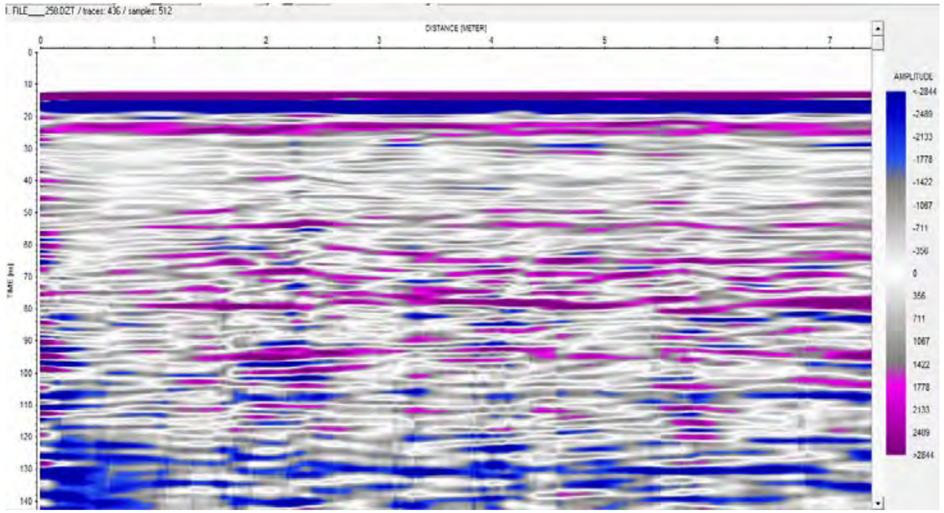


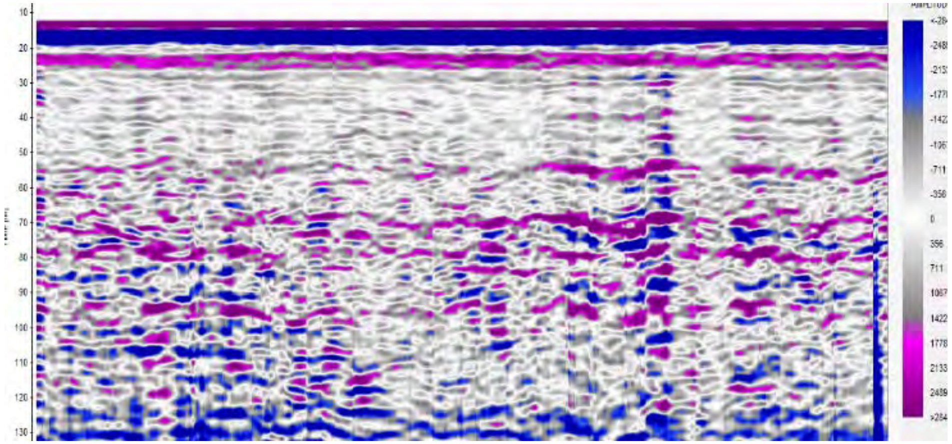


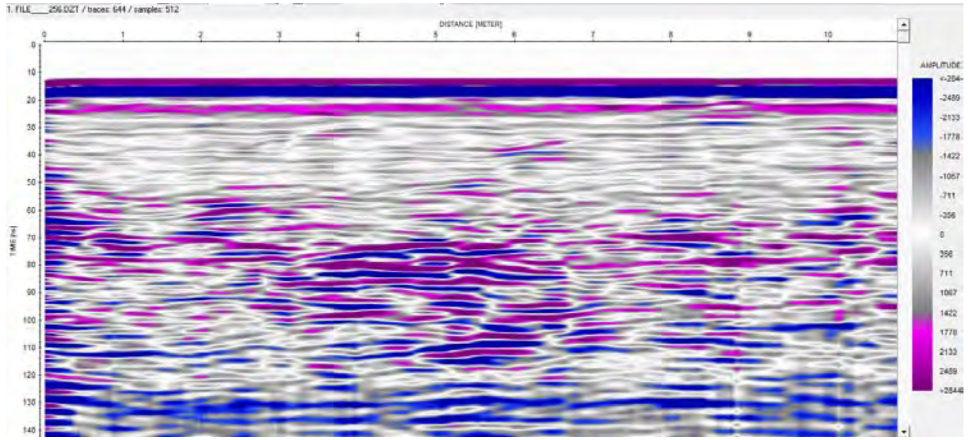









AMPLITUDE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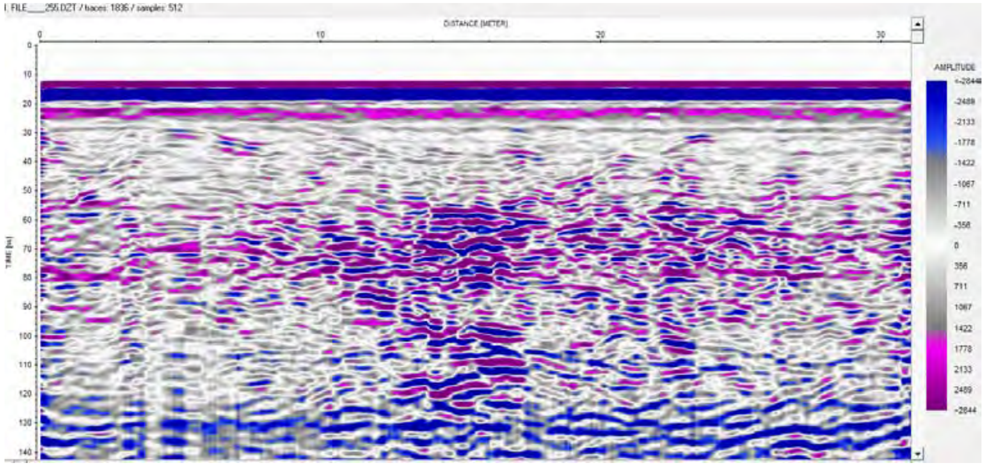
DISTANCE [METER]
AMPLITUDE
TIME [ns]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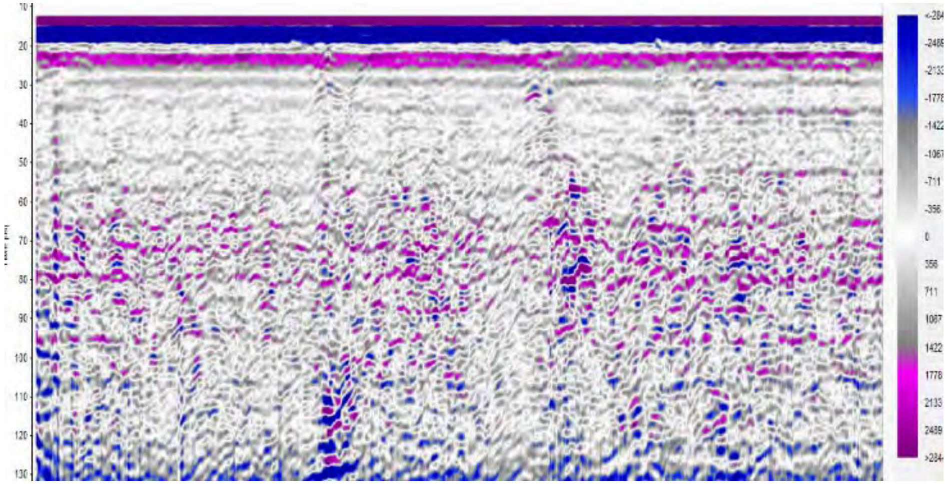
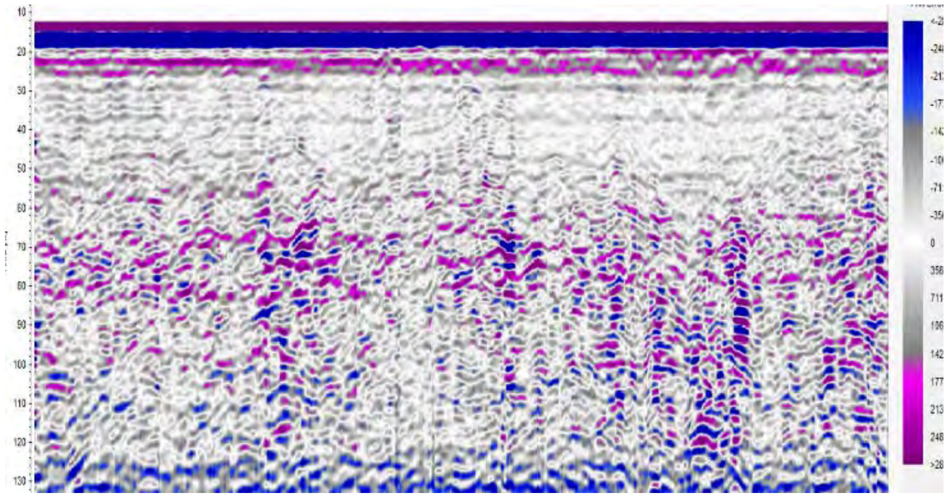
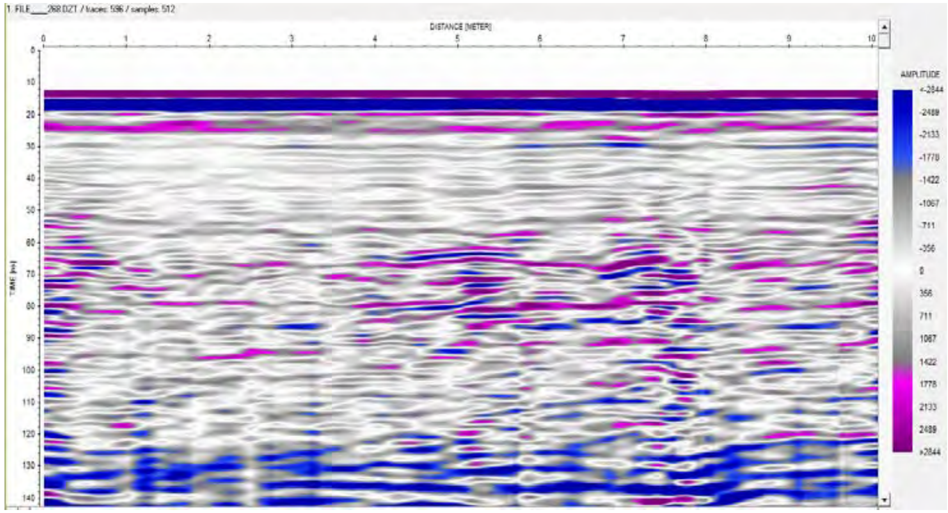
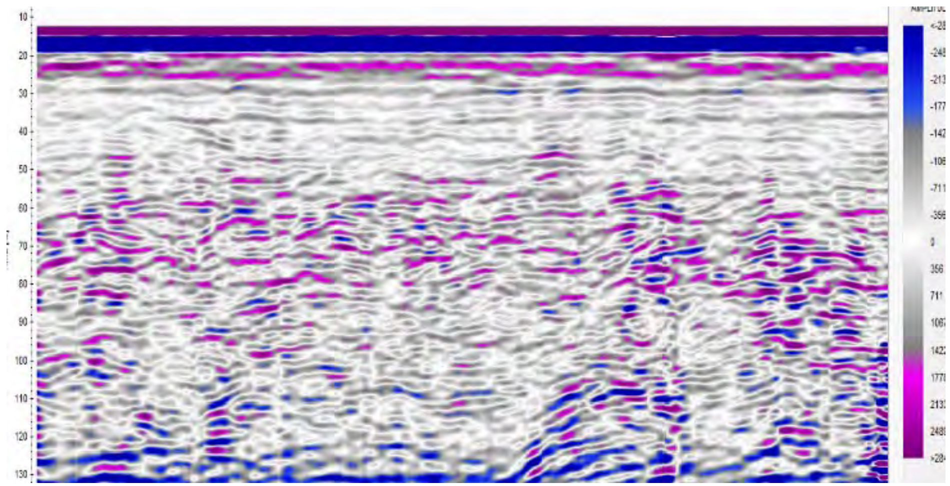
DISTANCE [METER]
AMPLITUDE
TIME [ns]

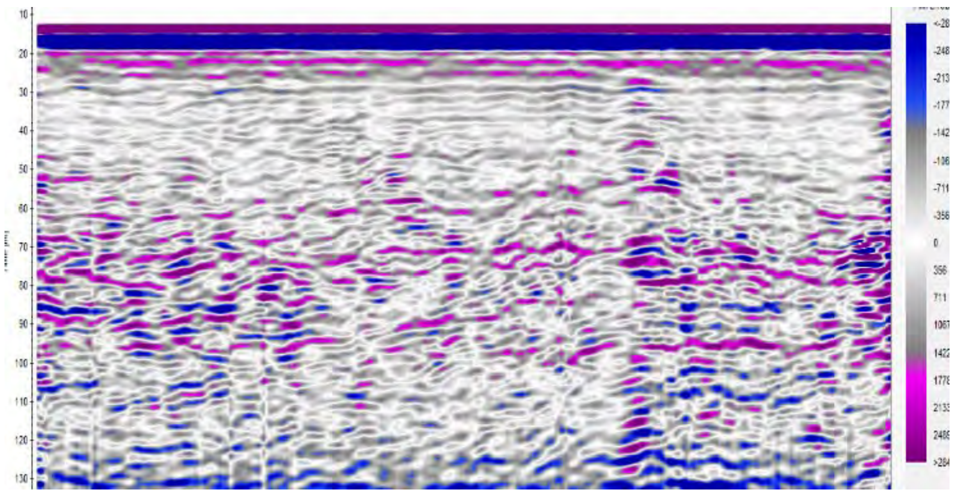
IMAGES OF GPR PROFILE SCANNED ALONG ERT-10

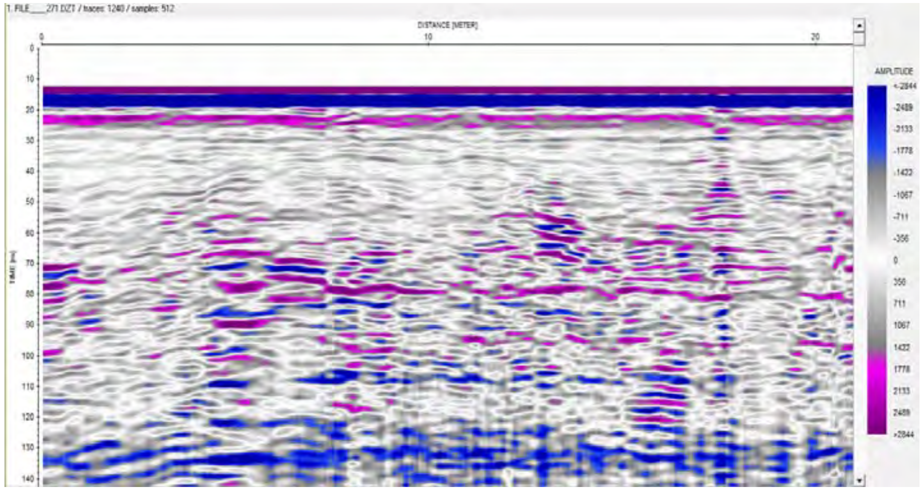








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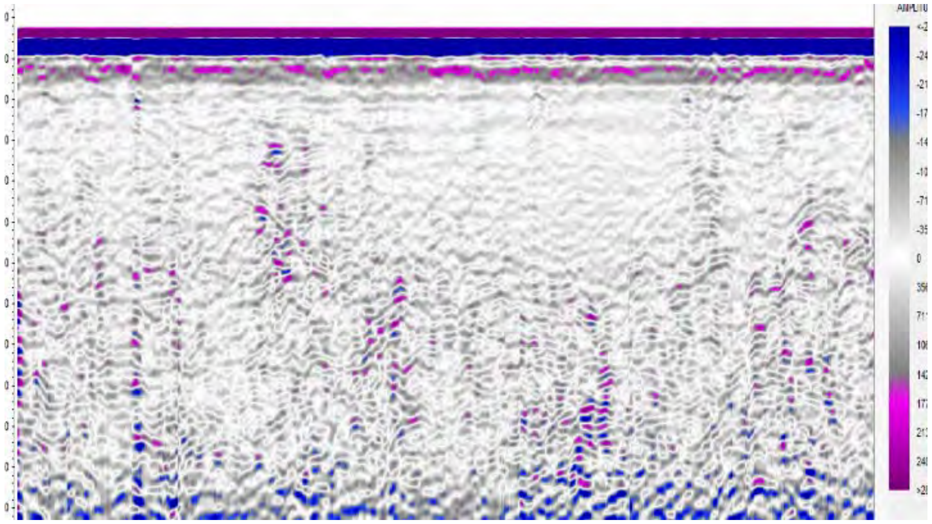
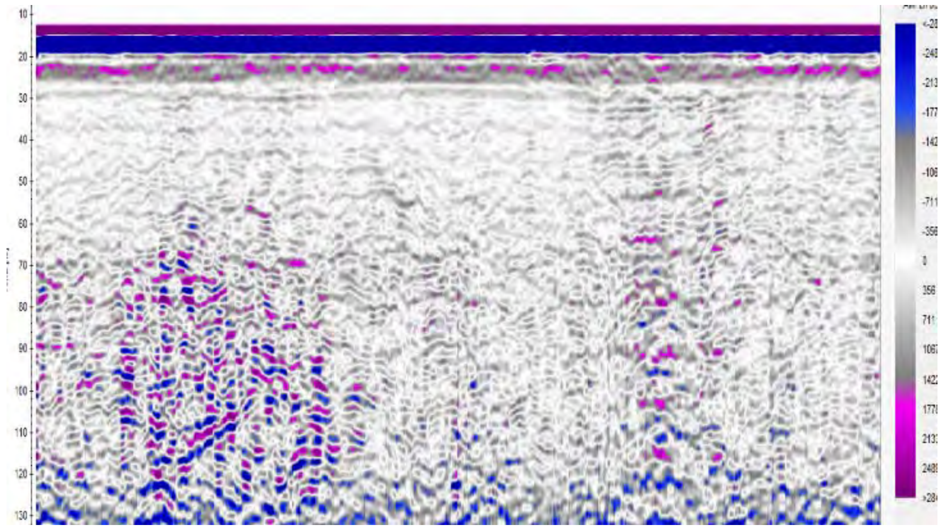
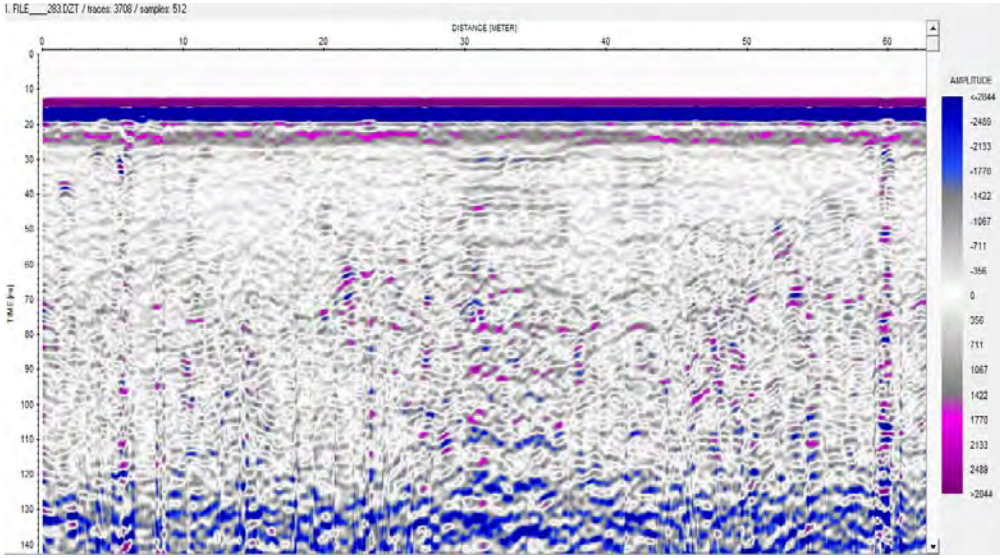
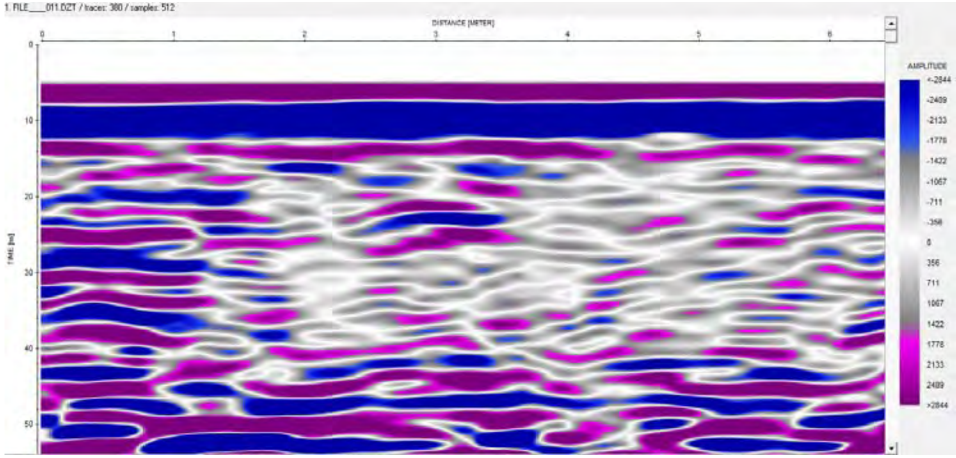
DISTANCE [METER]
AMPLITUDE
TIME [ns]

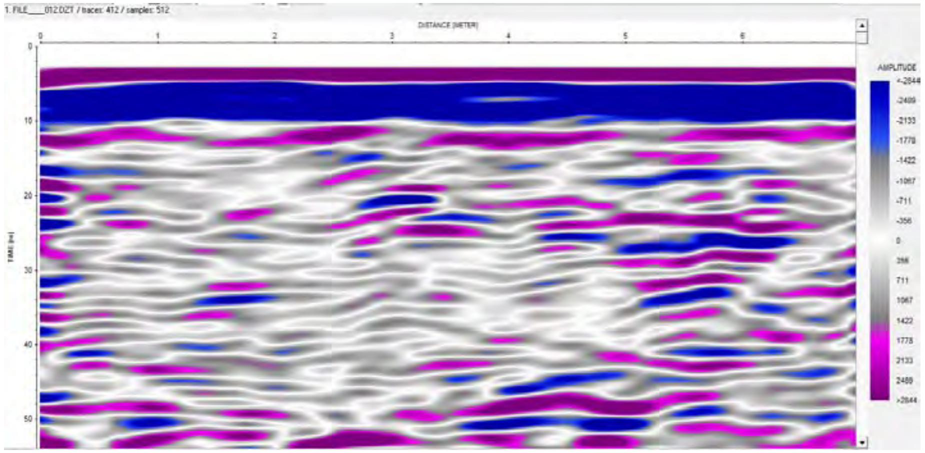


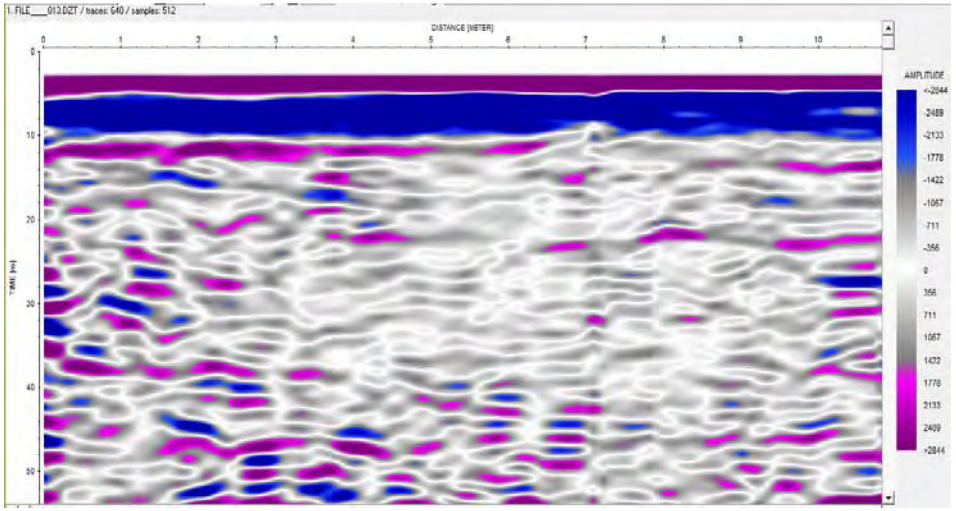


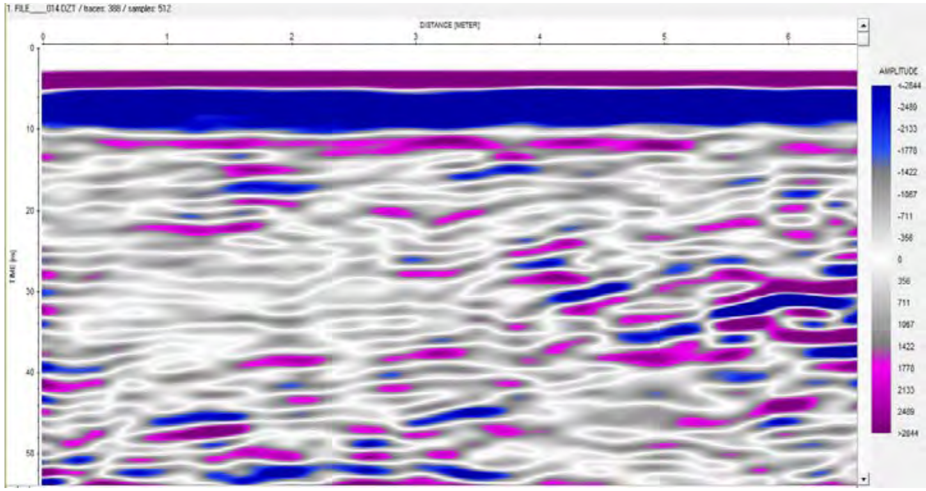


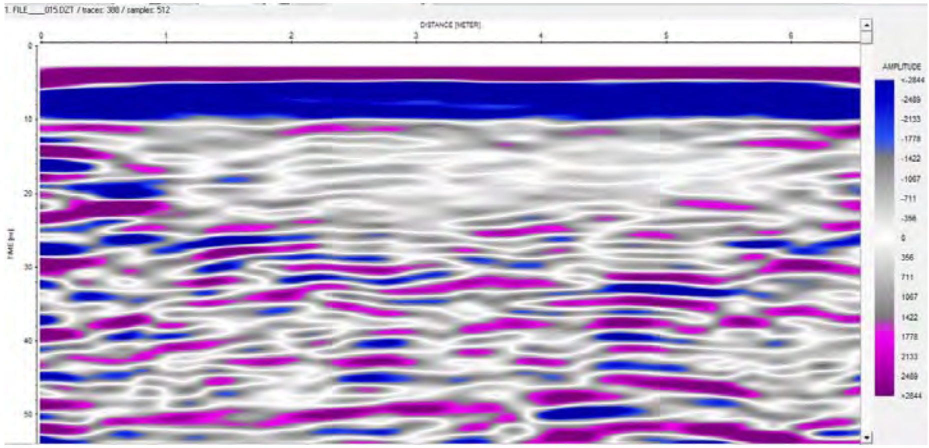
IMAGES OF GPR PROFILE SCANNED ACROSS ERT-1 ALIGNMENT

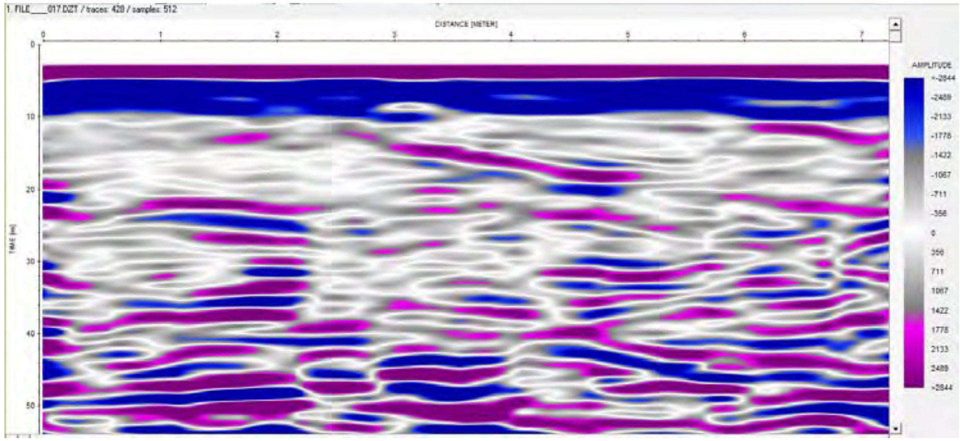









DISTANCE [METER]
AMPLITUDE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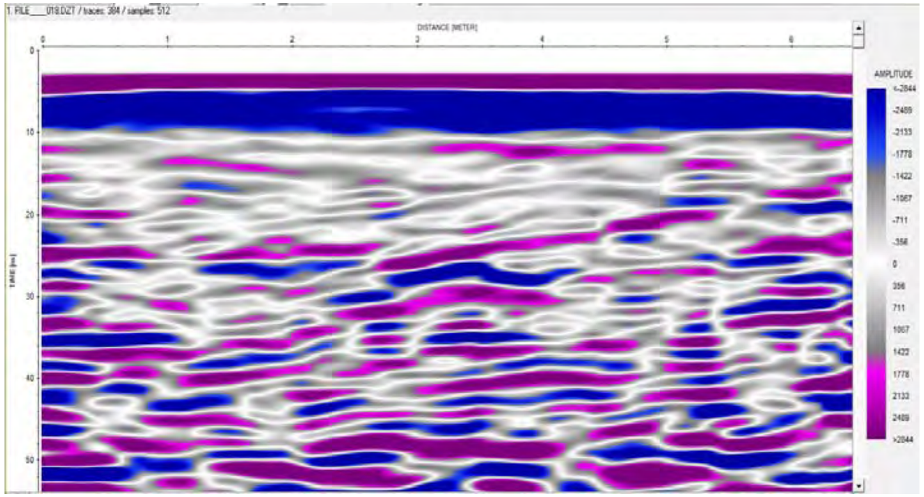
AMPLITUDE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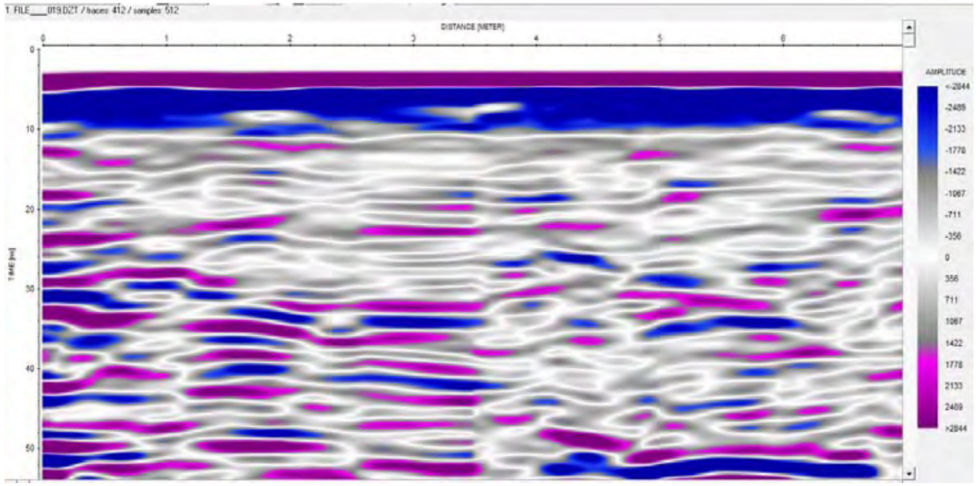
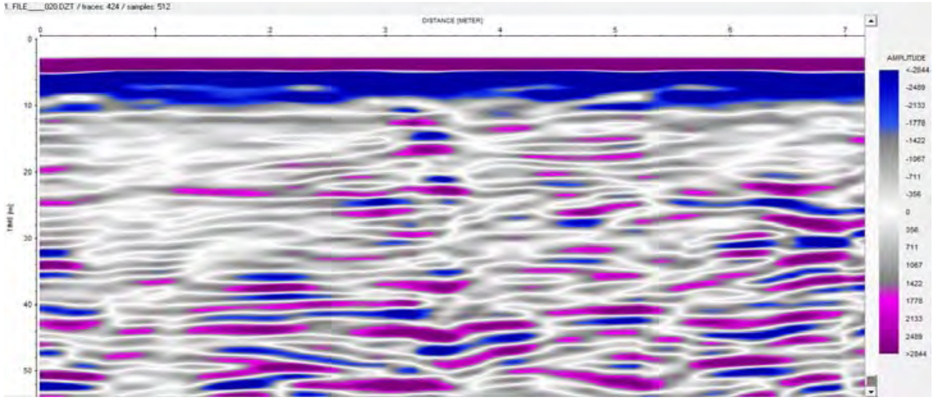
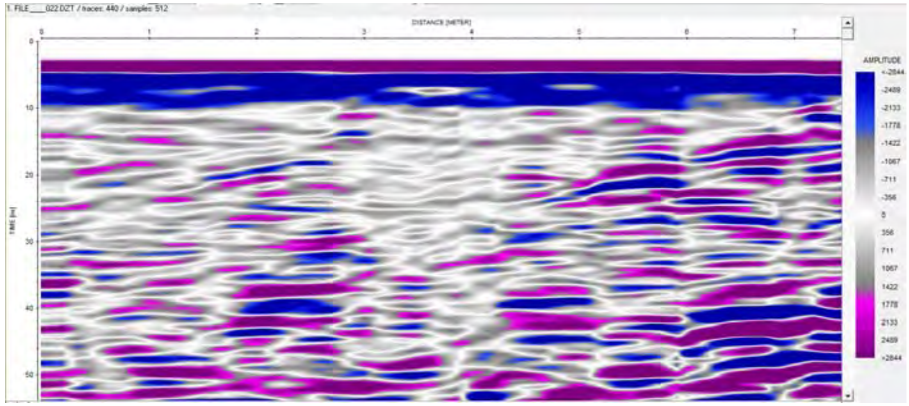
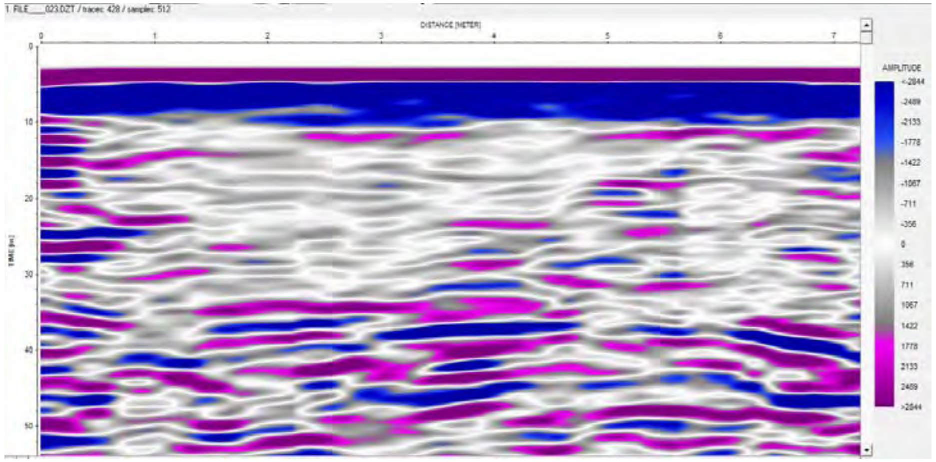
AMPLITUDE


DISTANCE [METER]
AMPLITUDE


1. FILE___020.DZT / traces: 424 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE


1. FILE___022.DZT / traces: 440 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE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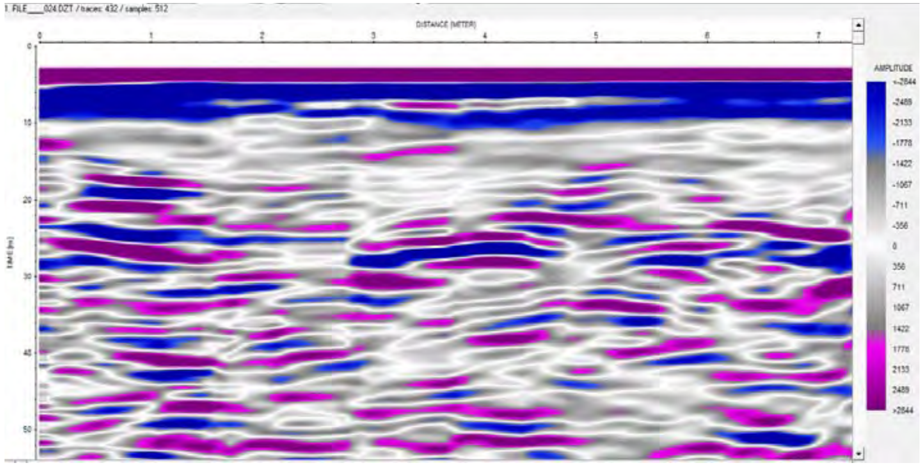
DISTANCE [METER]
TIME [ns]
AMPLITUDE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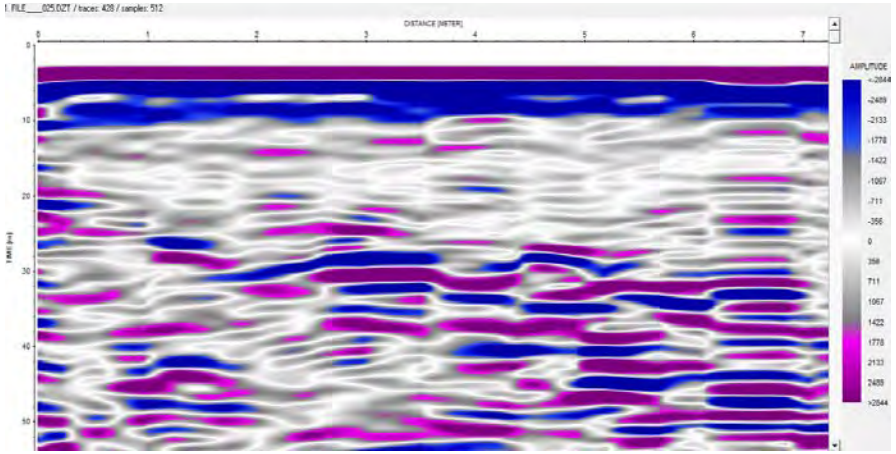
DISTANCE [METER]
TIME [ns]
AMPLITUDE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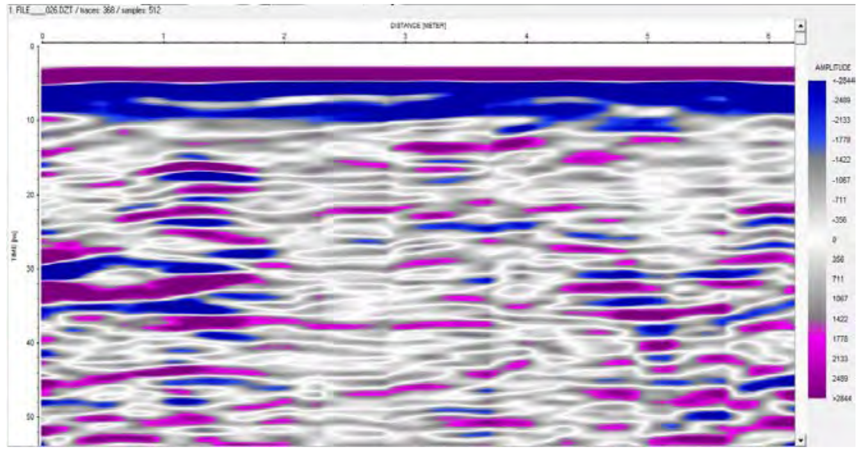
DISTANCE [METER]
AMPLITUDE
TIME [ns]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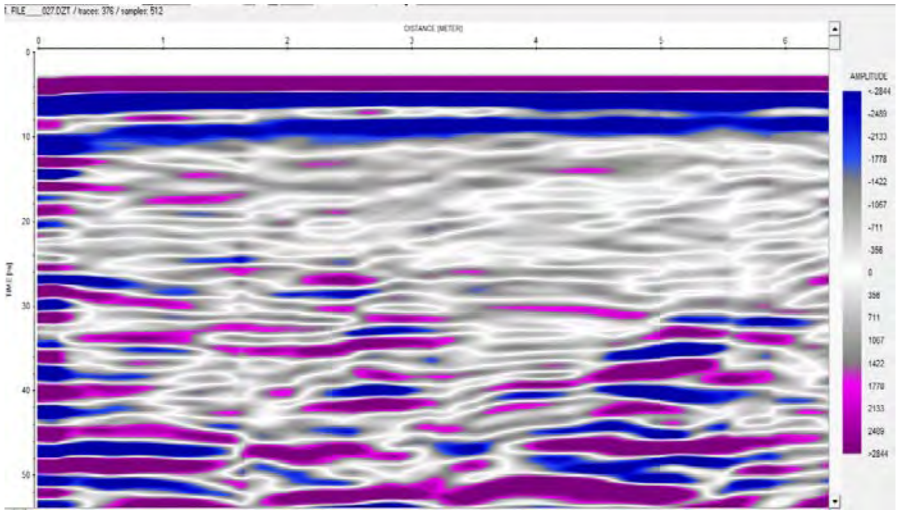
DISTANCE [METER]
AMPLITUDE
TIME [ns]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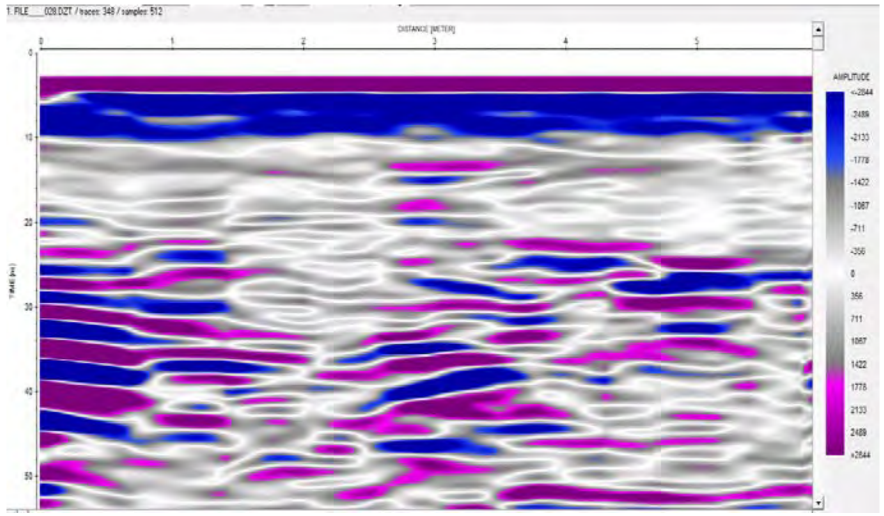
DISTANCE [METER]
AMPLITUDE
TIME [ns]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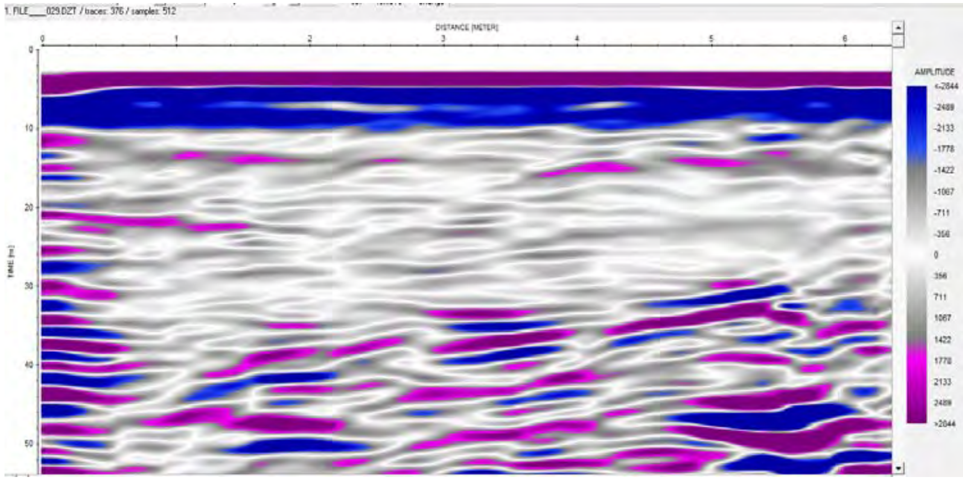
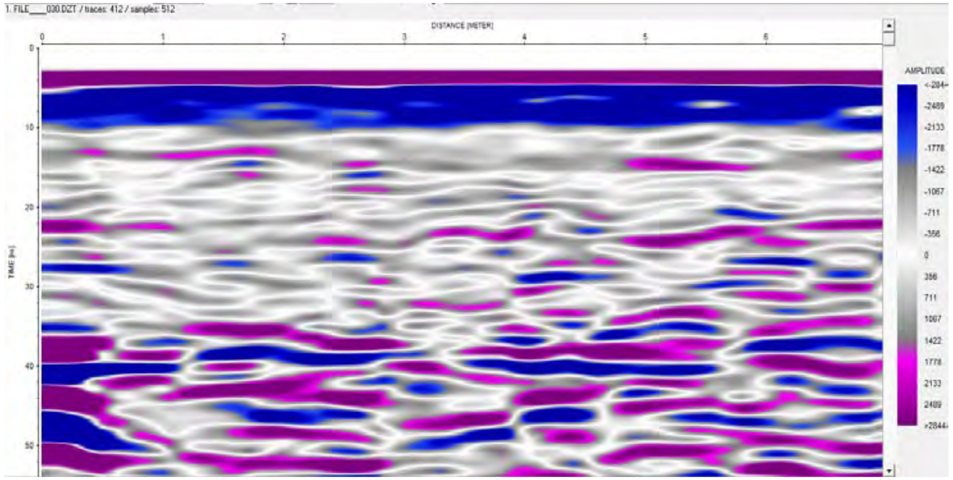
DISTANCE [METER]
AMPLITUDE
TIME [ns]


DISTANCE [METER]
AMPLITUDE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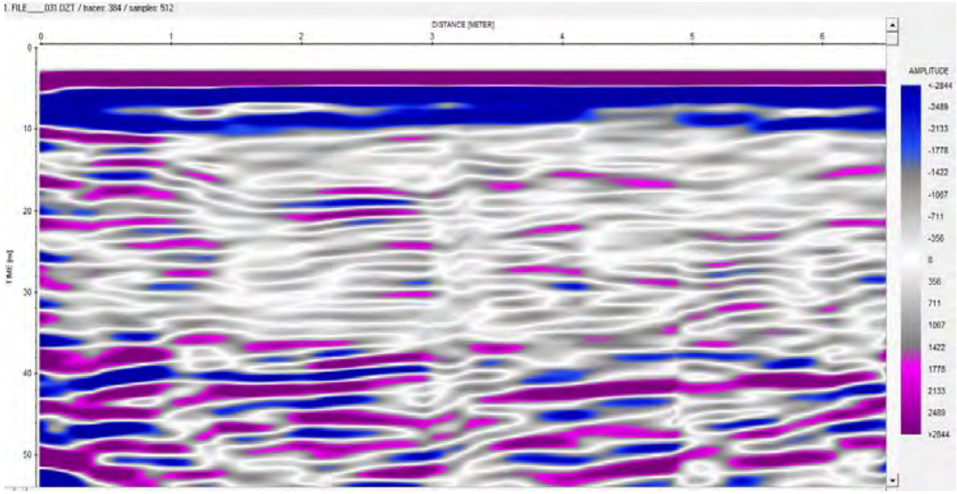
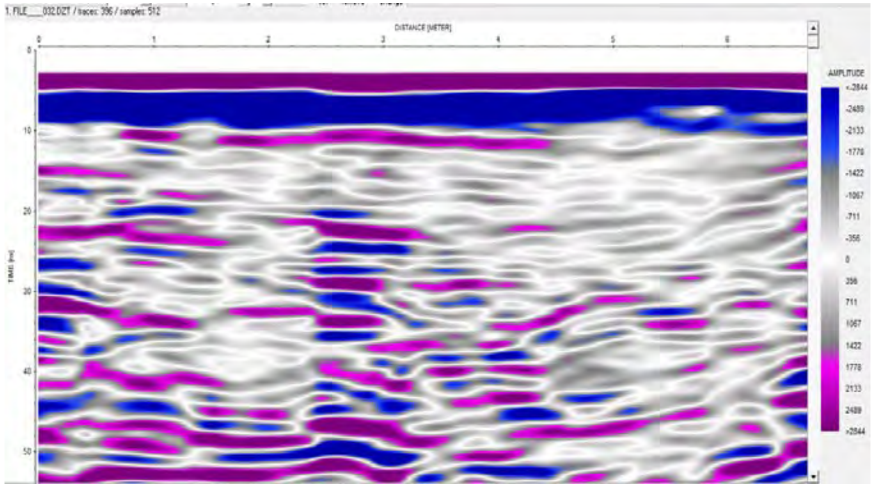
AMPLITUDE


DISTANCE [METER]
AMPLITUDE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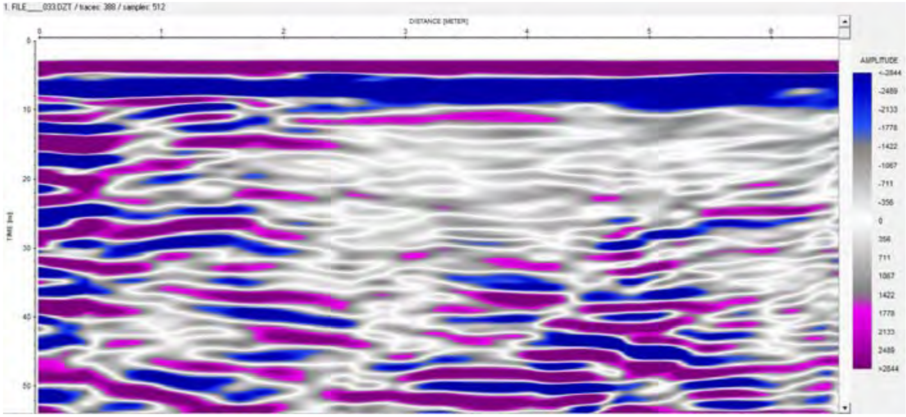
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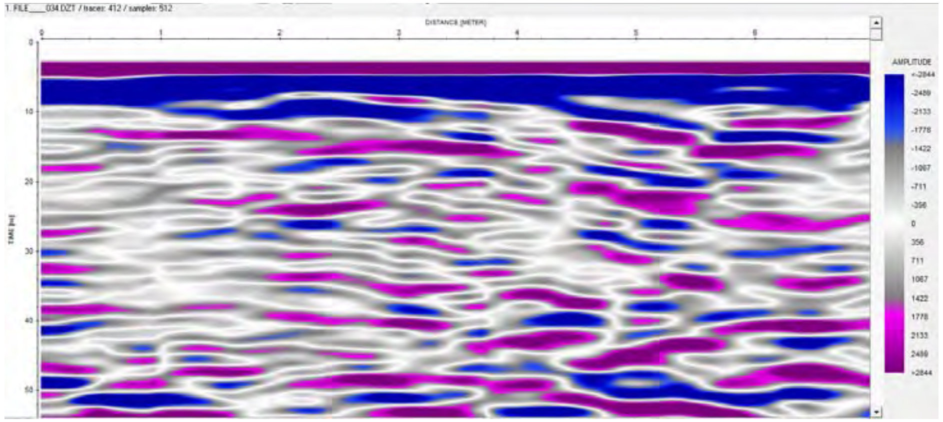
AMPLITUDE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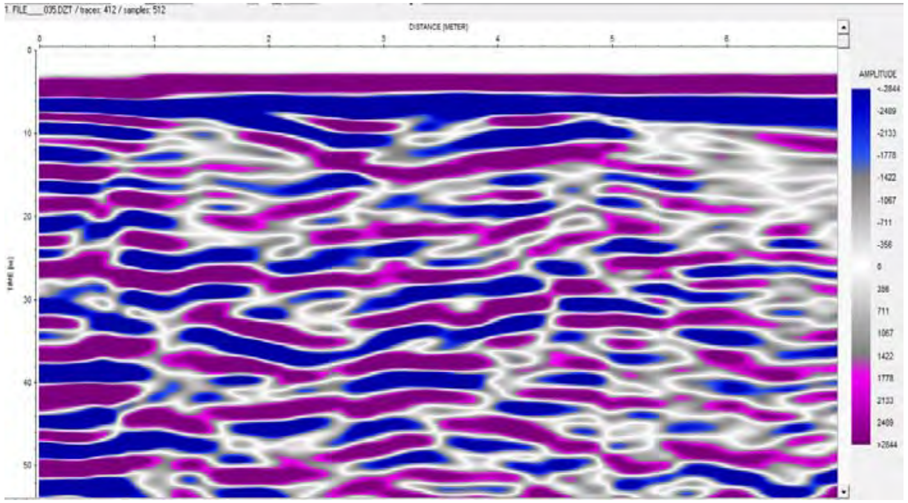
DISTANCE [METER]
AMPLITUDE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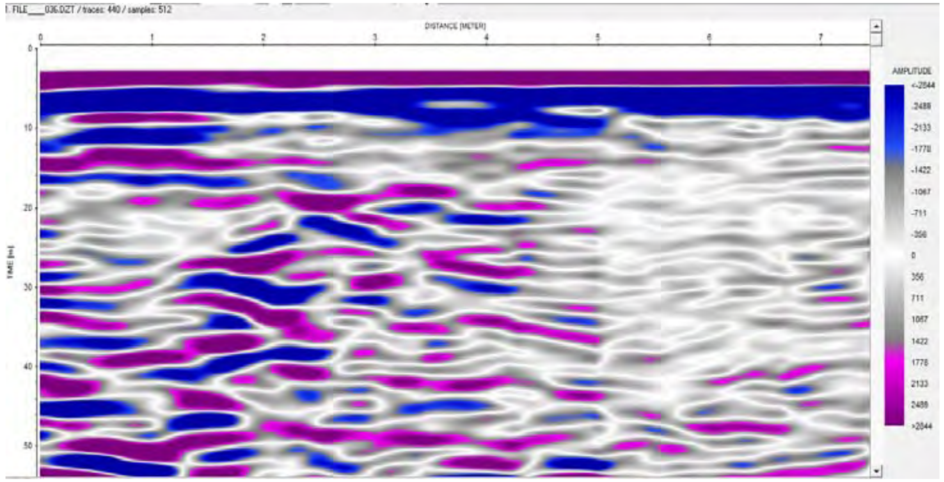
DISTANCE [METER]
AMPLITUDE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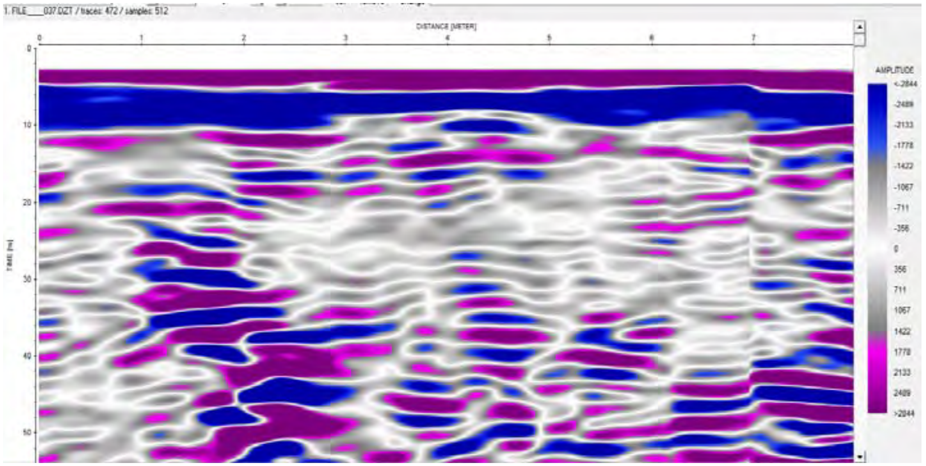
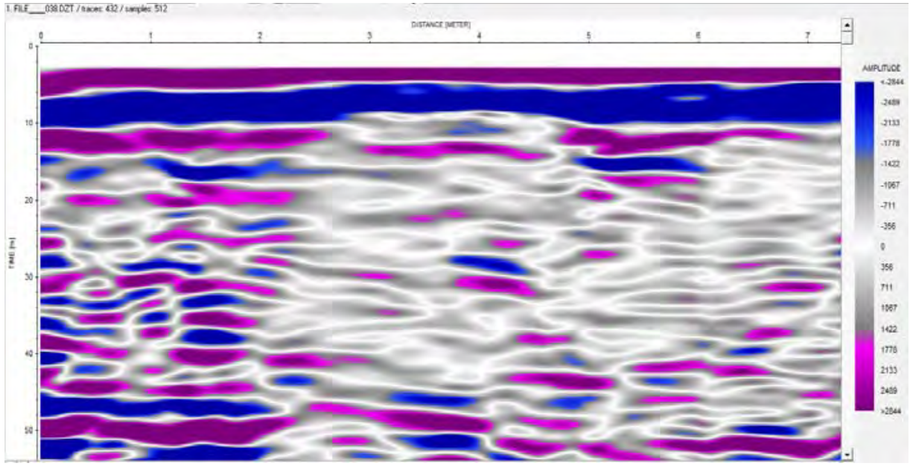
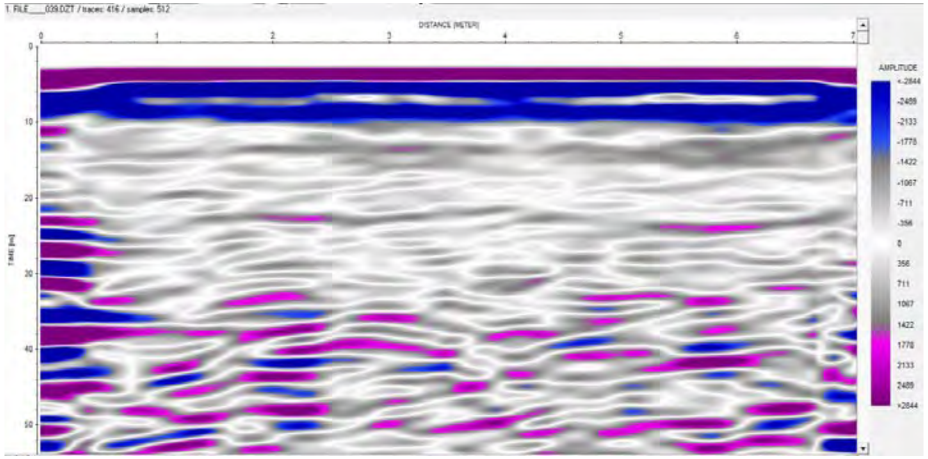
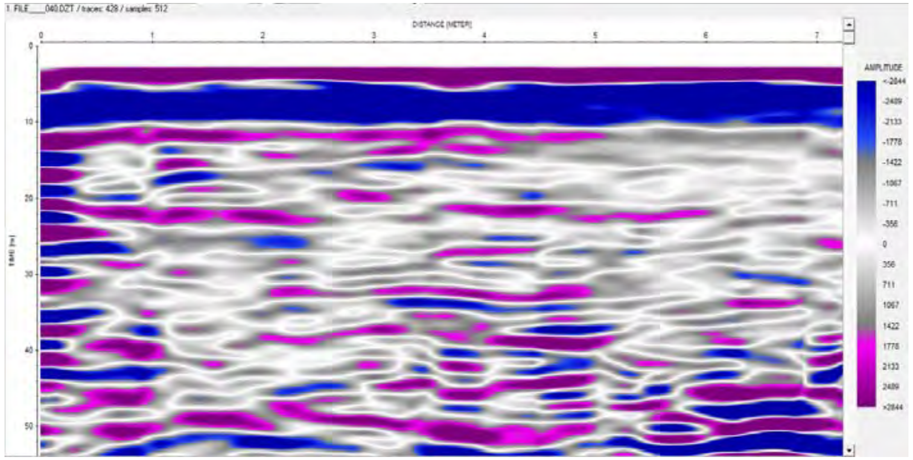
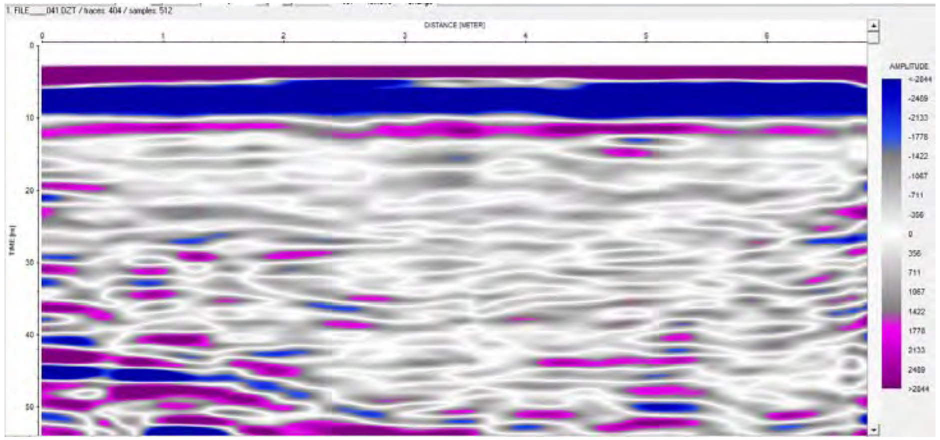
AMPLITUDE







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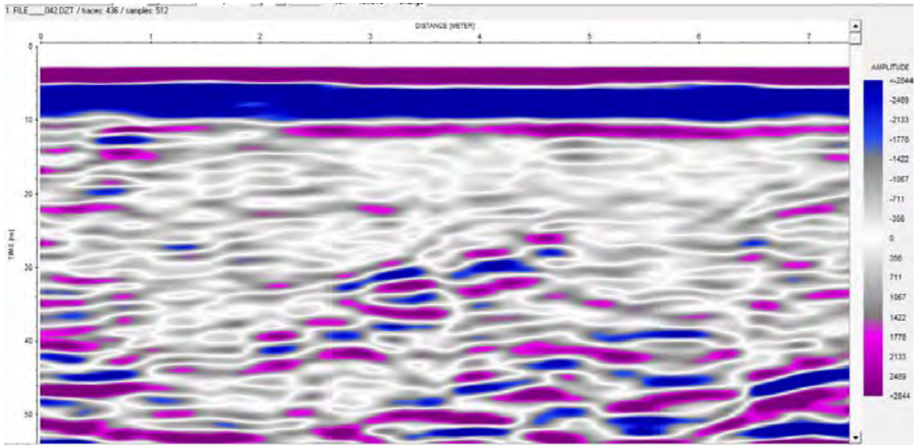
AMPLITUDE
TIME [ns]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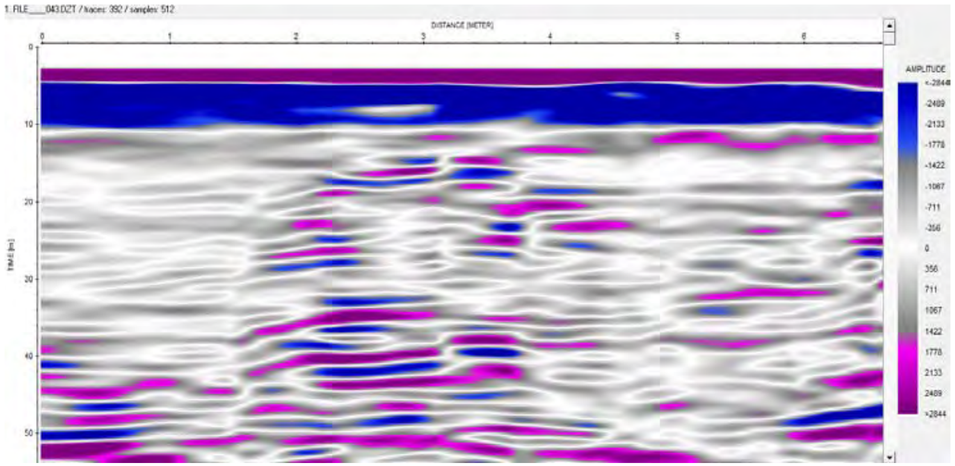
DISTANCE [METER]
AMPLITUDE
TIME [ns]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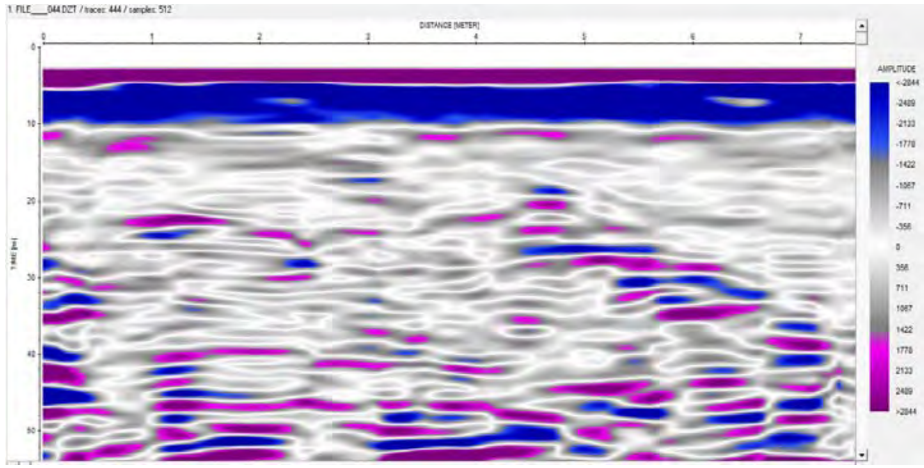
DISTANCE [METER]
AMPLITUDE
TIME [ns]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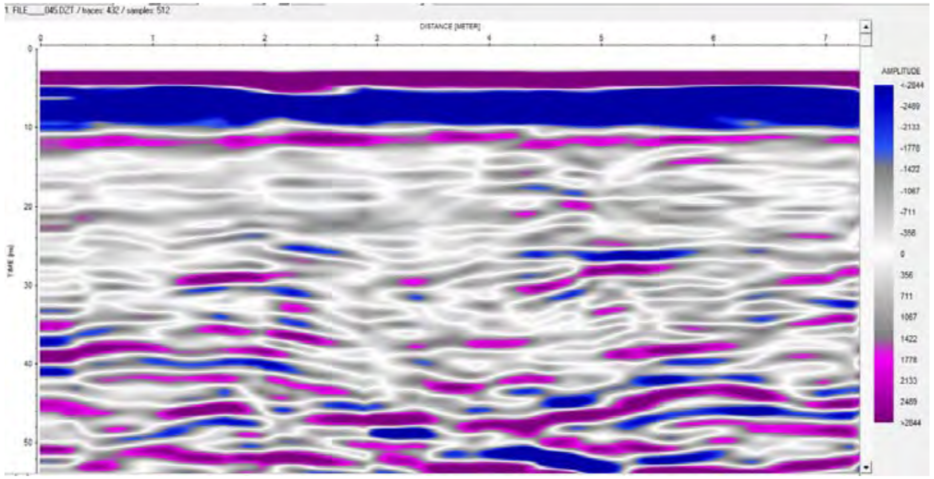
DISTANCE [METER]
AMPLITUDE
TIME [ns]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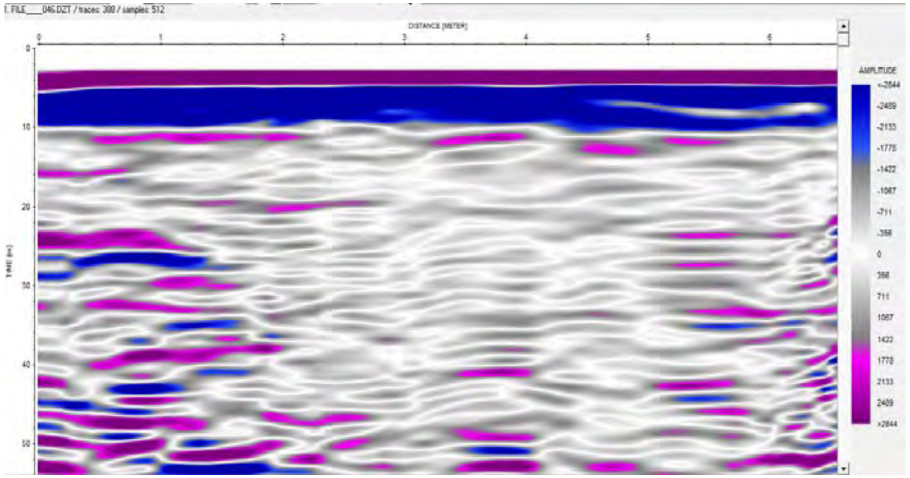
DISTANCE [METER]
AMPLITUDE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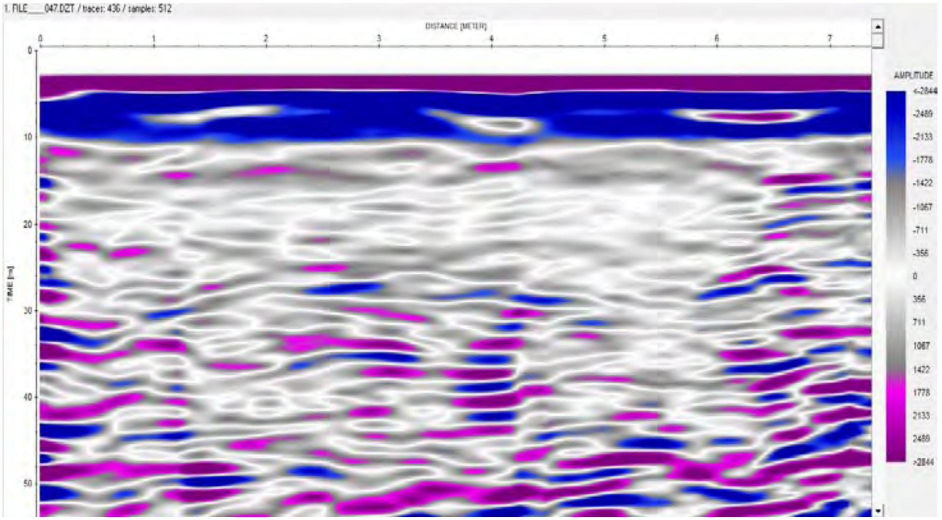
DISTANCE [METER]
AMPLITUDE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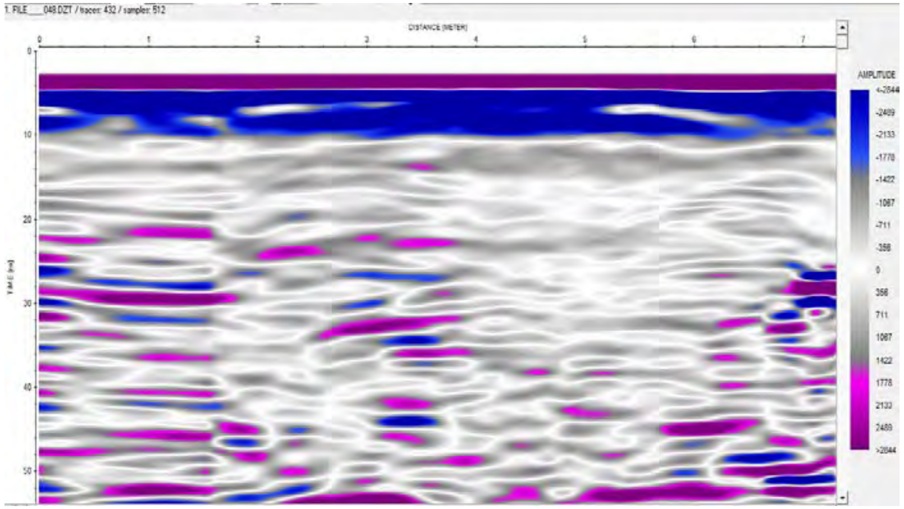
DISTANCE [METER]
AMPLITUDE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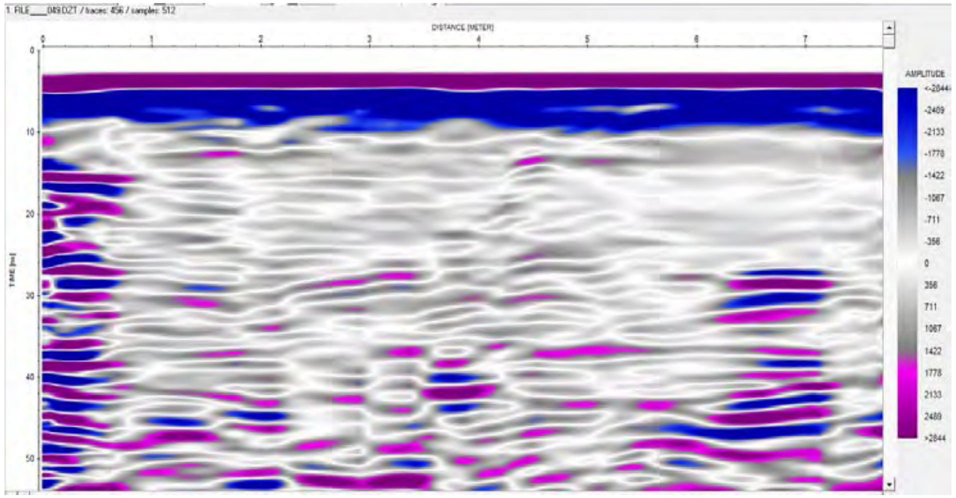
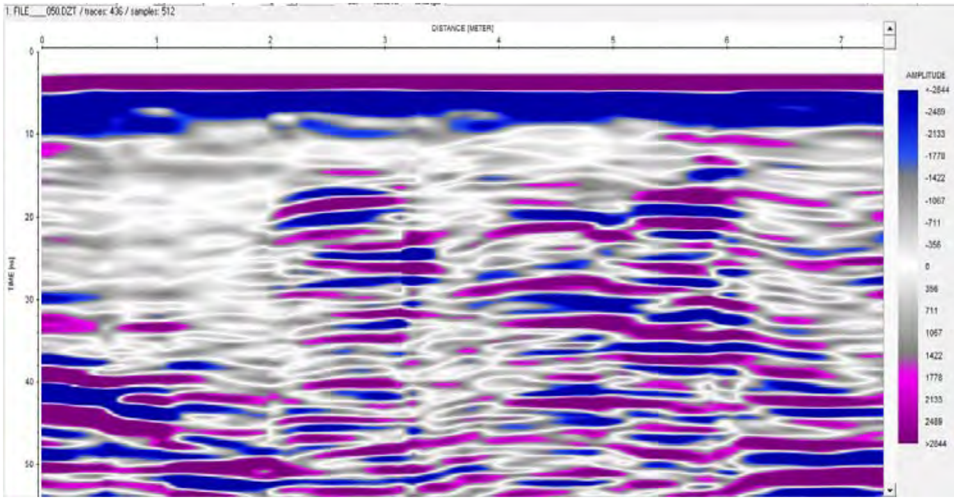
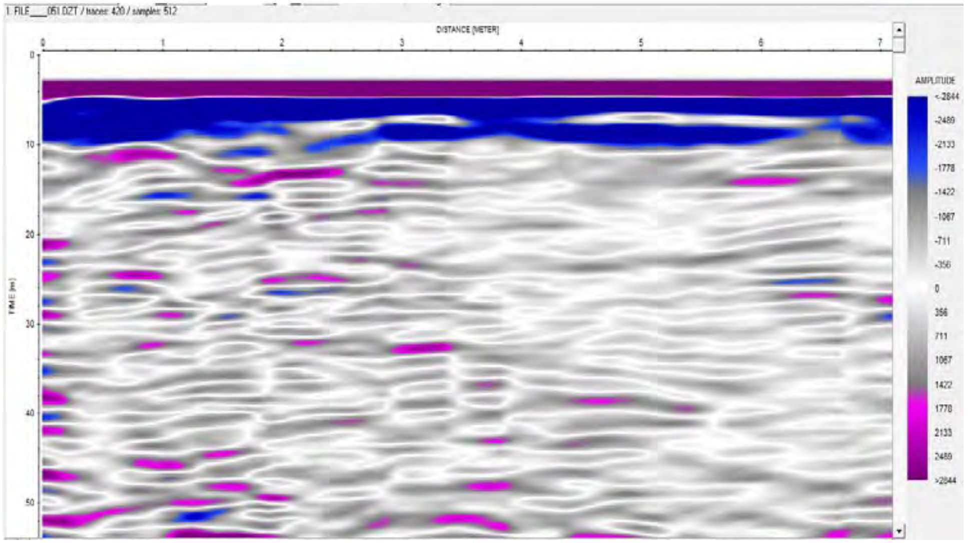
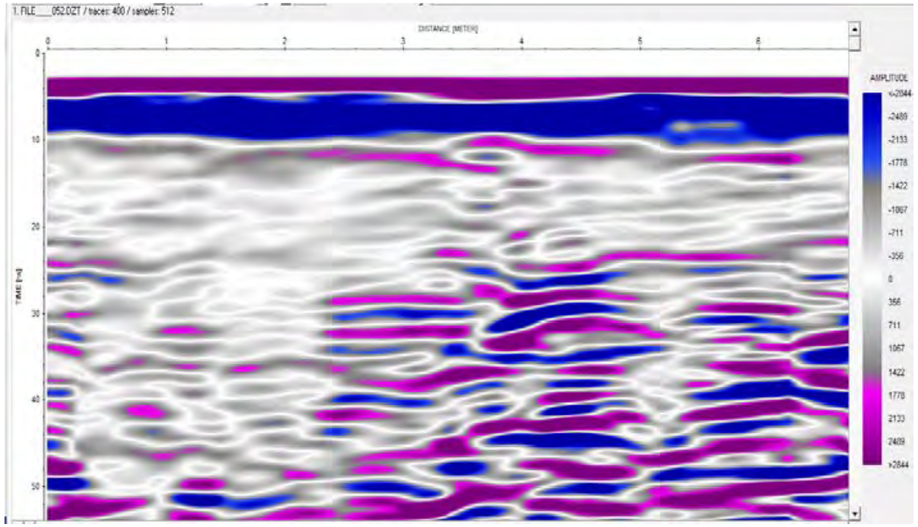
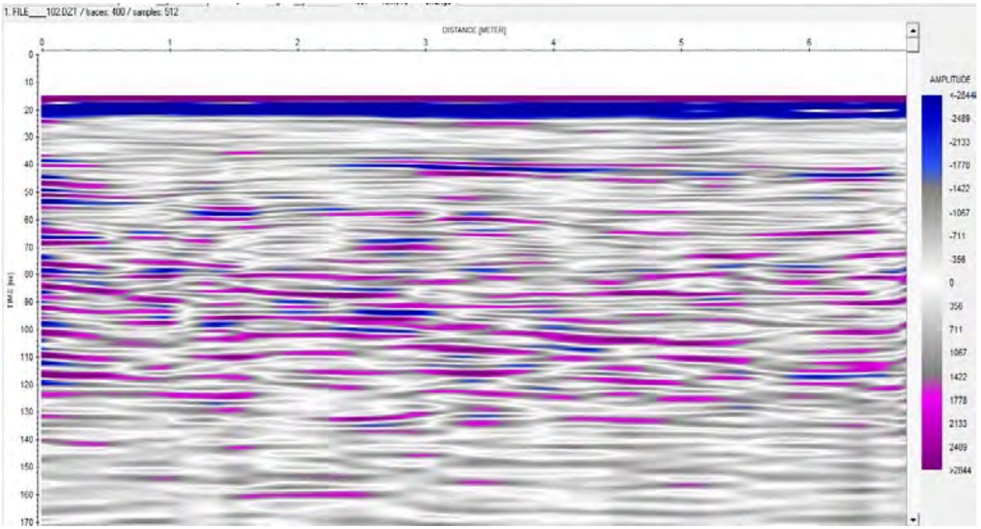
DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE


DISTANCE [METER]
AMPLITUDE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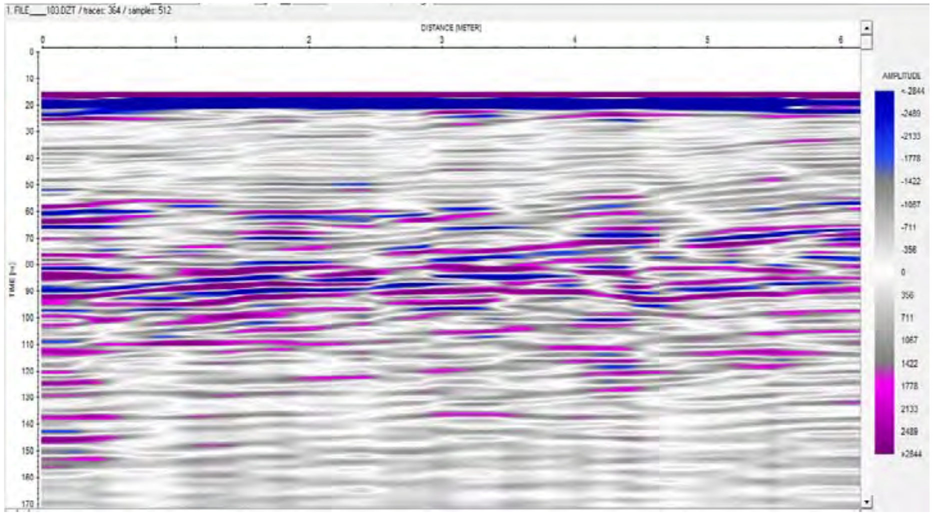
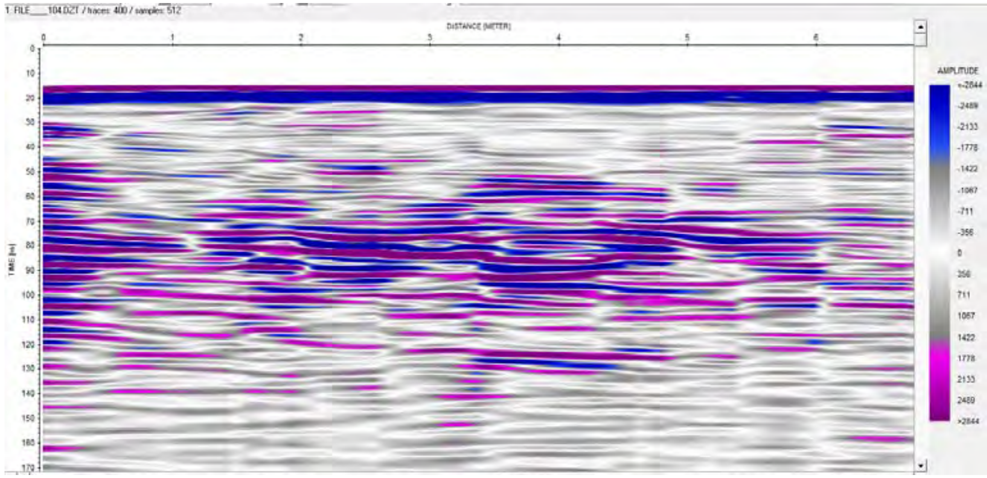
DISTANCE [METER]
TIME [ns]
AMPLITUDE


1. FILE___103.DZT / traces: 364 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE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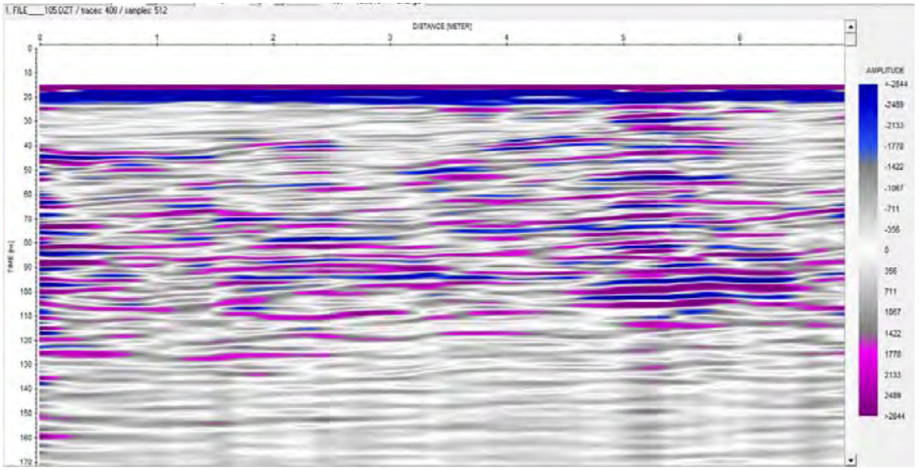
DISTANCE [METER]
TIME [ns]
AMPLITUDE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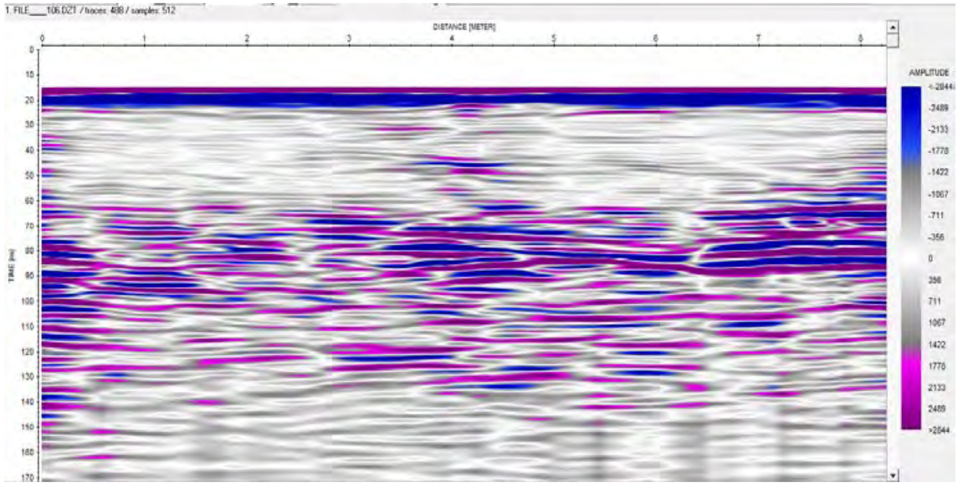
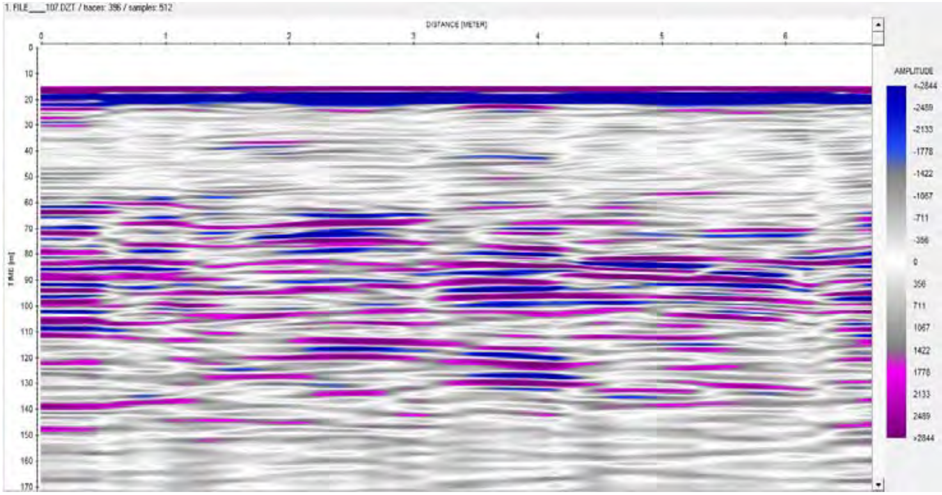
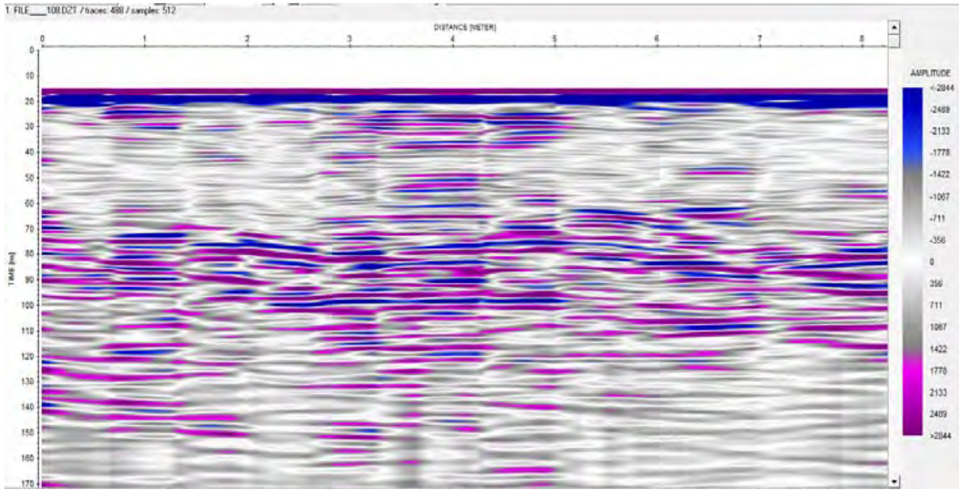
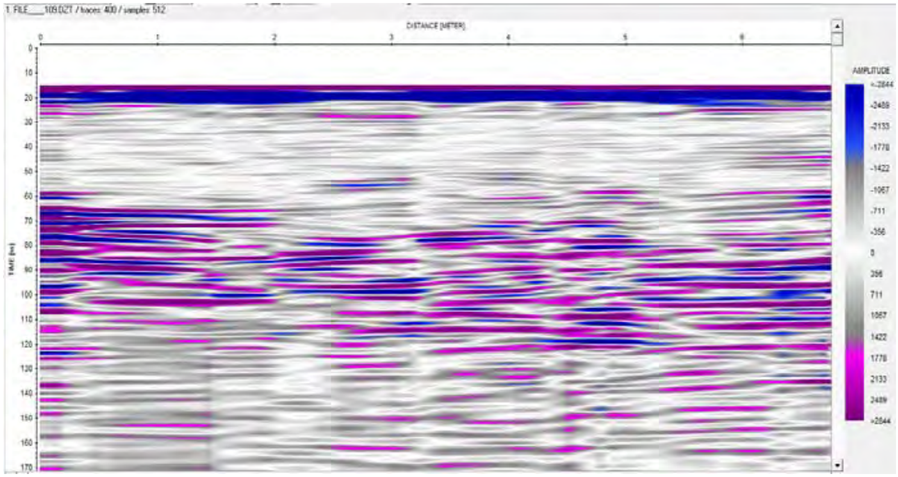
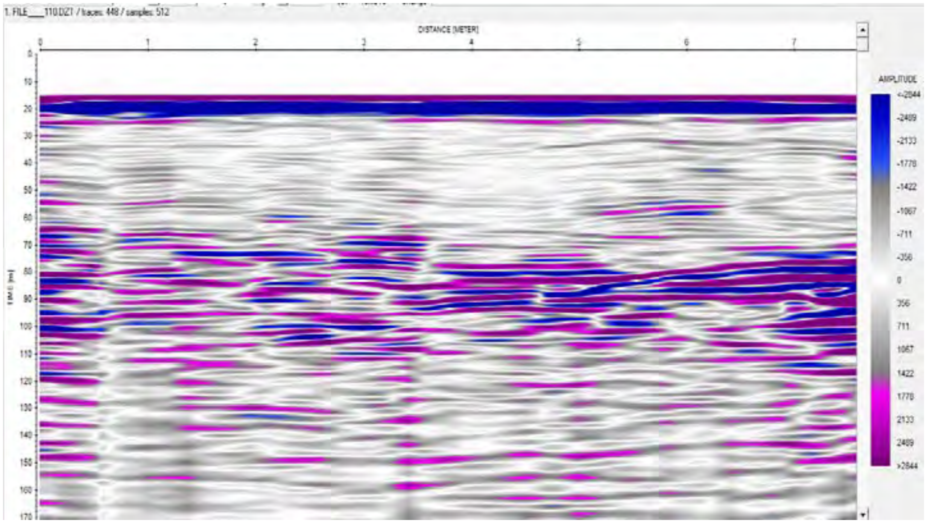
DISTANCE [METER]
TIME [ns]
AMPLITUDE

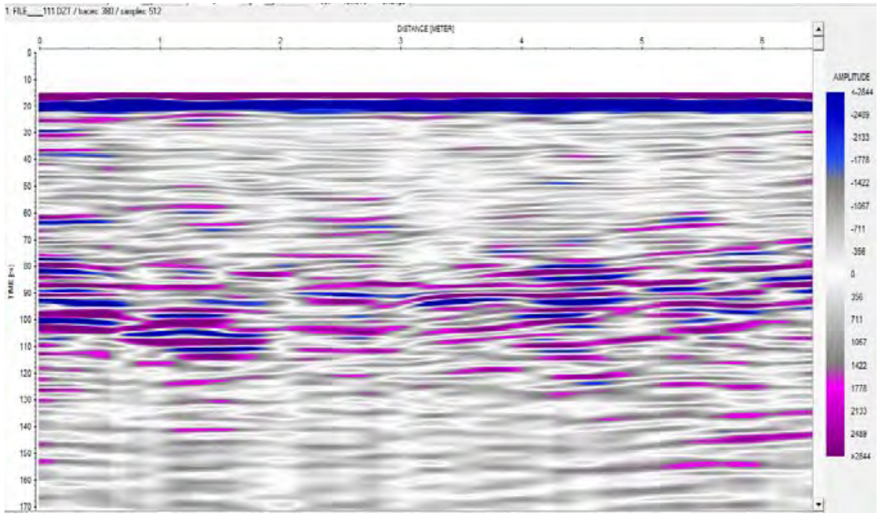

DISTANCE [METER]
AMPLITUDE

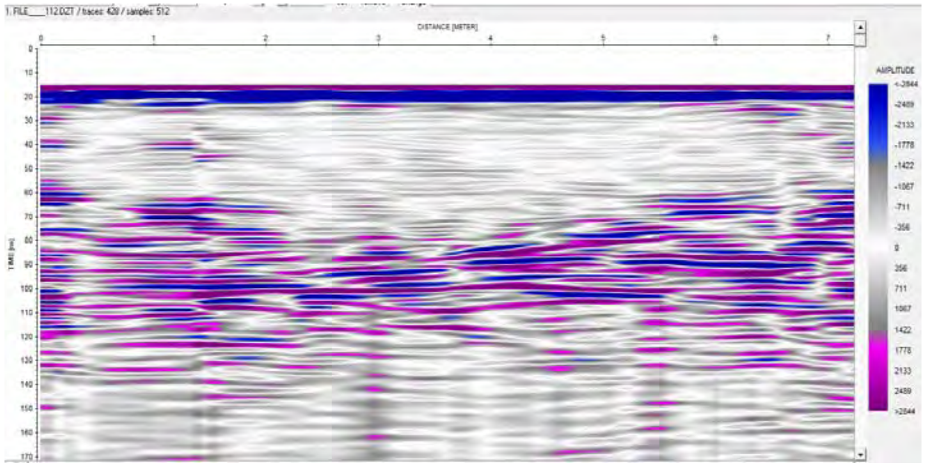

DISTANCE [METER]
AMPLITUDE

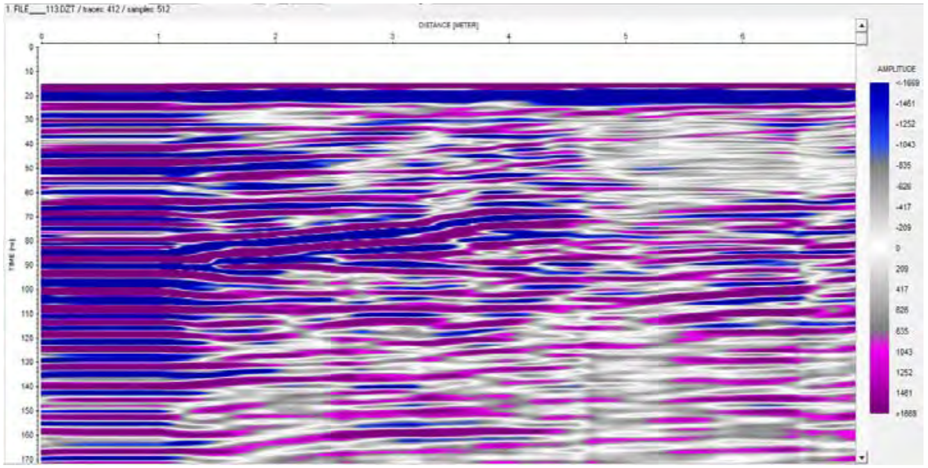

DISTANCE [METER]
AMPLITUDE

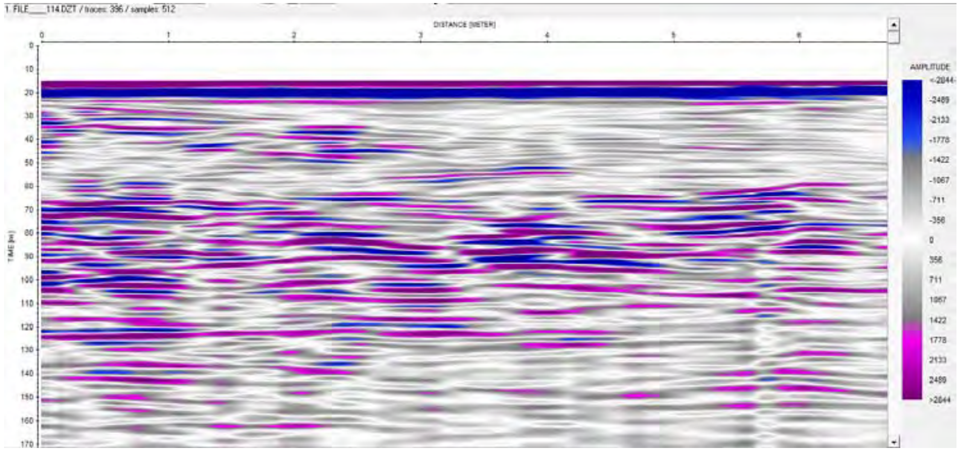

DISTANCE [METER]
AMPLITUDE

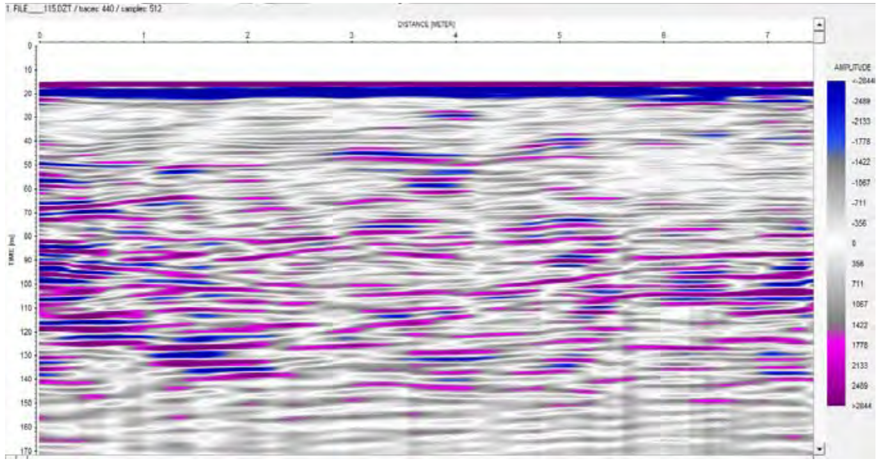


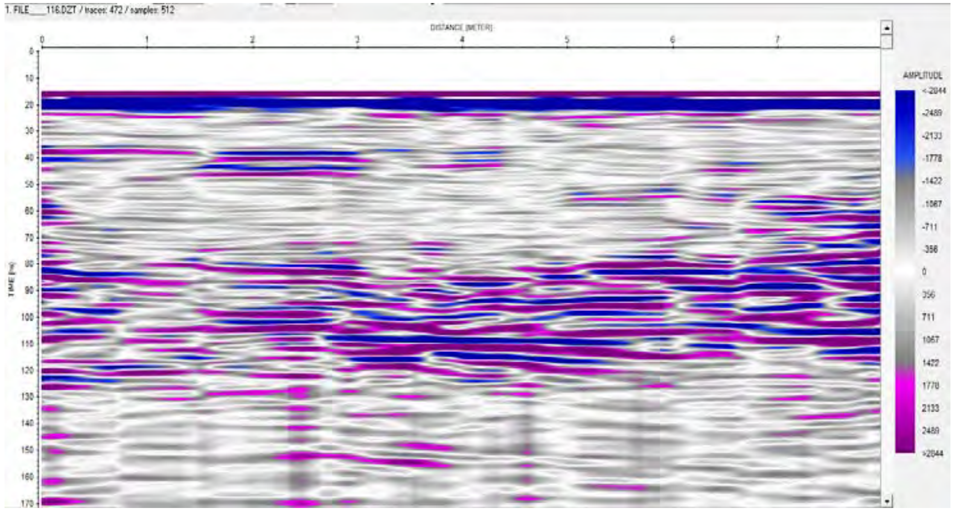


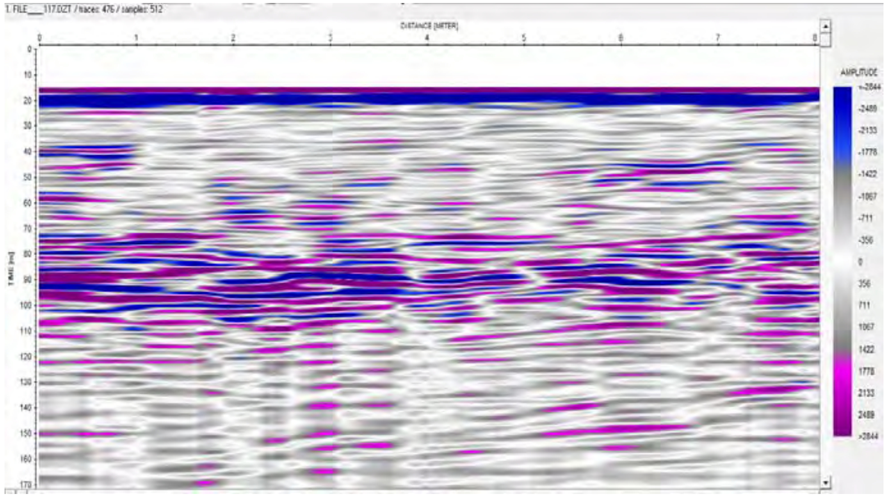


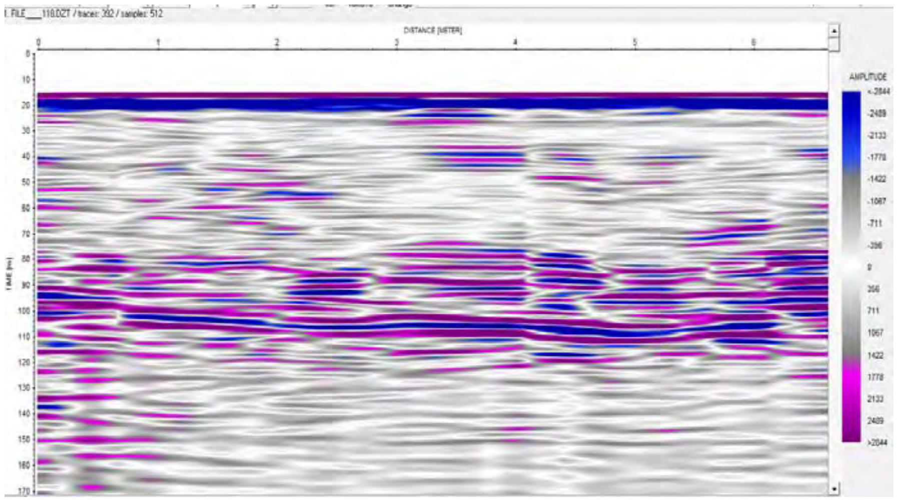


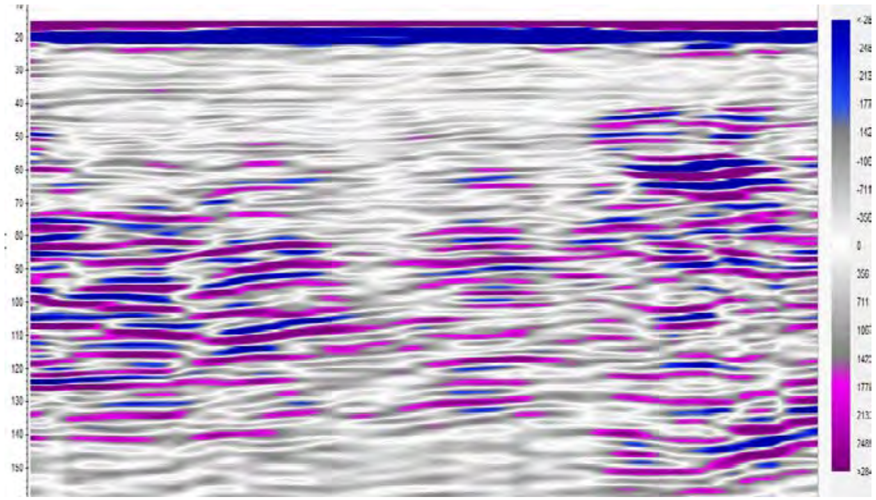






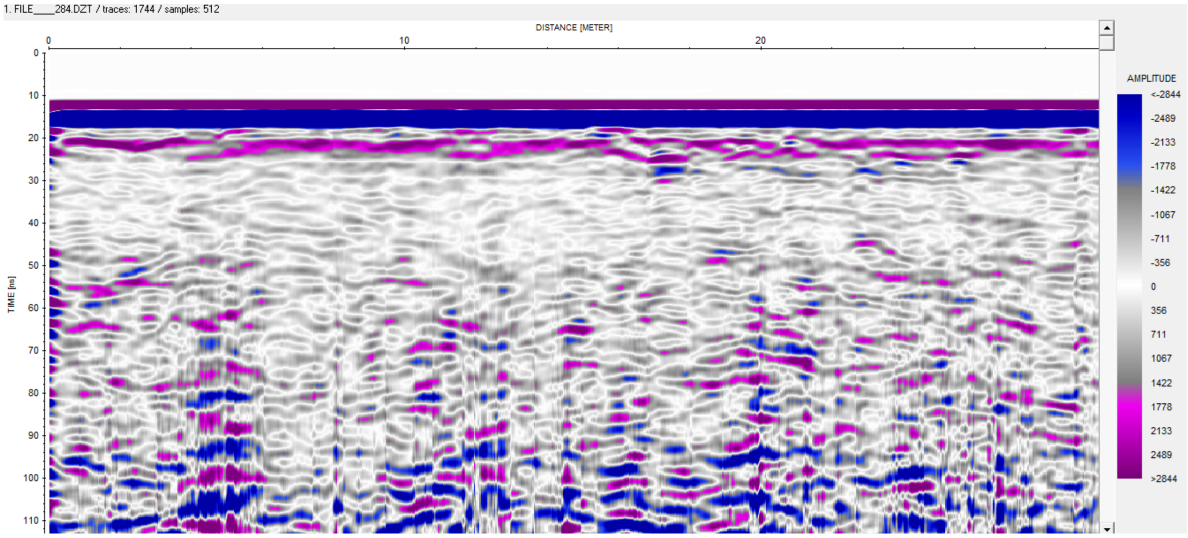


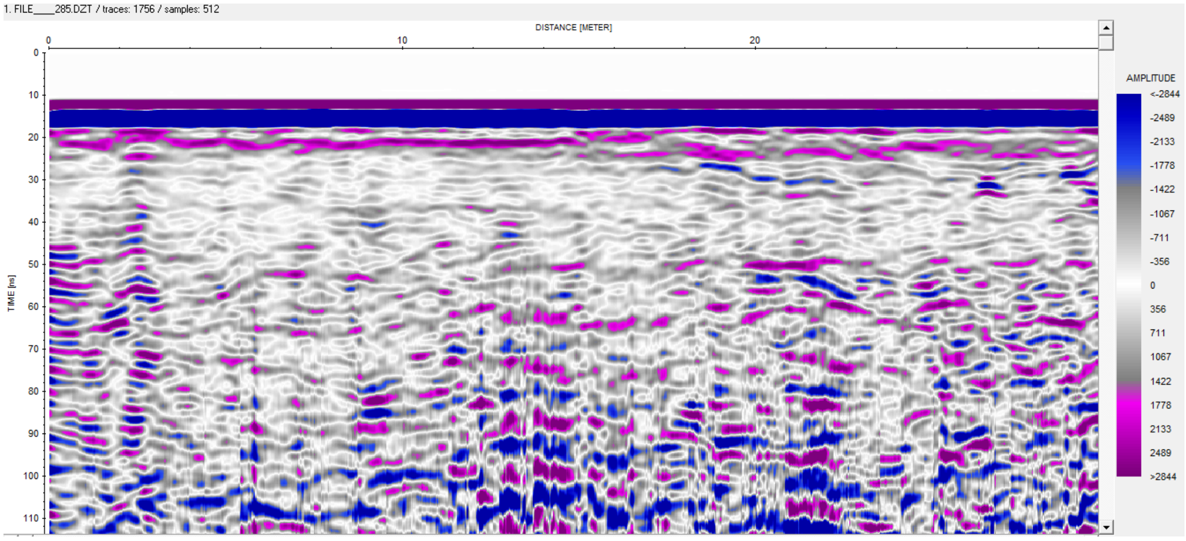

DISTANCE [METER]
AMPLITUDE

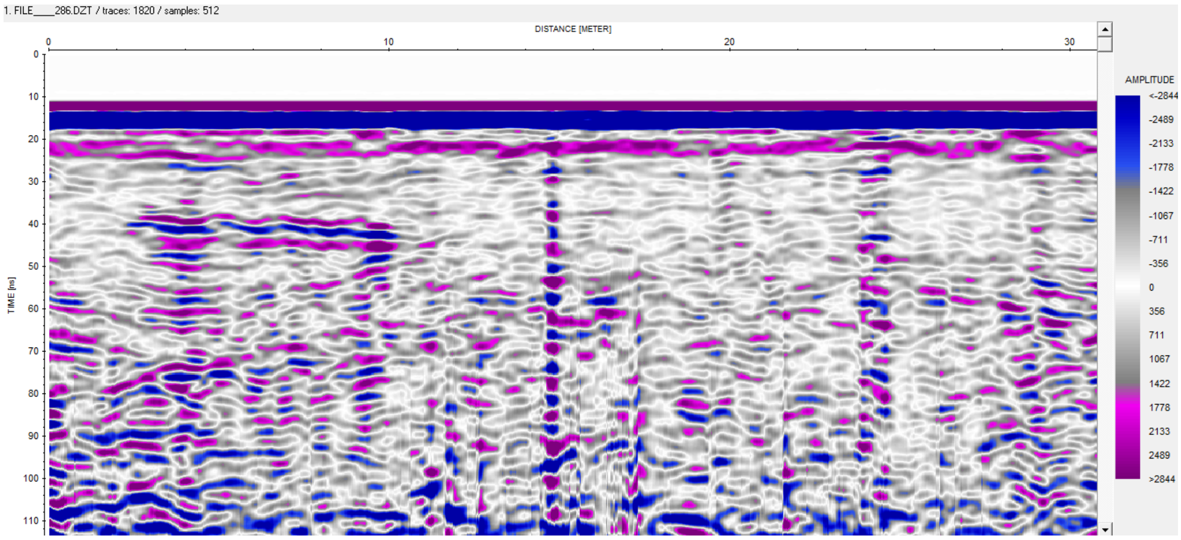


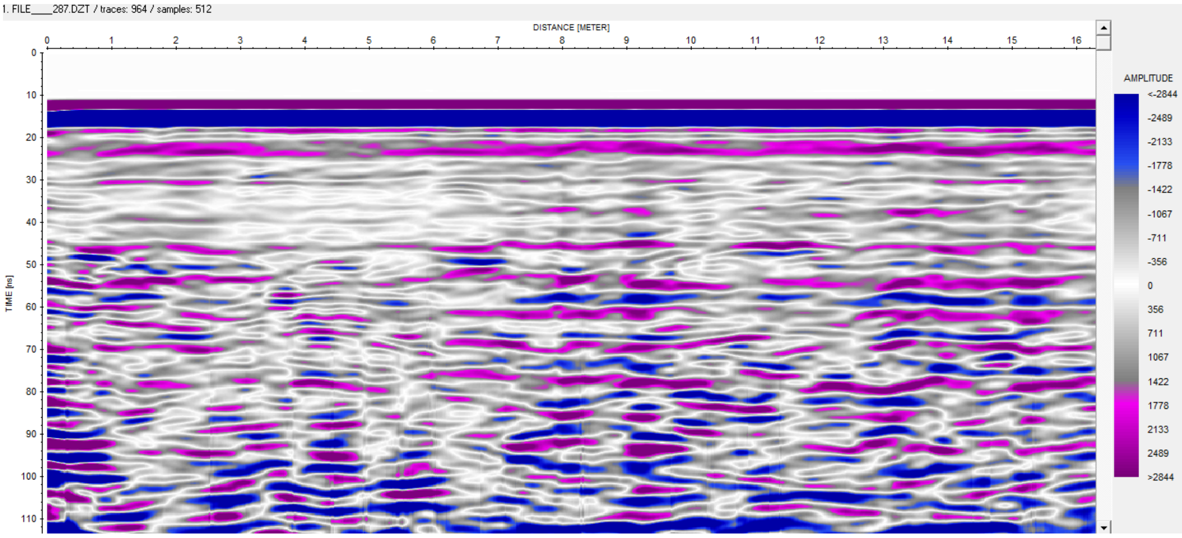
Annexure IX

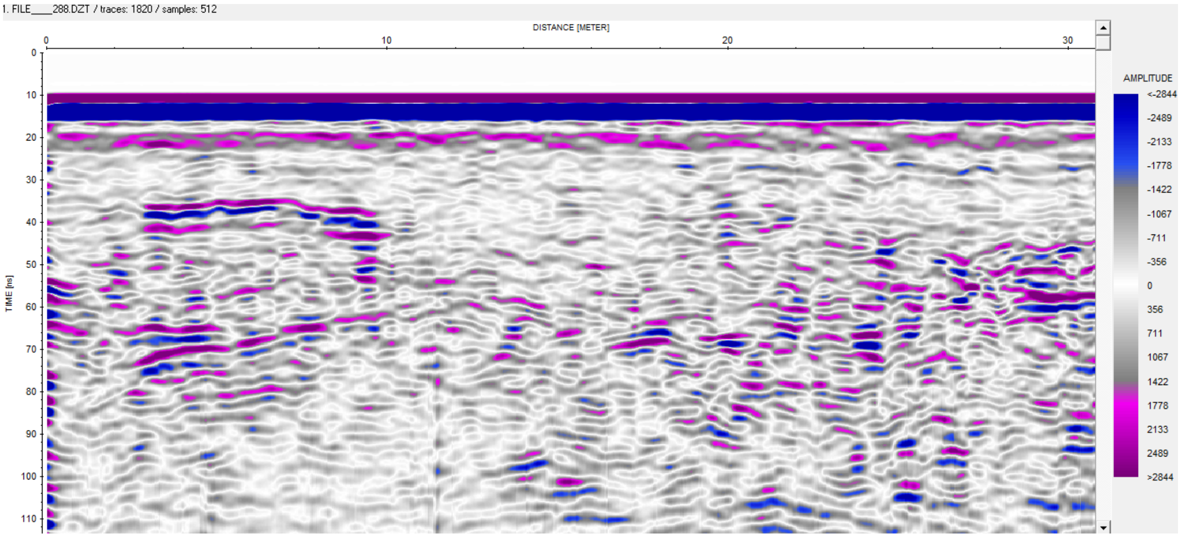
GPR PROFILES OF 270MHZ ANTENNA
(SAVED WITH REFLEX2DQUICK SOFTWARE)
At probable seepage area in the East (Location S2)

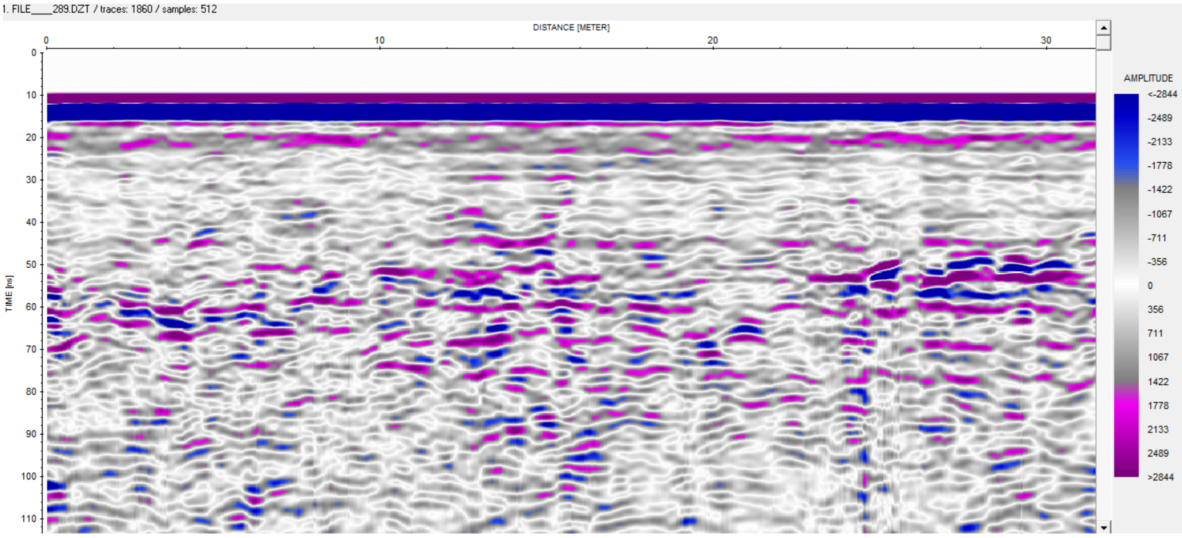




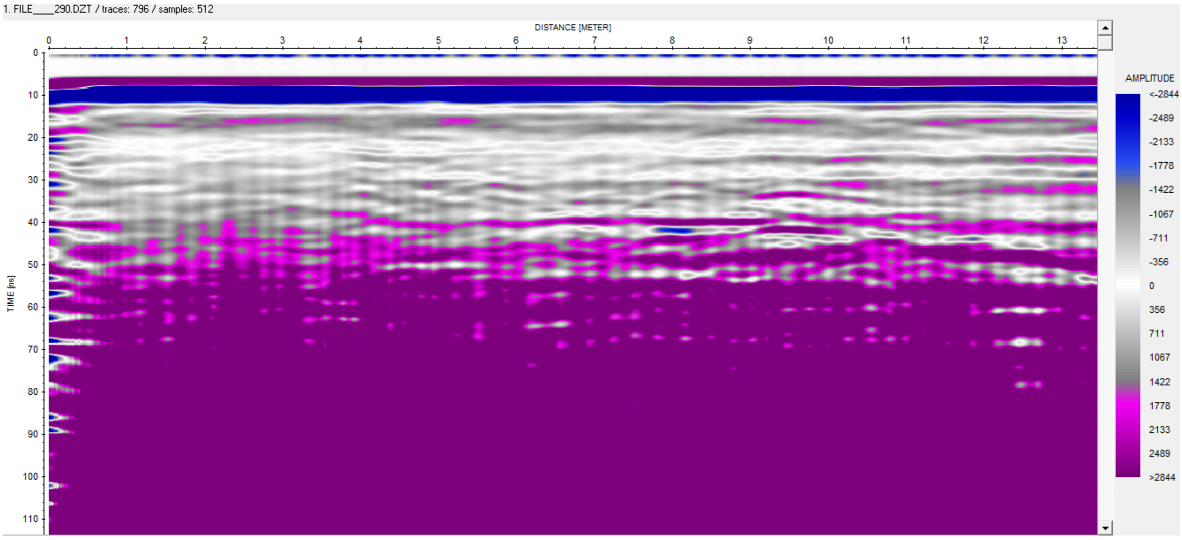


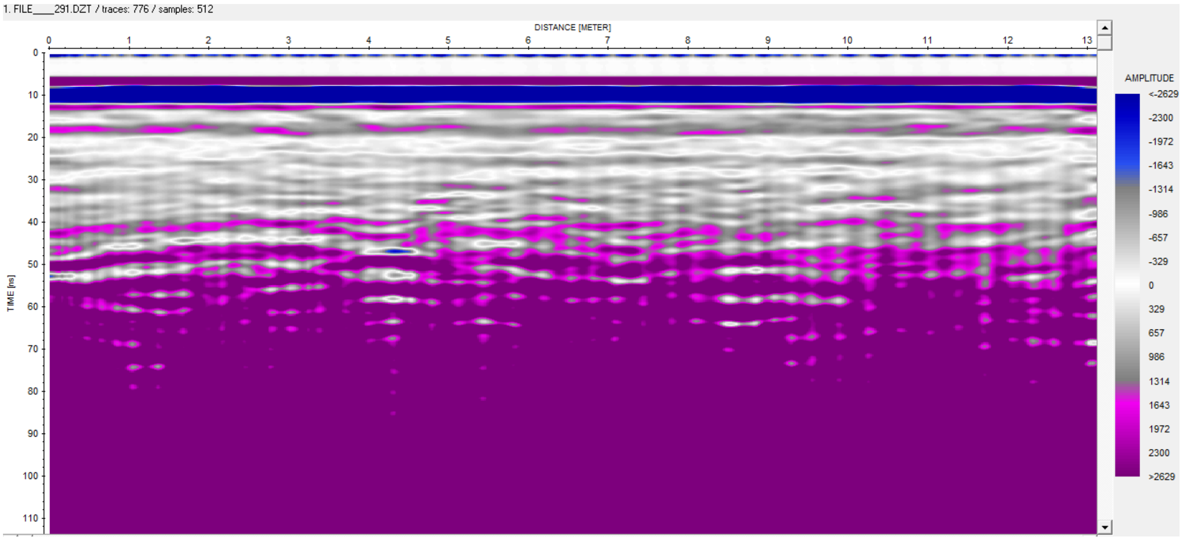

1. FILE____287.DZT / traces: 964 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE


1. FILE____288.DZT / traces: 1820 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

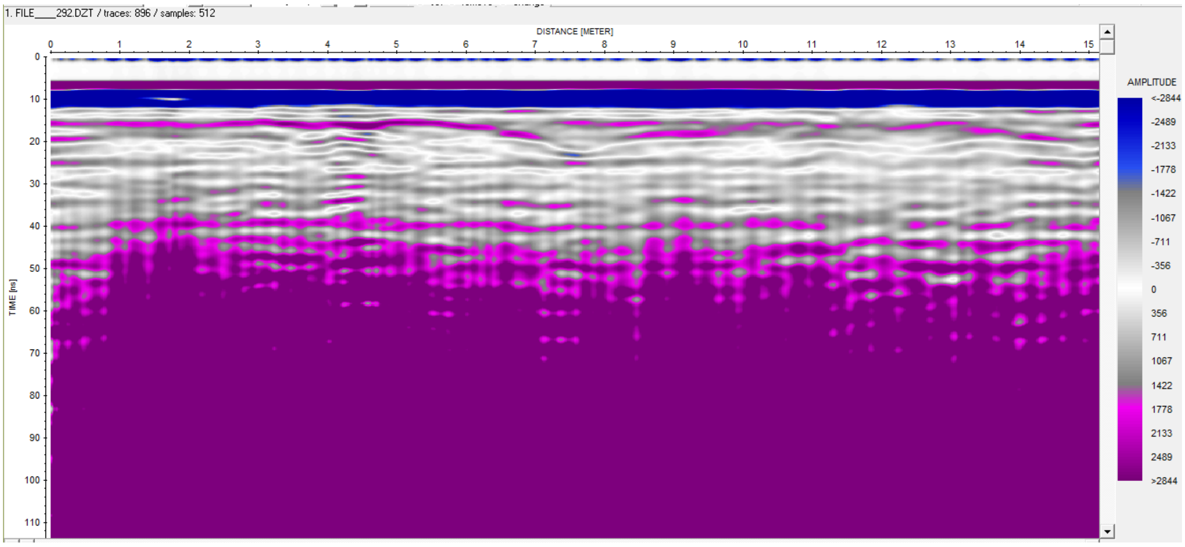

1. FILE____289.DZT / traces: 1860 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE

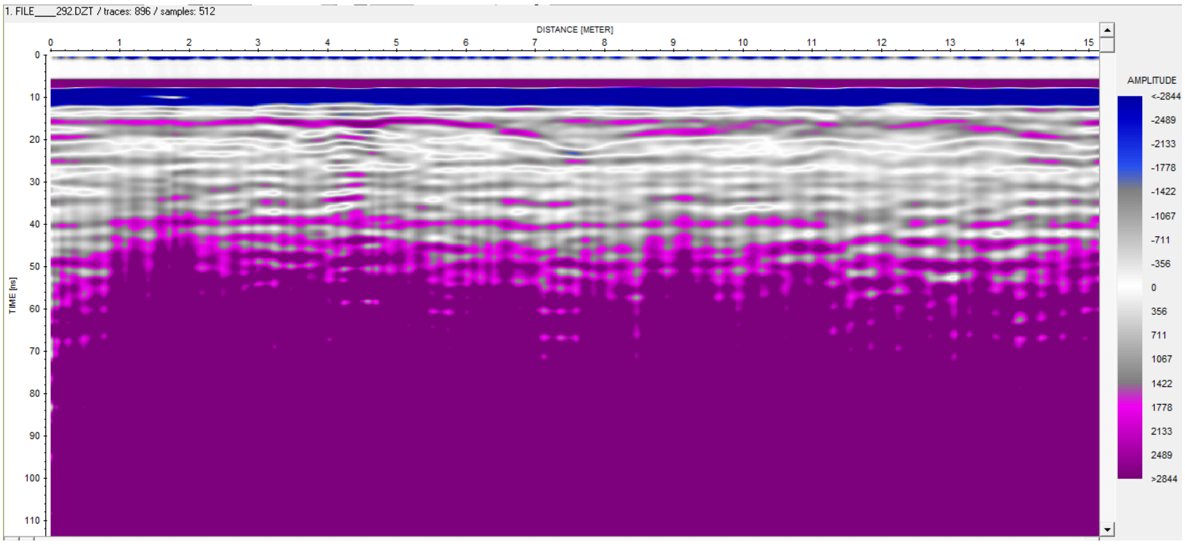
WEST SIDE 3D PROFILES

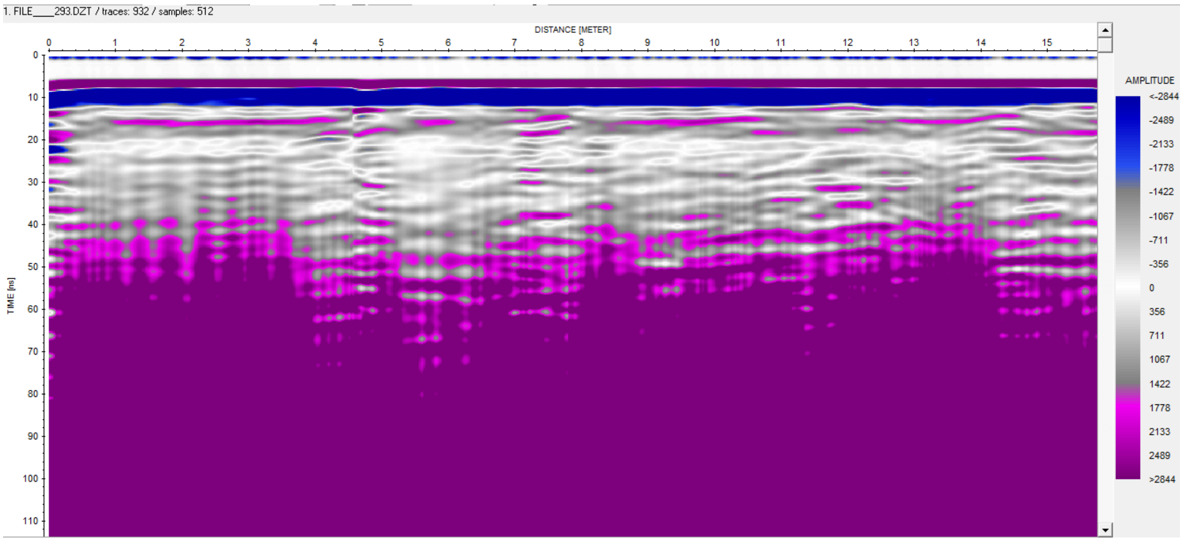


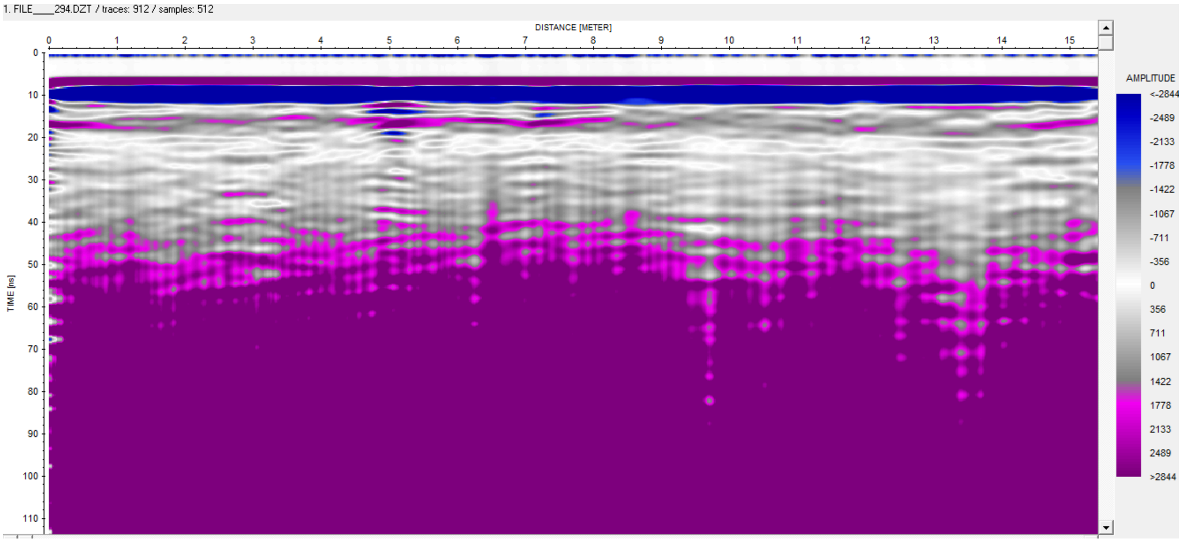


At probable seepage area in the West (Location S1)




1. FILE____292.DZT / traces: 896 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE


1. FILE____293.DZT / traces: 932 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE


1. FILE____294.DZT / traces: 912 / samples: 512
DISTANCE [METER]
TIME [ns]
AMPLITUDE