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Jamrani Dam Multipurpose Project

Geophysical Investigation Report

OBJECTIVE
Geophysical Investigation Studies at Jamrani Dam Multipurpose Project Site

CLIENT
Project Manager -IV
PIU Jamrani

REFERENCE
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WRITTEN BY
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VERIFIED BY
Dr. Sanjay Rana

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Annexure:

1. **Layout Plan (.DWG file)**

1 INTRODUCTION

1.1 General

ADB is supporting the State Government of Uttarakhand to execute Jamrani Multipurpose Project that will tinclude a 150-meter-high roller compacterd concrete (RCC) dam across the Gola River, about 10 kilometers upstream of Haldwani, Uttarakhand.

The project feasibility study was completed by the state of Uttarakhand and statutory clearances were obtained at both state and central government level. The project's executing agency is the Uttarakhand Irrigation Department (UID), under which a project implementation unit (PIU) has been established for delivering this project. The state government has prepared a detailed project report (DPR) for the dam project along with site investigations and preliminary design of the diversion structures and dam structures.

For the dam component, a panel of experts (POE) has been established for undertaking independent safety review of the new dam. The objective of the POE is to provide an independent review of the investigation, design and construction of the dam, and the start of operations and recommends on the required actions to ensure the safety of the dam and associated facilities to acceptable standards as per ADB's, World Bank's, and Government of India's requirements. The POE will provide due consideration to the administrative procedure/guidelines of the Government of India, ADB, and the World Bank's safeguard policy OP4.37.

It was felt necessary to have geophysical field measurements and the investigation of dynamic underground properties by means of state-of-the-art seismic and electric resistivity methods. The assignment of conducting these investigations using geophysical methods of seismic refraction tomography, electrical resistivity imaging, multi-channel analysis of surface waves (MASW) and cross-face seismic tomography was entrusted to M/s PARSAN Overseas Pvt. Limited. This report covers geophysical investigations carried out as part of this assignment.

General Geology of Area

The bedrock is composed of alternant sandstone, siltstone and claystone layers, the sandstone layers being predominant. The sandstone layers are often several meters thick. The thickness of claystone and siltstone layers ranges mostly from several decimeters to one meter, rarely reaching a few meters. Some of the sandstone layers exhibit relatively high porosity.

The geological structure is characterized by regular bedding dip, around an average of 40 to 50° to the NNE. Shearing parallel with the bedding is especially associated with thin claystone interlayers; the maximum width of such shear zones is about 1 m. Shear zones cross-cutting the bedding planes are very rare and thin.

In the river channel, the thickness of the alluvial deposits reaches up to about 20 m.

Location of studied area

The latitude & Longitude of Dam site are 29o16'15" N and 79o36'36" E respectively. The dam & all appurtenant works are located in the foothills of Himalayas about 10 Kms upstream of Gola Barrage at Kathgodam in district Nainital.

Scope of Work

The scope of work under the assignment was as follows:

1. Conducting seismic refraction tomography along left bank, right bank and river crossing
2. Conducting electrical resistivity imaging along left bank, right bank and river crossing
3. Conducting MASW along left bank and right bank
4. Conducting seismic tomography between drifts on left bank & right bank
5. Data acquisition, processing and interpretation of all geophysical investigations

Objective of Study

The key objectives of the study defined are:

1. Identification of dynamic underground properties of foundation bedrock as input parameter for probabilistic seismic hazard assessments and dynamic dam analysis modelling dynamic soil structure interaction
2. Inferring the bedrock characteristics at large scale, principally in the foundation of the dam and of the cofferdams, from correlations with the geophysical parameters.
3. Identification and location of weakness zones which could be especially concealed by the alluvial deposits, including a hypothetical fault along the river channel.

Details of Team Members

Details of team members is as follows: -

1. Dr Sanjay Rana- Team Lead- M Tech (Applied Geophysics) IIT Roorkee
2. Cdr Ashutosh Kaushik (Retd) – Logistics and Site Management- BE, MBA
3. Mr Ajay Mishra- Geophysicist – M.Sc.Tech (Applied Geophysics), ISM Dhanbad
4. Mr Chendhoor B – Geophysicist- M. Sc. (Applied Geophysics), MS University Tamil Nadu
5. Mr M J Dwivedi- Senior Geophysical Technician
6. Mr Raghvendra- Geophysical Technician
7. Mr Ajit Kumar- Surveyor

2 EQUIPMENT USED

Equipment for Seismic Investigations	N°
Engineering Seismograph (24 channels)	1
Dell lap top (GUI)	1
Geophones 10 Hz for Seismic Refraction	24
Geophones 4.5 Hz for MASW	24
Geophones (360 degree) for tomography	24
Seismic hammer	2
Seismic cable	2
Trigger cable (600m)	1
Electric drill machine	1
Equipment for Resistivity Imaging	**N°**
Mangusta 60E	1
Electrodes	60
Electrode Cable	2
Batteries	2
Equipment for Land Survey	**N°**
Total Station with accessories	1

3 GEOPHYSICAL SURVEY METHODS

3.1 Electrical Resistivity Imaging

2D Resistivity Imaging uses an array of electrodes connected by multicore cable to provide a linear depth profile, or pseudo-section, of the variation in resistivity both along the survey line and with depth. Switching of the current and potential electrode pairs is done automatically using a laptop computer and relay box. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased and the process repeated in order to provide an increased depth of investigation.

The maximum depth of investigation is determined by the spacing between the electrodes and the number of electrodes in the array. For a 64 electrode array with an electrode spacing of 5m this depth is approximately 60m. However, as the spacing between the active electrodes is increased, fewer and fewer points are collected at each 'depth level', until on the final level only 1 reading is acquired. In order to overcome this the array is 'rolled-along' the line of investigation in order to build up a longer pseudo section. The raw data is initially converted to apparent resistivity values using a geometric factor that is determined by the type of electrode configuration used. Once converted the data is modeled using finite element and least squares inversion methods in order to calculate a true resistivity versus depth pseudo-section.

3.2 Seismic Refraction Tomography

Seismic refraction tomography consists of recording the length of time taken for an artificially provoked surface vibration to propagate through the earth. By processing the data recorded at various sensors absolute velocities, velocity contrasts and the depths of the underlying layers are determined. These results give information about the nature and thickness of overburden (alluvium deposits), surface of bedrock, the depth of weathering zones in the rock mass, location of geological boundaries and identifies faults or weak zones, scale and width, etc. The seismic velocities are characteristics of the nature and quality of the bedrock; reduced seismic velocities will characterize a fissured, fractured or sheared rock.

The measurements made with the refraction technique can be processed with the tomographic procedure in order to highlight in detail the local variations in speed. The tomographic technique involves the creation of a synthetic model of the subsoil and its perturbation in search of the minimum difference between the measurements taken on the ground and the "virtual" measurements.

3.3 Multi-Channel Analysis of Surface Waves (MASW)

First introduced in GEOPHYSICS (1999), the multichannel analysis of surface waves (MASW) method is one of the seismic survey methods evaluating the elastic condition (stiffness) of the ground. MASW first measures seismic surface waves generated from various types of seismic sources—such as sledge hammer—analyses the propagation velocities of those surface waves, and then finally deduces shear-wave velocity (Vs) variations below the surveyed area that is most responsible for the analyzed propagation velocity pattern of surface waves. Shear-wave velocity (Vs) is one of the elastic constants and closely related to Young's modulus. Under most circumstances, Vs is a direct indicator of the ground strength. After a relatively simple procedure, final Vs information is provided in 1-D, 2-D, and 3-D formats.

3.4 Seismic Tomography

Seismic tomography principle is based on generation of elastic energy using various sources which is propagated through the investigated structure depending on elastic properties variations of particular mass of material crossed. The elastic waves are recorded by receiver sensors in the form of electric signals.

Velocity analysis consists of an estimation of time required by the elastic impulse to cover the distance between the transmitter-receiver combinations. After estimation of the travel time of elastic waves over a known distance, next step consists of time-distance processing of data set to calculate seismic velocity distributions and to estimate a tightly linked parameters with elastic properties of investigated area.

Seismic tomography can be applied between boreholes or between 02 faces.

Seismic tomography survey provides maps (called tomograms) that show the velocity distributions of elastic waves. This process starts from travel time measurement of longitudinal waves along high number of ray tracks which reciprocally cross each other within the area between transmitter and receiver position. Tomography resolution and then the final results accuracy are determined by numbers of ray paths acquired and with their angular covering.

The acquisition is carried out through the acquisition of each signal transmitter point related to different receiver points. In this way , it is possible to obtain the data grid necessary to next data processing phase. Every receiver and transmitter points coordinates are determined by an appropriate geometry mapping.

In processing stage, the investigated section is divided by a rectangular grid cell where velocities are calculated for each single node, assuming bilinear velocity variation along the cells. Cell dimensions are chosen in such a way that these are of same magnitude as either with signal wave length and relative distances between consecutive transition and receiver points. Such division is also aimed to calculating process adopted but is justified by the assumption that seismic waves mediate the characteristics of the investigated materials, having length different by zero, in a finite width portion (first Fresnel Zone). Starting from a velocity model described at the beginning of the process, an iterative inversion progressively minimizes the gap between the times measured along the different measuring paths and those computed on the basis of the velocity model defined at the previous step. The processing algorithm used, for the computation of the path times between transmitter and receiver, takes into account the effects of the refraction of the seismic rays along the path, using a “pseudo-bending” “ray -tracing” procedure (Um and Thurber, 1983), which enables the reconstruction of the rays’ path as a function of the velocity field.

The results of the processing are plotted as colored tomograms, which show the variations of the P wave velocity field, along with the representation of the measuring paths as obtained from the ray-tracing processing. Depending on type and geometrical characteristics of the investigated structure, on transmitter-receiver location points and on the specific requirements to be carried out, the most adequate measurement methods and the most suitable receivers are selected.

4 DATA ACQUISITION

The data acquisition was carried out during April-May 2022. Excellent data was obtained adhering to strict quality control procedures. Following are the details of data acquired during the field campaign:

Seismic Refraction Tomography:

SRT data was obtained using a 24-channel equipment, using explosives as source. Shot holes were dug to place explosive charge and depth of charge was carefully measures. 11 shots per profile were taken to have a high-resolution image of subsurface. The shot plan was kept as under:

- Left Bank: 04 profiles of 230m each, in continuation, with last 02 geophones overlapping
- Right Bank: 04 profiles of 230m each, in continuation, with last 02 geophones overlapping
- Cross Lines: 02 profiles of 161m each (oblique lines)

Electrical Resistivity Imaging

ERT data was obtained using a 60-electrode equipment. Roll along with half profile length was conducted to have a continuous deep profile.

- Left Bank: 05 profiles of 295m each, in continuation, with half profile overlapping
- Right Bank: 05 profiles of 295m each, in continuation, with half profile overlapping
- Cross Lines: 03 profiles of 295m each

MASW:

MASW data was obtained with geophone spacing of 2m, and shift of 2 meters for each consecutive 1D profile.

- Left Bank: 02 profiles to cover the entire length at left bank
- Right Bank: 02 profiles to cover the entire length at right bank

Seismic Tomography:

Seismic tomography was conducted with 1m geophone spacing and 1m shot spacing. At least half spread overlap was observed to collect a very dense data.

- Left Bank: 03 planes between 04 drifts
- Right Bank: 03 planes between 04 drifts

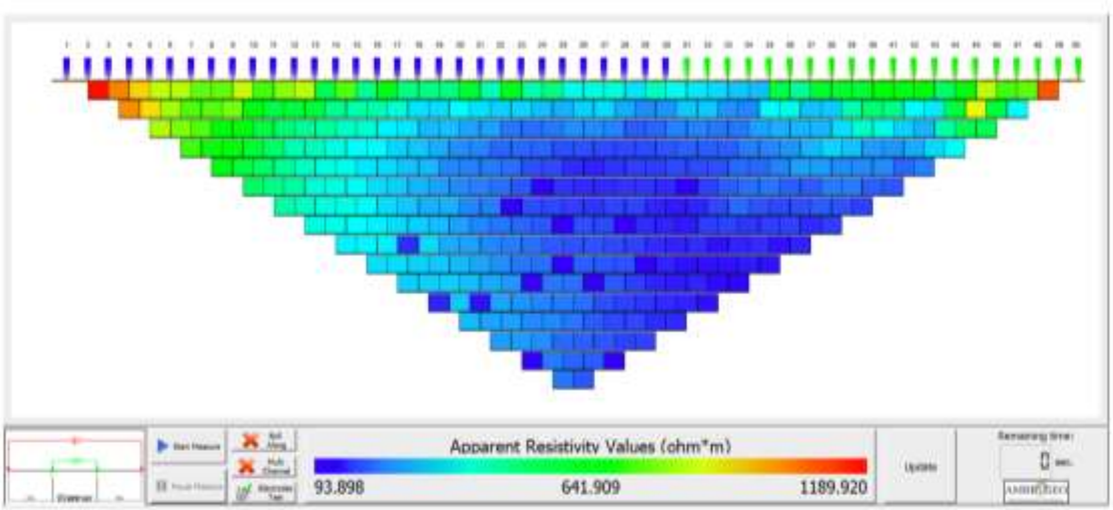
The layout plan has been provided separately as annexure.

5 DATA QUALITY

Strict quality control was observed on recorded data. Sample data obtained using various methods are as under:

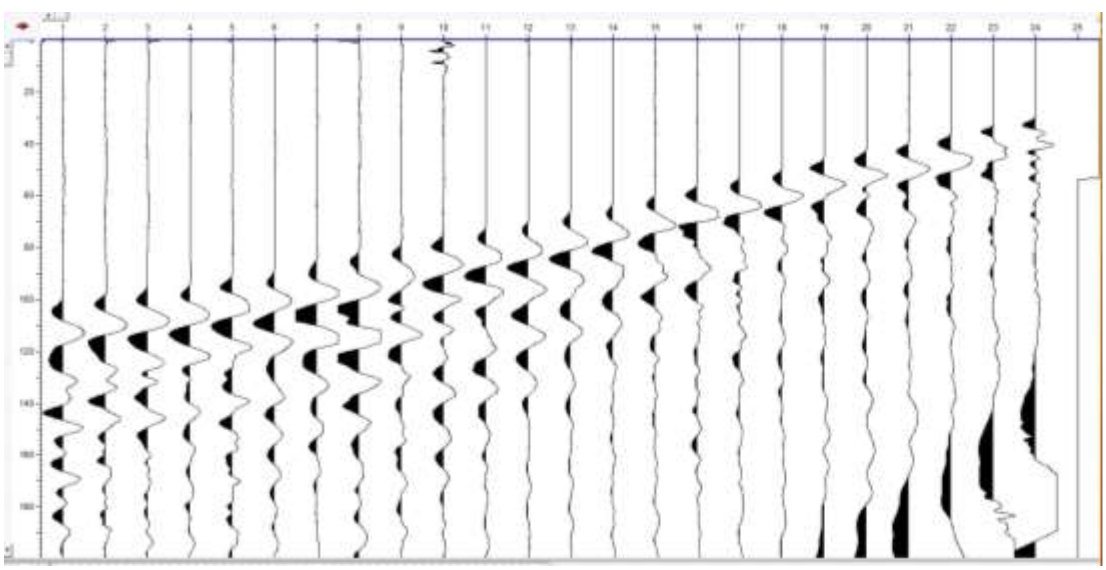
Electrical Resistivity Imaging:

Electrode tests were performed keeping a stringent pass value, and ground contact was improved using water/ salt water/ deepening of electrode, till the time each electrode passes the test. As a result excellent data was collected with negligible bad data points requiring rejection.

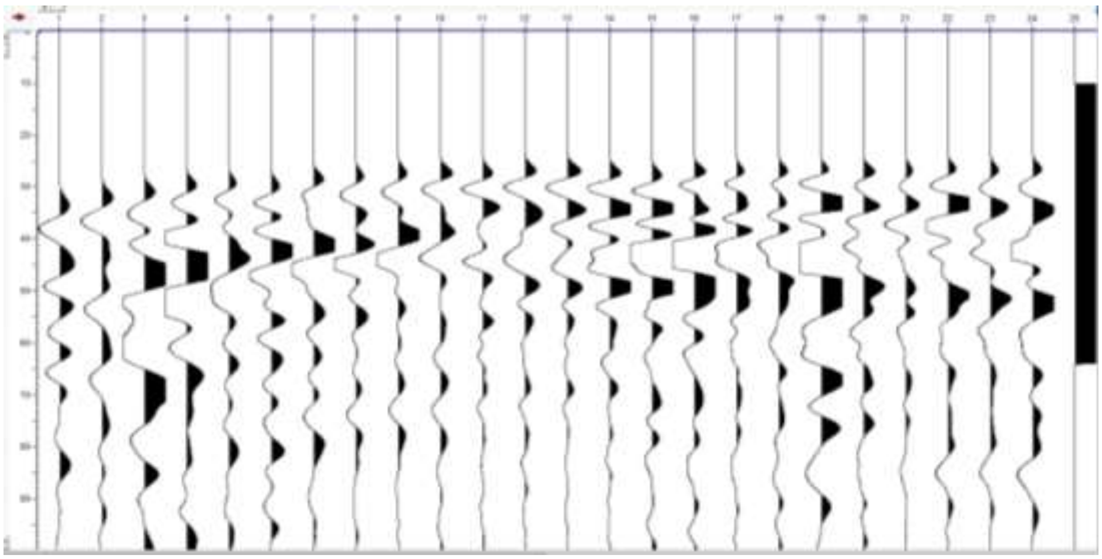


Seismic Refraction Tomography:

It was ensured that all 24 channels were in working condition all the time, and first arrivals are visible on all the channels. As a result, even on far shots, where energy source is farthest from the geophones, excellent data was obtained. Trigger was recorded separately on channel 25 for additional accuracy.



Similar quality control was also observed for MASW and Seismic Tomography data. Following is an example of data of seismic tomography conducted between drifts at right bank:

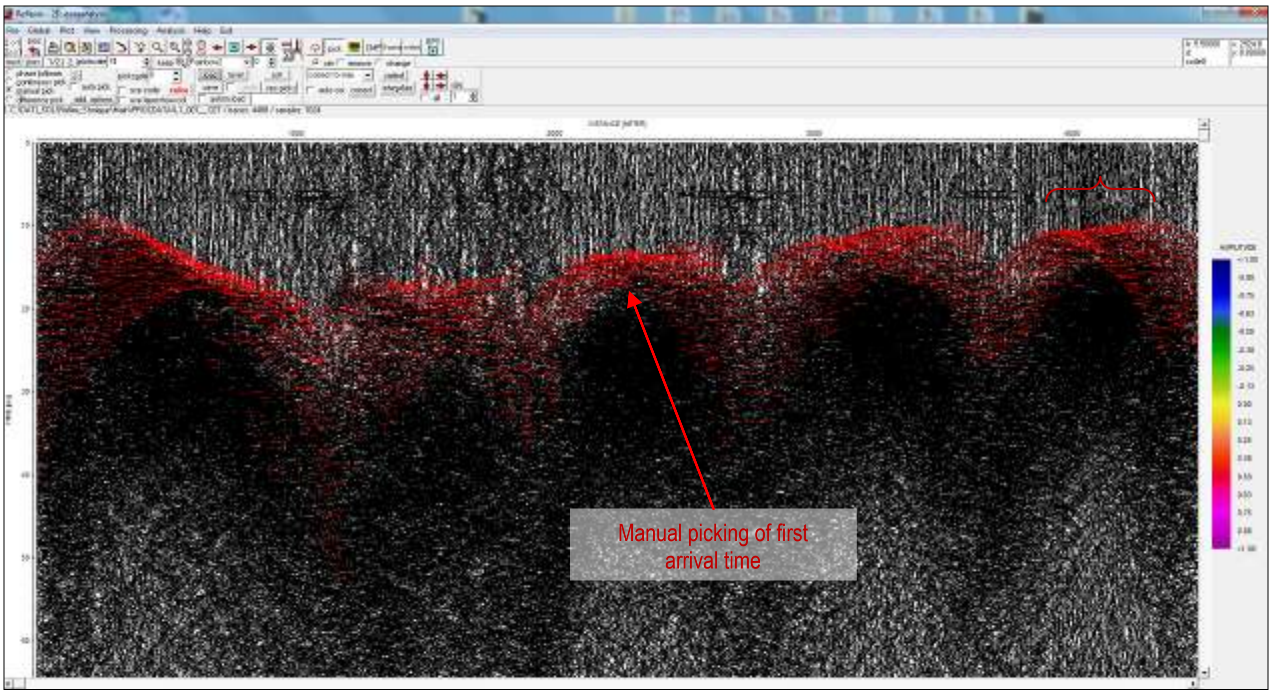


6 DATA PROCESSING

6.1 Seismic tomography

The data acquisition was conducted using 24 channel digital signal enhancement type seismograph and sensitive 360° geophones. The system allows to carry out operations of "averaging" and "stack" of signal so as to obtain, when necessary, an enhancement of the ratio signal/noise.

For the analysis and filtering of raw signals the program *Lakkolit* has been used while the tomography processing was performed with the software *aTom and GeoTomCG*. As shown in the picture below, for each sensor used it has been acquired a different traces number, depending by the number of combinations used for each section.

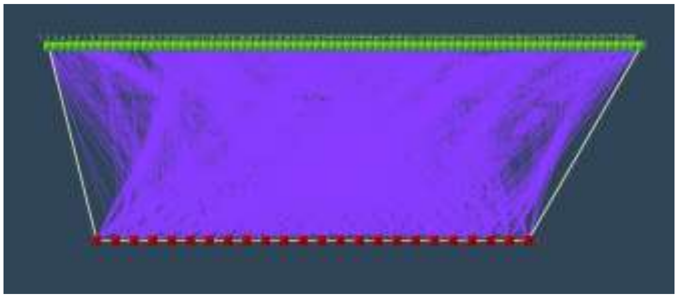


An example of seismogram of the Longitudinal Section with picking of first time arrival

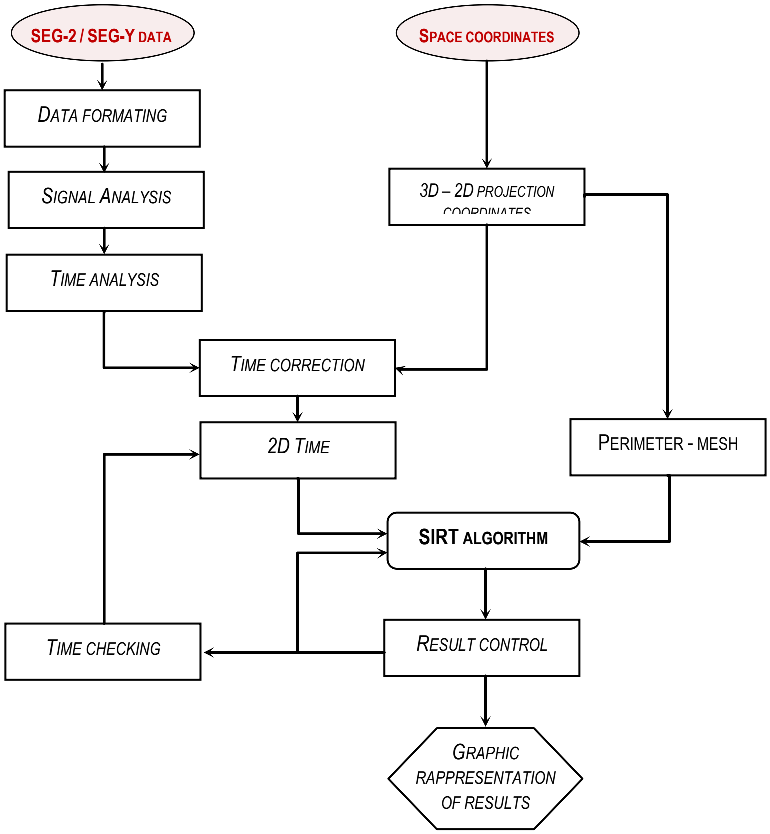
The tomography processing starts from the construction of a section that better approximates the 3D coordinates of all points of transmission and reception. On that plane of reference were projected the coordinates of all the points and the initial mesh constructed, set up with square cells.

To compensate the variation of the distances in the passage from coordinated 3D to plane of reference properly coefficients have been calculated.

The velocity section reconstruction was obtained with a S.I.R.T. (*Simultaneous Iterative Reconstruction Technique*) algorithm. Starting from the initial grid, the calculation of the velocity fields is executed through a series of iterations for the progressive reduction of the residual between the times measured along the various distances and the times calculated. At each iteration is performed an automatic update of the velocity values for every node of the grid, and therefore the ray-tracing is re-calculated in function of the velocity field, as well as the update of the travel times between transmitter and receiver. The result of this process is a new grid of velocities, and so a new residual value between measured time and calculated time to start a new iteration.



One example of ray tracing computed on longitudinal section



A flow chart of different processing steps

The information in this report is based on geophysical measurements obtained by generally accepted methods and procedures and our interpretation of the data. Individual values may in some instances, be erroneous due to noise occurring simultaneously with the measurements.

6.2 Electrical Resistivity Imaging

The data processing of ERI data was conducted using RES2DINV software.

Electrical resistivity of rock is high, whereas that of soils is lower and for saturated zones it is lowest. Details of the method have been explained in elaborate in earlier section.

The interpretation of ERT data is carried out using inversion process. It is worth mentioning here that finest grid was used with parameters chosen to reflect most accurate internal conditions, though it took extensive time for iterations.

In original models, the minimum and maximum resistivity values, obtained for each profile separately, is considered as the two end values for defining the full range of the color scheme while developing sections with color contours. Due to this reason, same range of resistivity values may be represented by different colors for different ERT sections in original models.

6.3 MASW

MASW data processing was carried out using Geogiga Surface Plus software. The software is able to process active surface waves with SASW and MASW. The dispersion spectrum can be calculated in F-K, F-V, or F-P domain, where the fundamental and higher-mode dispersion curves are interactively picked. The robust forward modeling and the global genetic algorithm (GA) assure the quick convergence of inversion.

6.4 Seismic Refraction Tomography

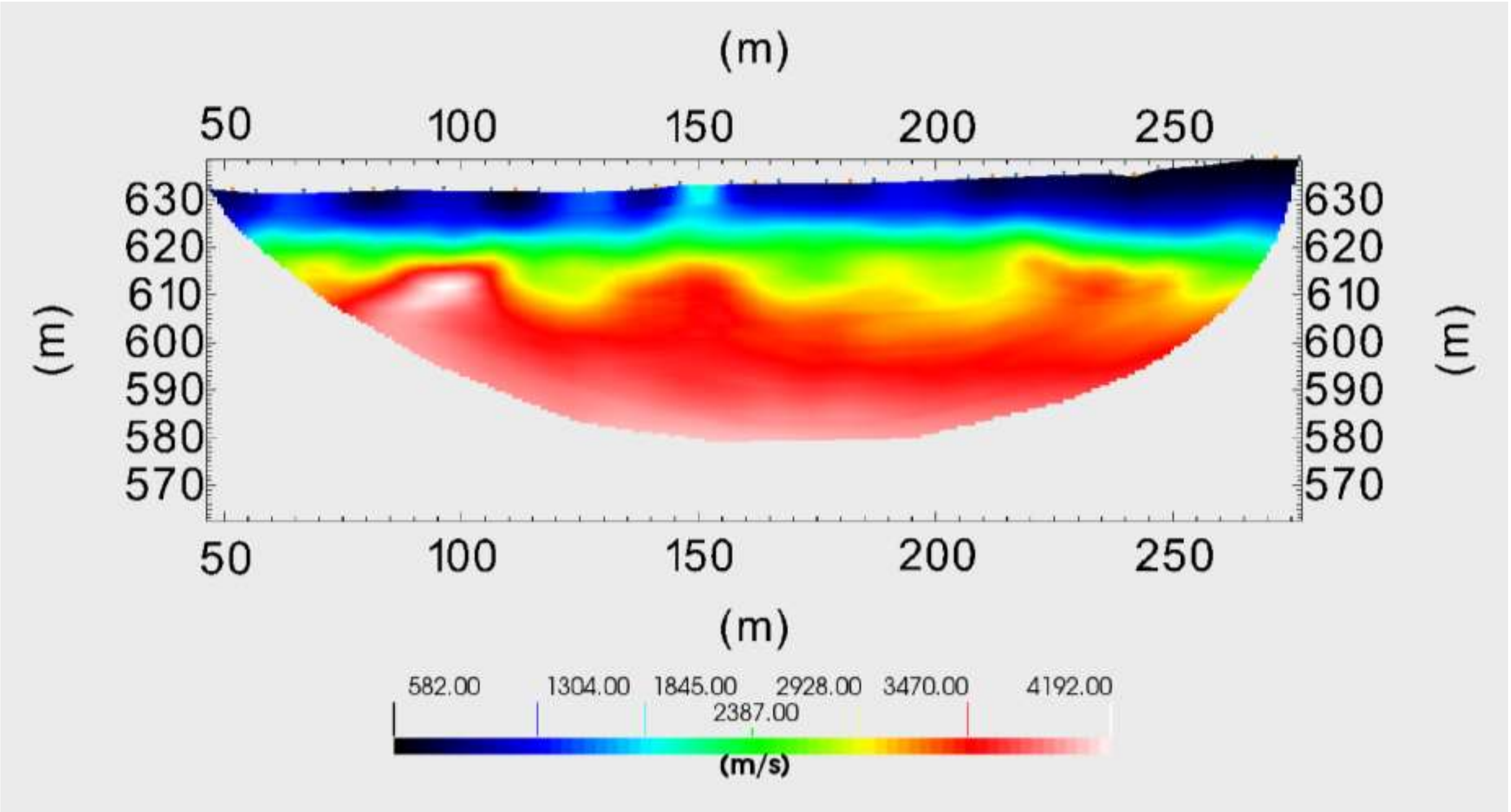
Layer velocity estimation was done using Geogiga Refractor. Tomographic processing was done using SmartTomo software. The tomographic technique involves the creation of a synthetic model of the subsoil and its perturbation in search of the minimum difference between the measurements taken on the ground and the "virtual" measurements recorded on the synthetic model through an iterative procedure that alternates the following two phases:

1. In the "direct" phase the arrival times of the seismic impulse are calculated on the synthetic model (smartTomo is based on the work of Moser, TJ "Shortest path calculation of seismic rays." Geophysics 56.1 (1991): 59-67). The initial velocity model is divided into a grid whose cells have assigned an initial velocity value. On the sides of the cell there are several nodes (the number is chosen by the user) which constitute the nodes of the network of hypothetical seismic rays that connect all the sources and all the receivers which are also nodes. Each node is connected with the nodes of the adjacent cells. The path of the refracted waves corresponds to the path along the seismic rays that takes the shortest time to travel the path between the source and the receiver.
2. In the "reverse" phase, the synthetic times calculated in the "direct" step are compared with the measured times; the differences between the two times are used to update the synthetic model (smartTomo uses an algorithm referable to the “Simultaneous Iterative Reconstruction Technique” family).

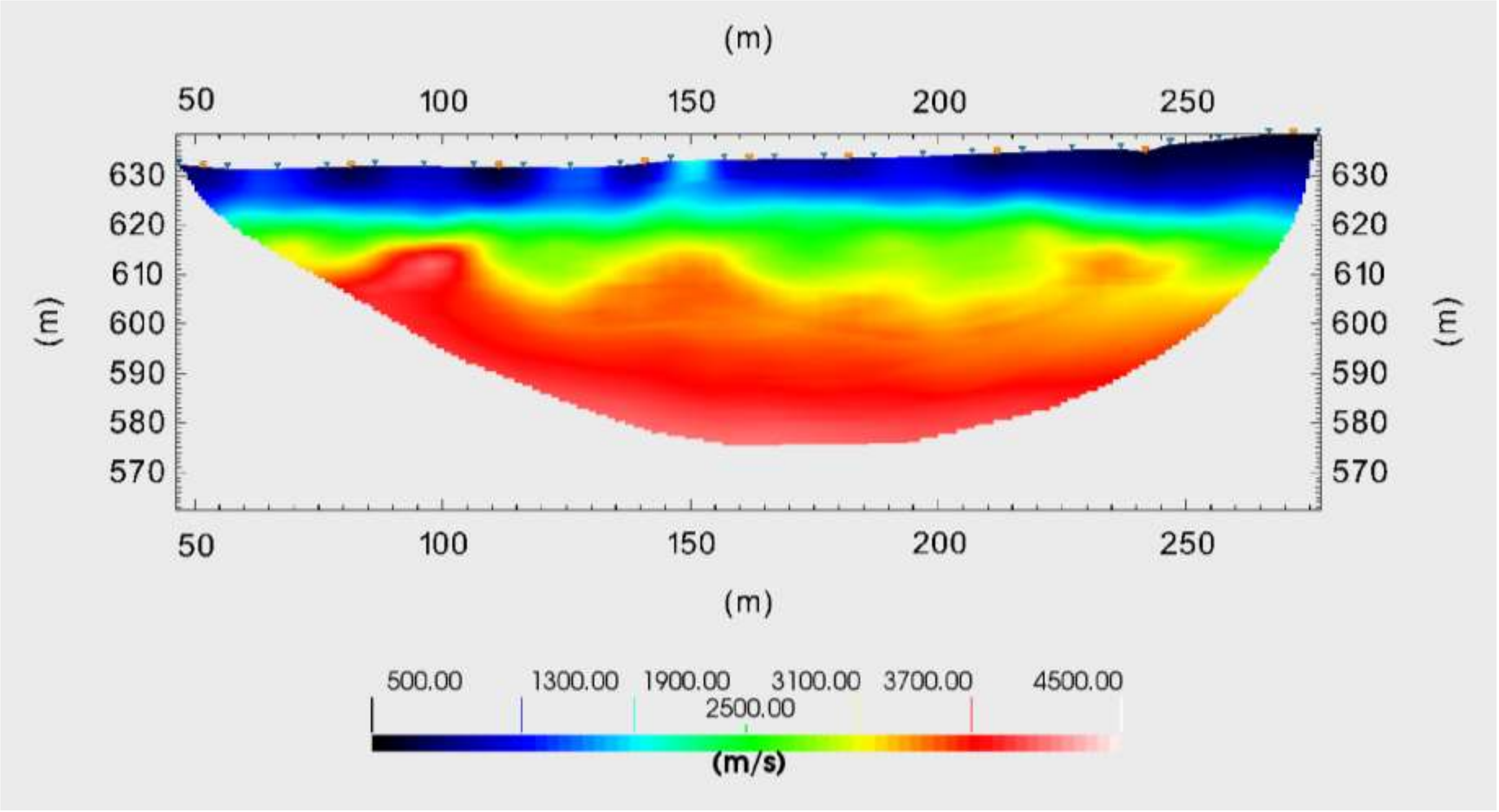
Velocity scale of 500m/s to 4500m/s has been used in all SRT profiles to have uniformity and presented as ‘constrained’ results. Original profiles with default scale have been termed as ‘unconstrained’.

7 RESULTS- SEISMIC REFRACTION TOMOGRAPHY

Left Bank- Profile-1- Unconstrained:



Left Bank- Profile-1- Constrained:



Shot points in red, receiver points in blue.

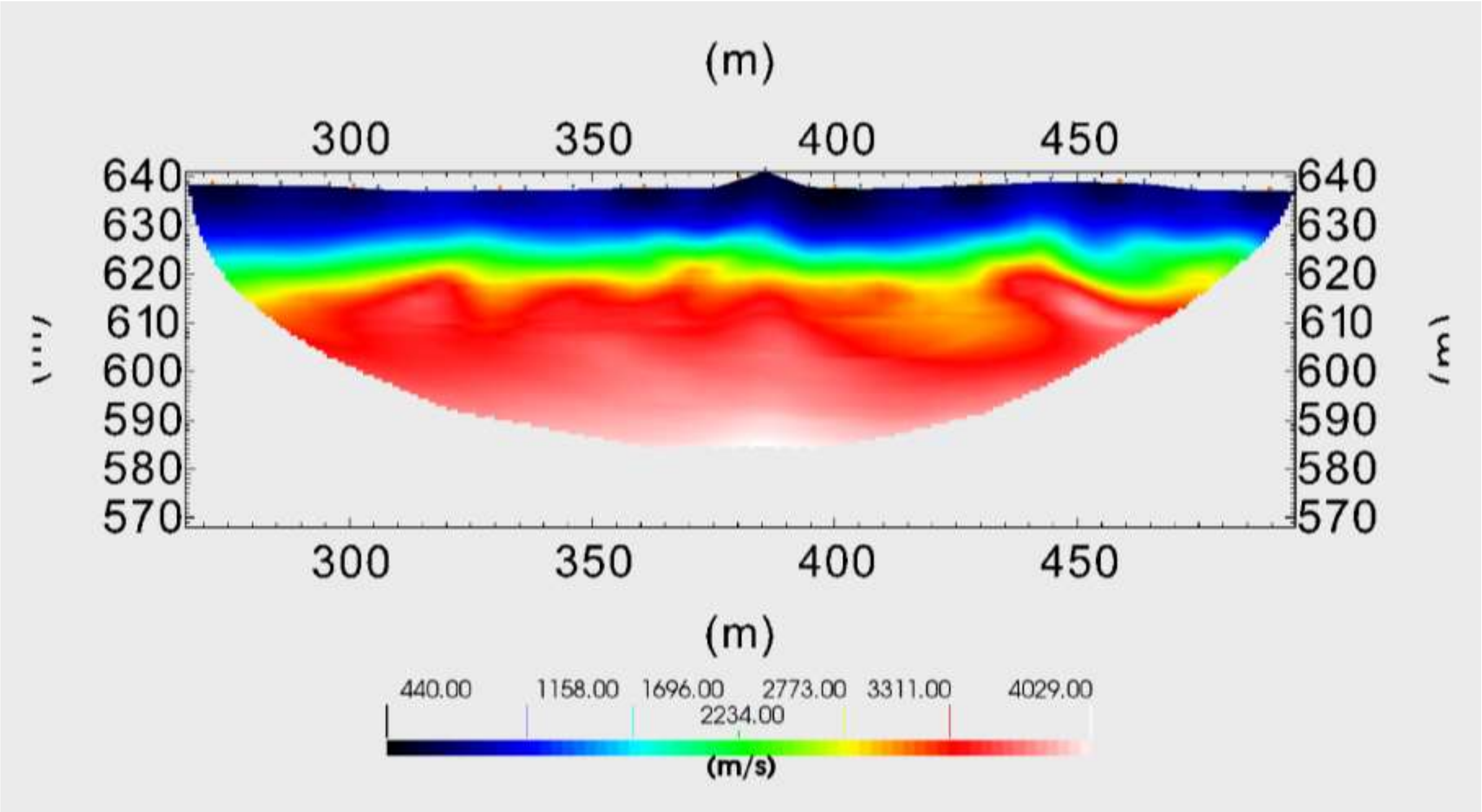
Discussions:

Seismic Source Used: Explosives

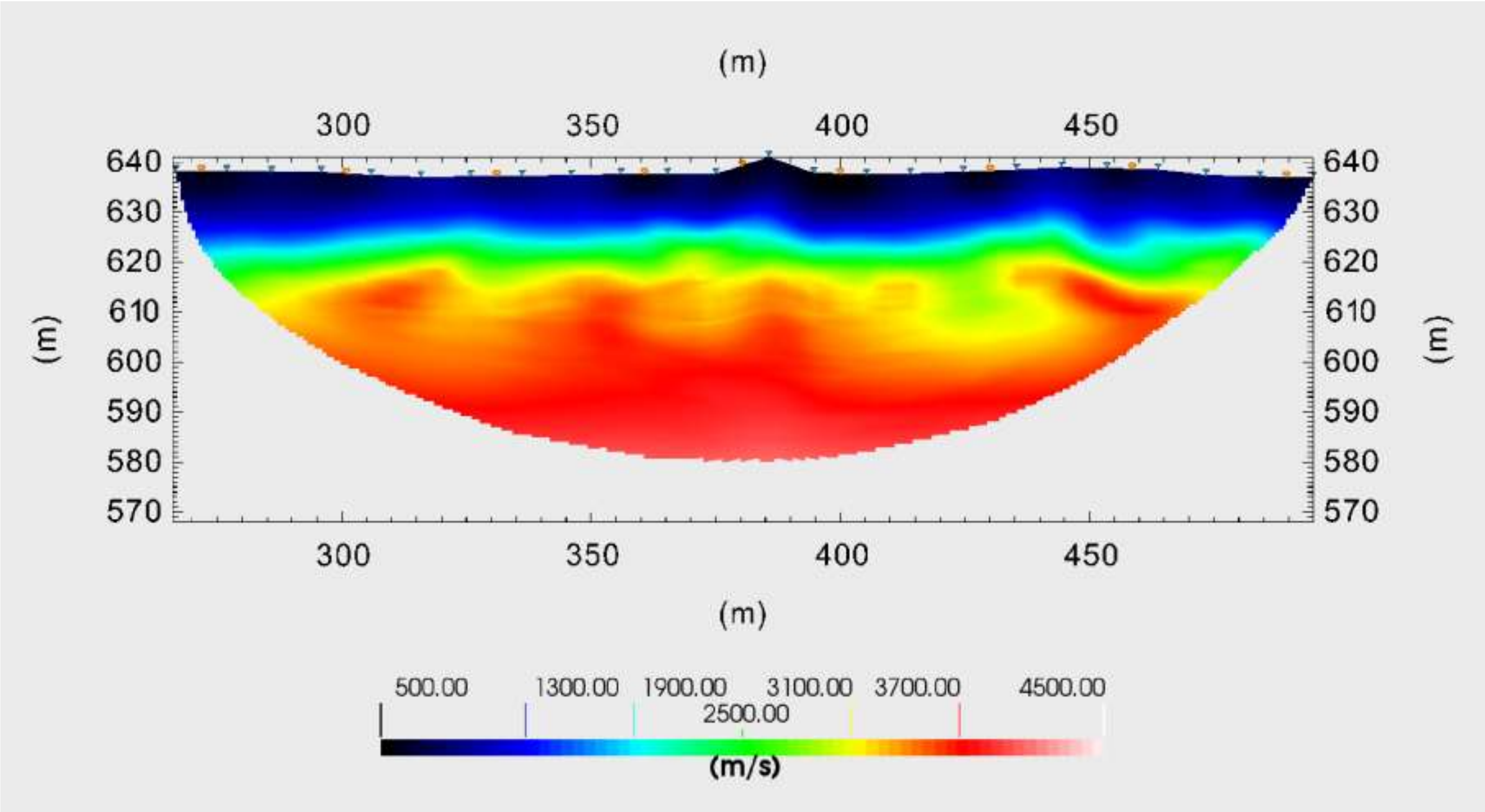
The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 610-615 with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip.

The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is consistent along the profile at 8-10m. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extend upto RL 610-615m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3100m/s. The interface has undulating topography.

Left Bank- Profile-2- Unconstrained:



Left Bank- Profile-2- Constrained:

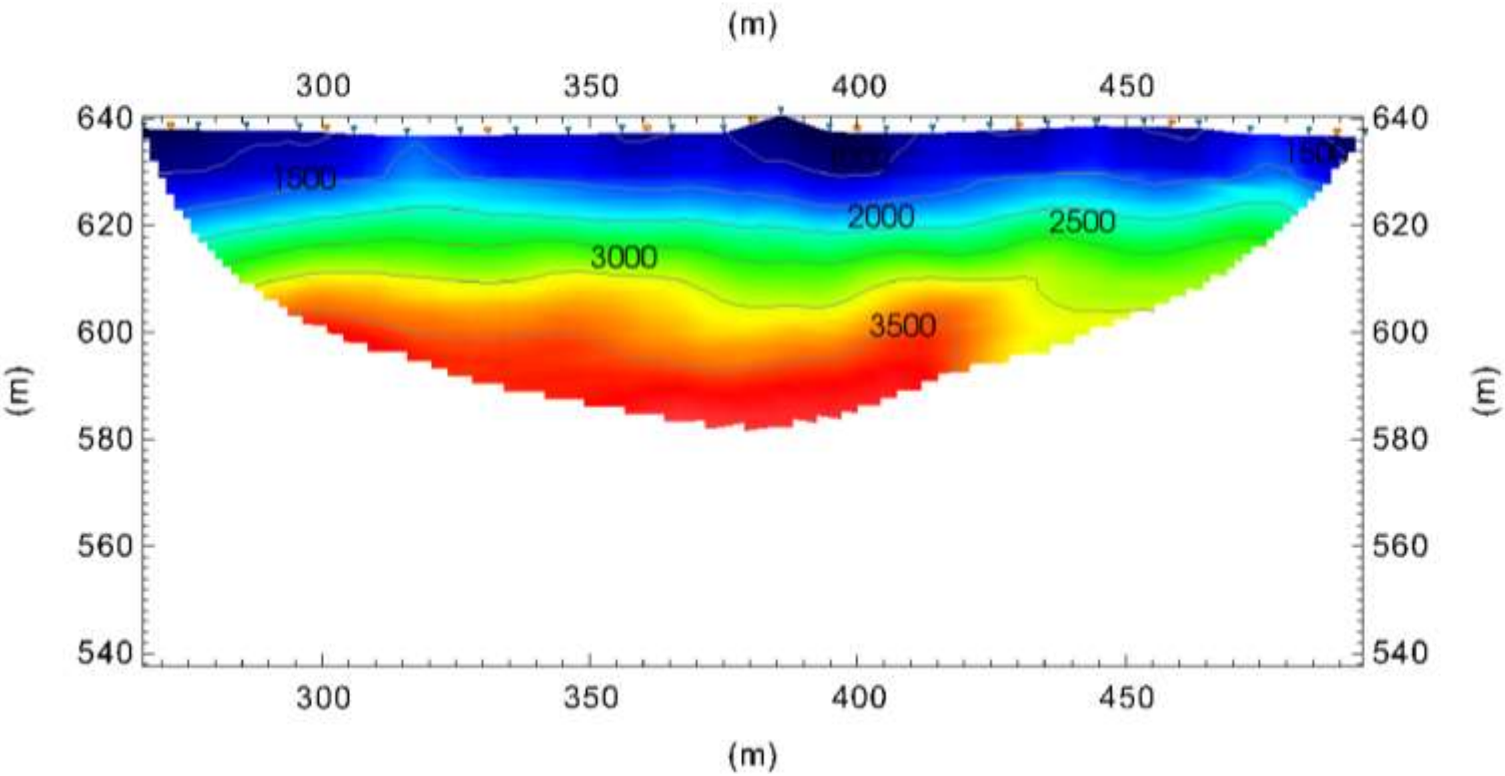


Discussions:

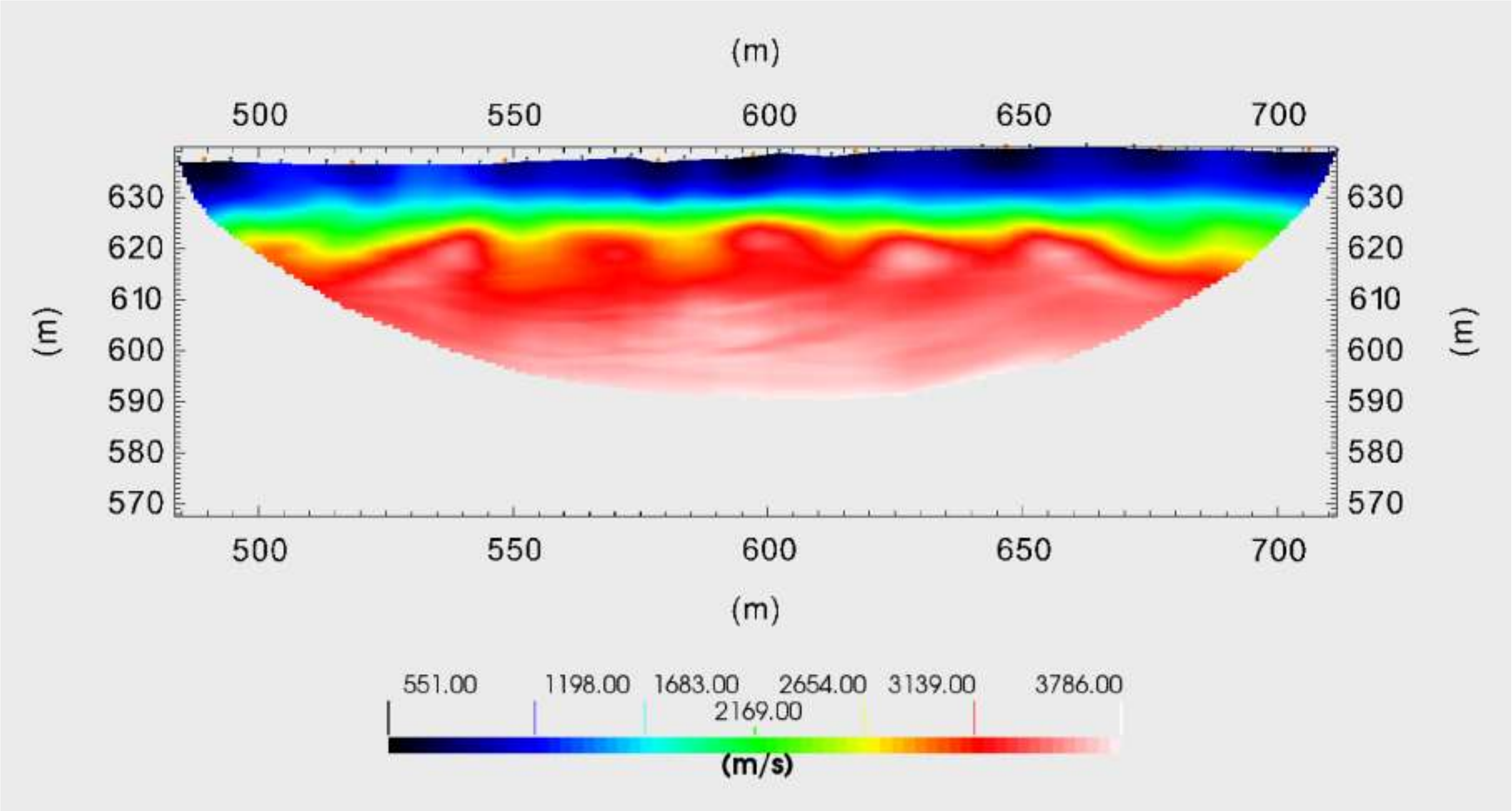
Seismic Source Used: Explosives

The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 610-620 with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip.

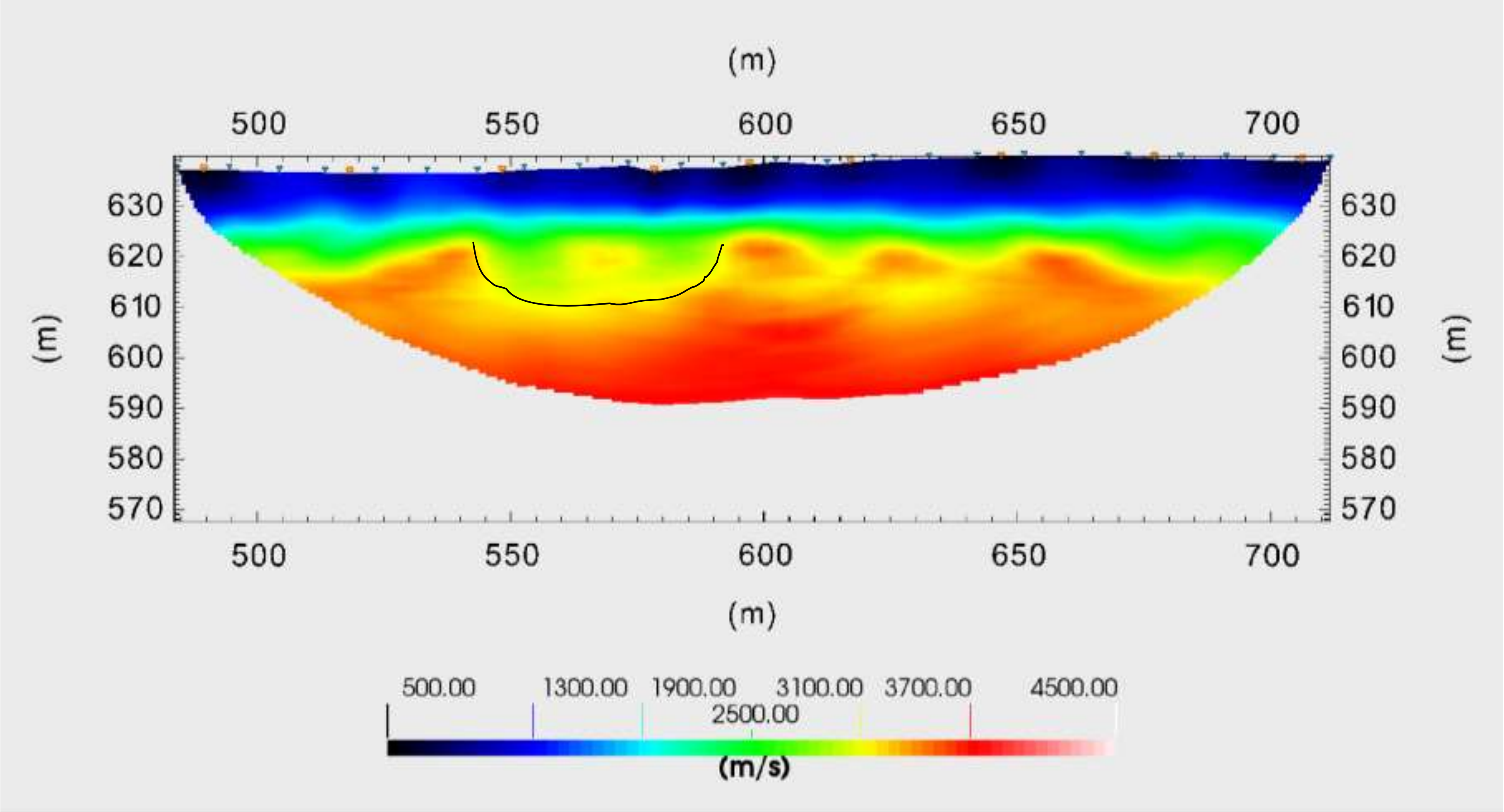
The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is consistent along the profile at 10-15m. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extend upto RL 610-615m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3100m/s. The interface has undulating topography. The profile shows a shart inclined feature towards the right which seems to be linked to ray path , and hence raypath based smoothing algorithm was further used on the data to obtain following profile, more representative of geology:



Left Bank- Profile-3: Unconstrained:



Left Bank- Profile-3: Constrained:



Shot points in red, receiver points in blue.

Discussions:

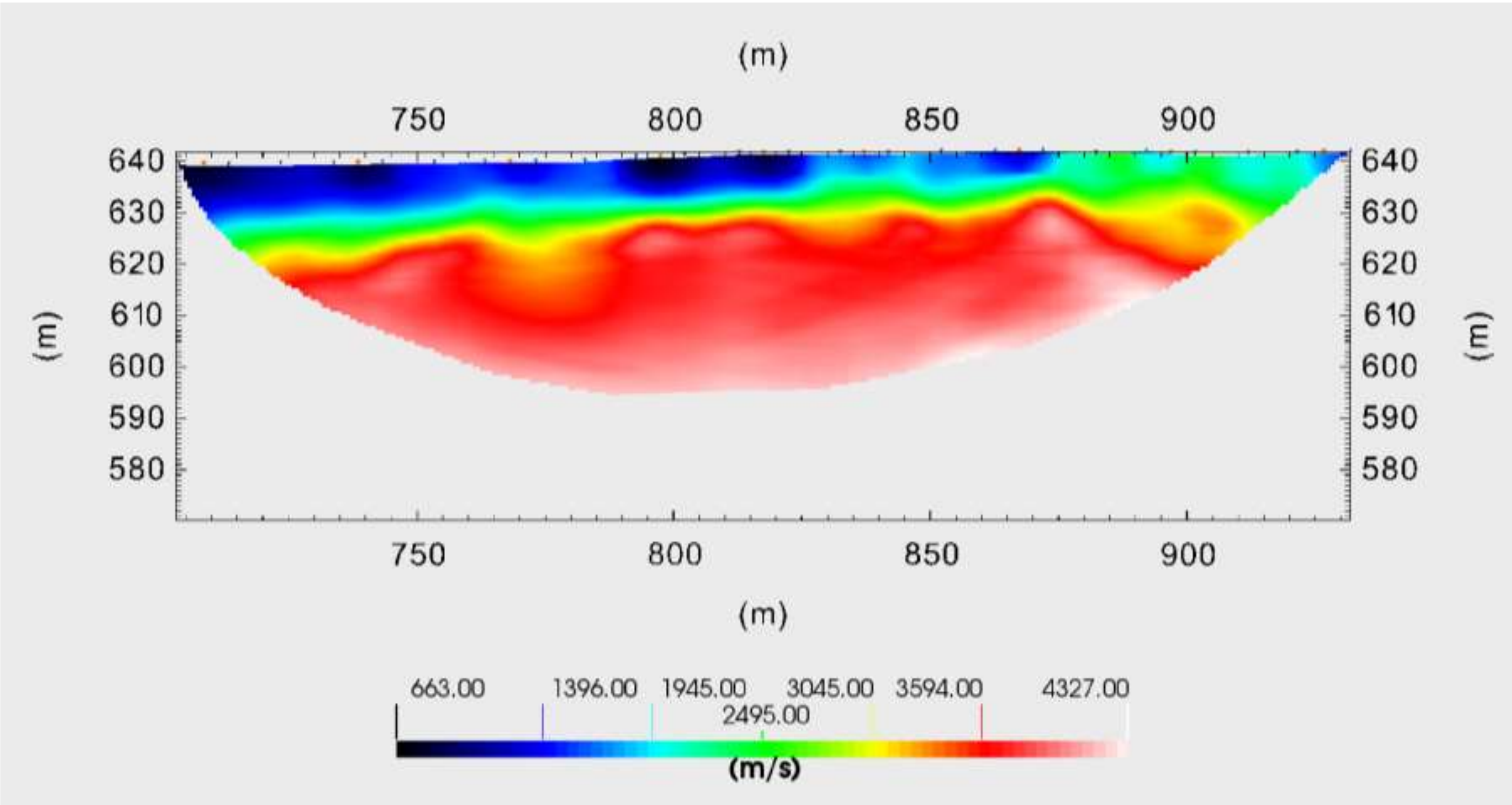
Seismic Source Used: Explosives

The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 610-620 with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip.

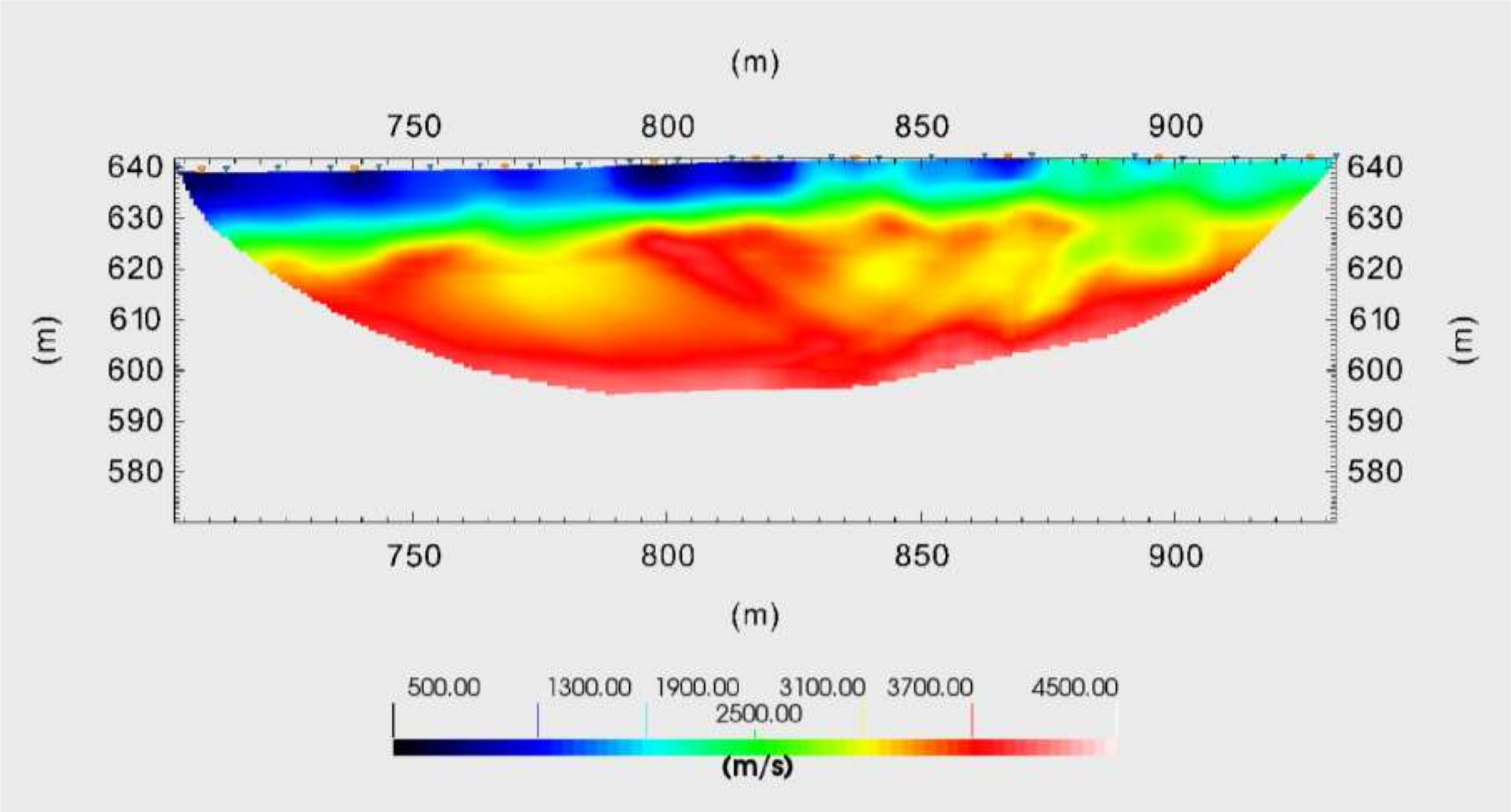
The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is consistent along the profile at 8-10m. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extend upto RL 610-615m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3100m/s. The interface has undulating topography.

The rock interface is slightly deeper between Ch 545- Ch 590m as indicated in the section.

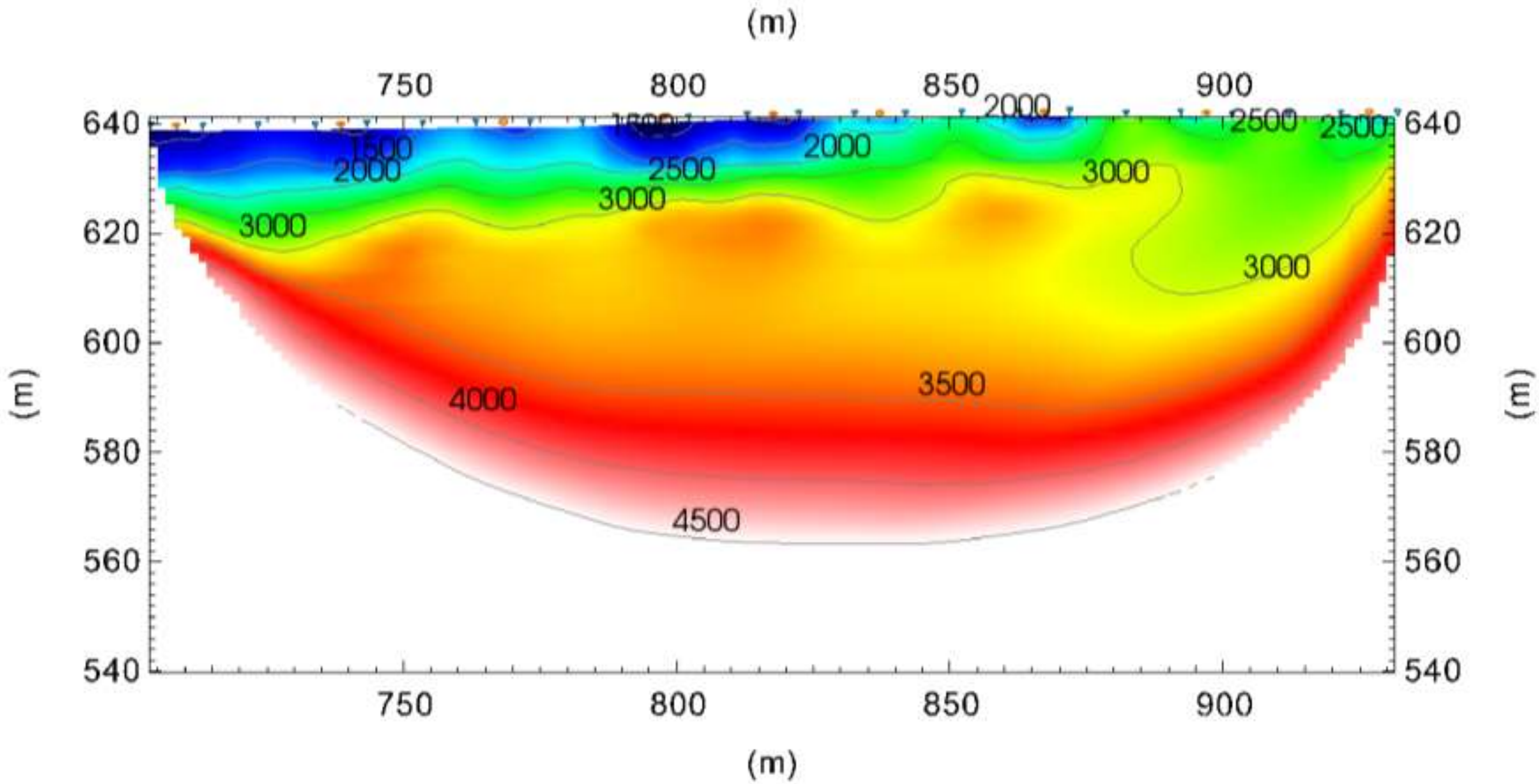
Left Bank- Profile-4: Unconstrained:



Left Bank- Profile-4: Constrained:

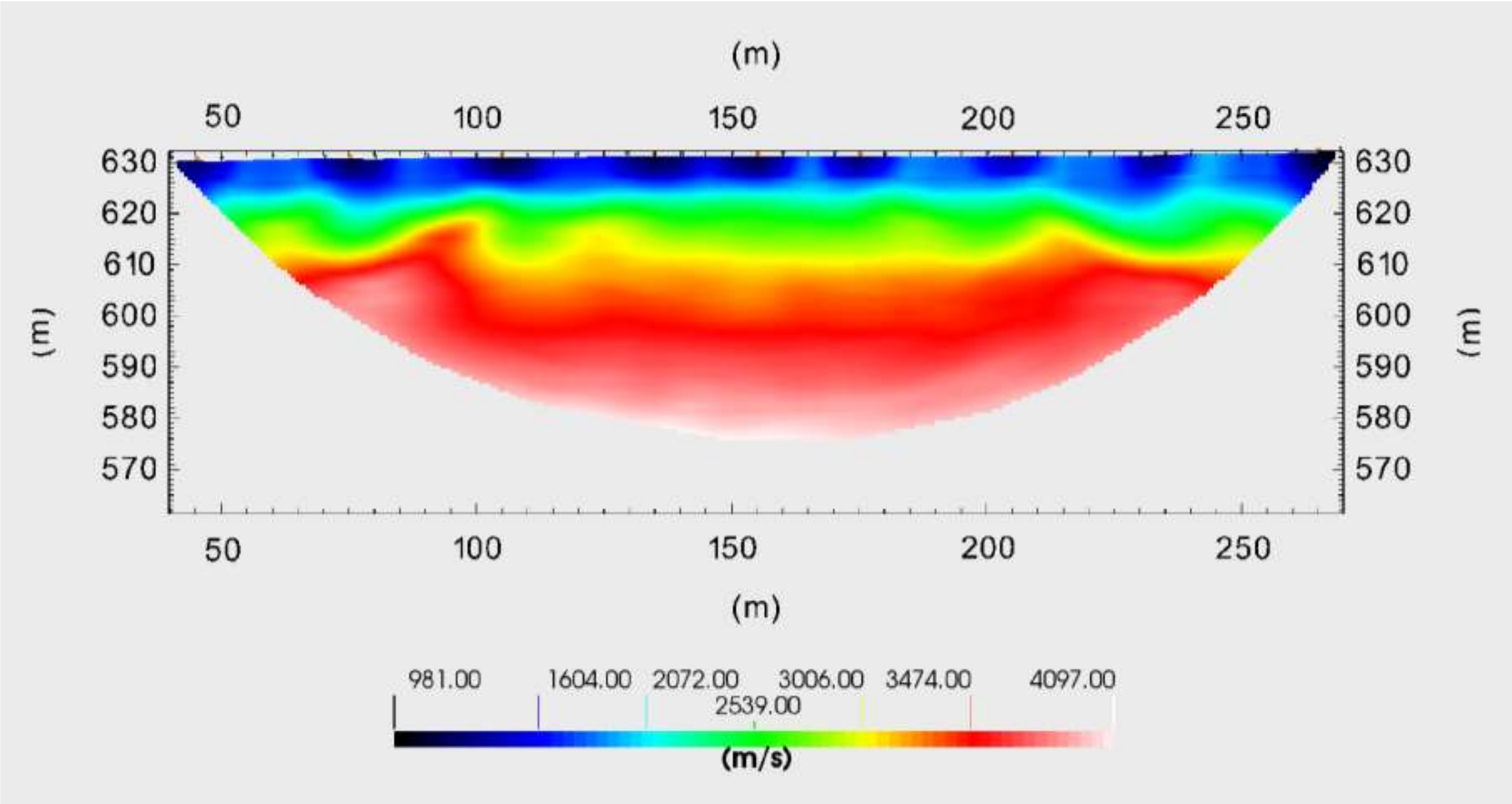


The constraint profile shows a middle zone affected by ray paths, and hence raypath based smoothing algorithm was further used on the data to obtain following profile, more representative of geology:

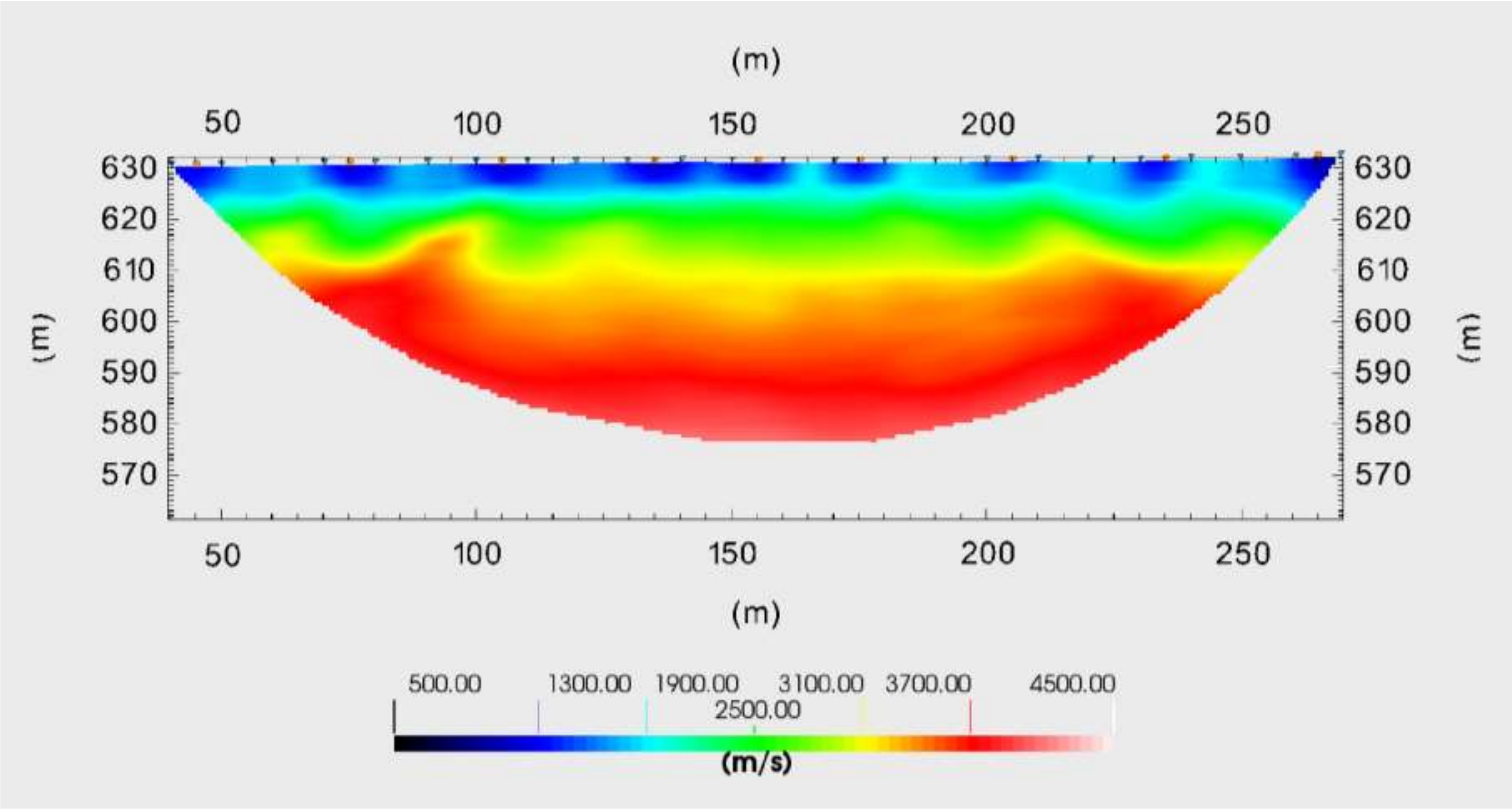


The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 620 with undulating topography of the interface and lowering to a level of 610m towards the right of the profile. This might correspond to rock interface along this profile.

Right Bank- Profile-1: Unconstrained



Right Bank- Profile-1: Constrained



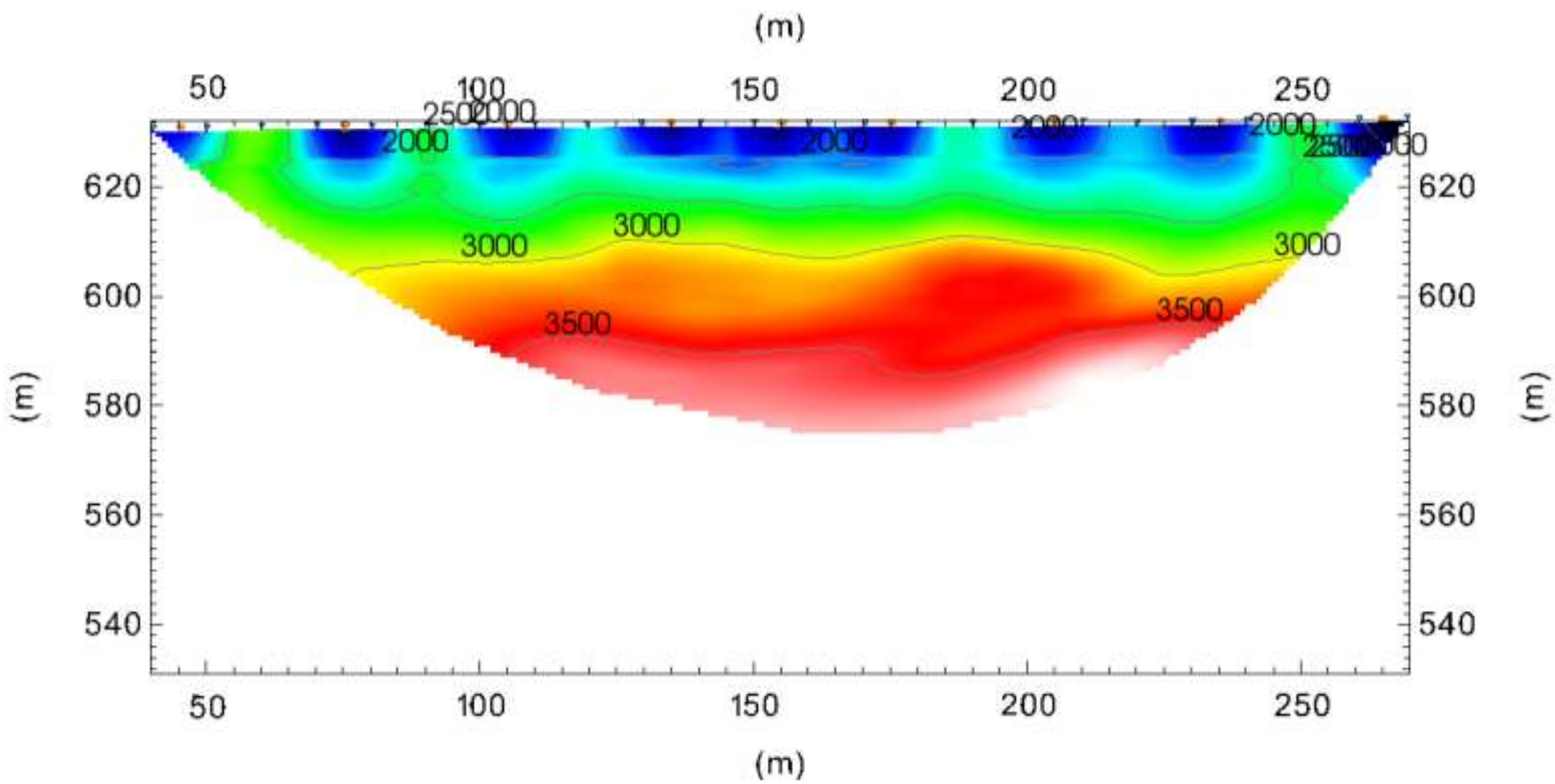
Shot points in red, receiver points in blue.

Discussions:

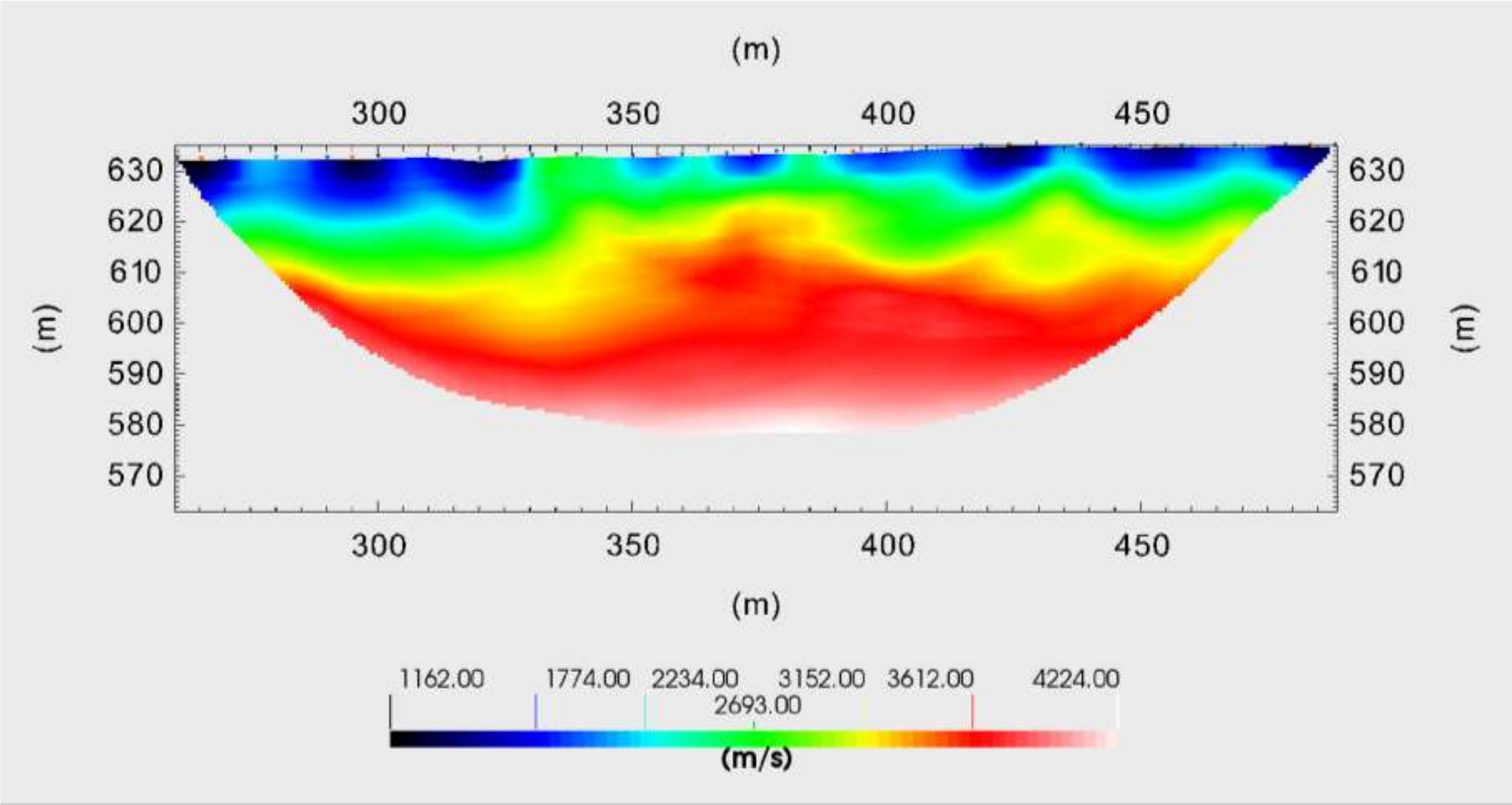
Seismic Source Used: Explosives

The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-612m with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip.

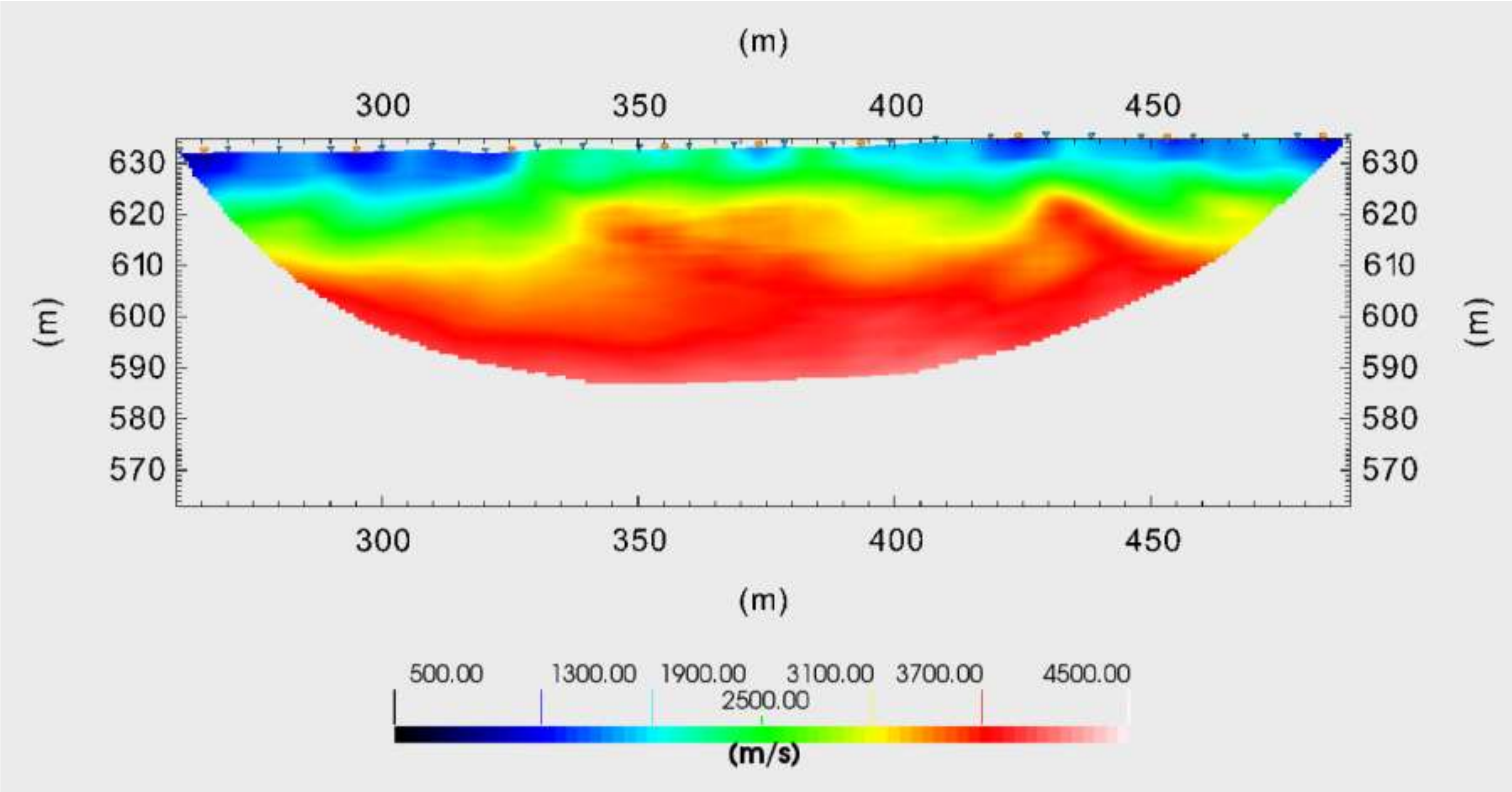
The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is very small at this bank. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extends upto RL 610-615m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3300m/s. The interface has almost flat topography. Most undulations are related to ray paths, which are eliminated when ray path smoothing algorithm is applied to data as under:



Right Bank- Profile-2: Unconstrained



Right Bank- Profile-2: Constrained

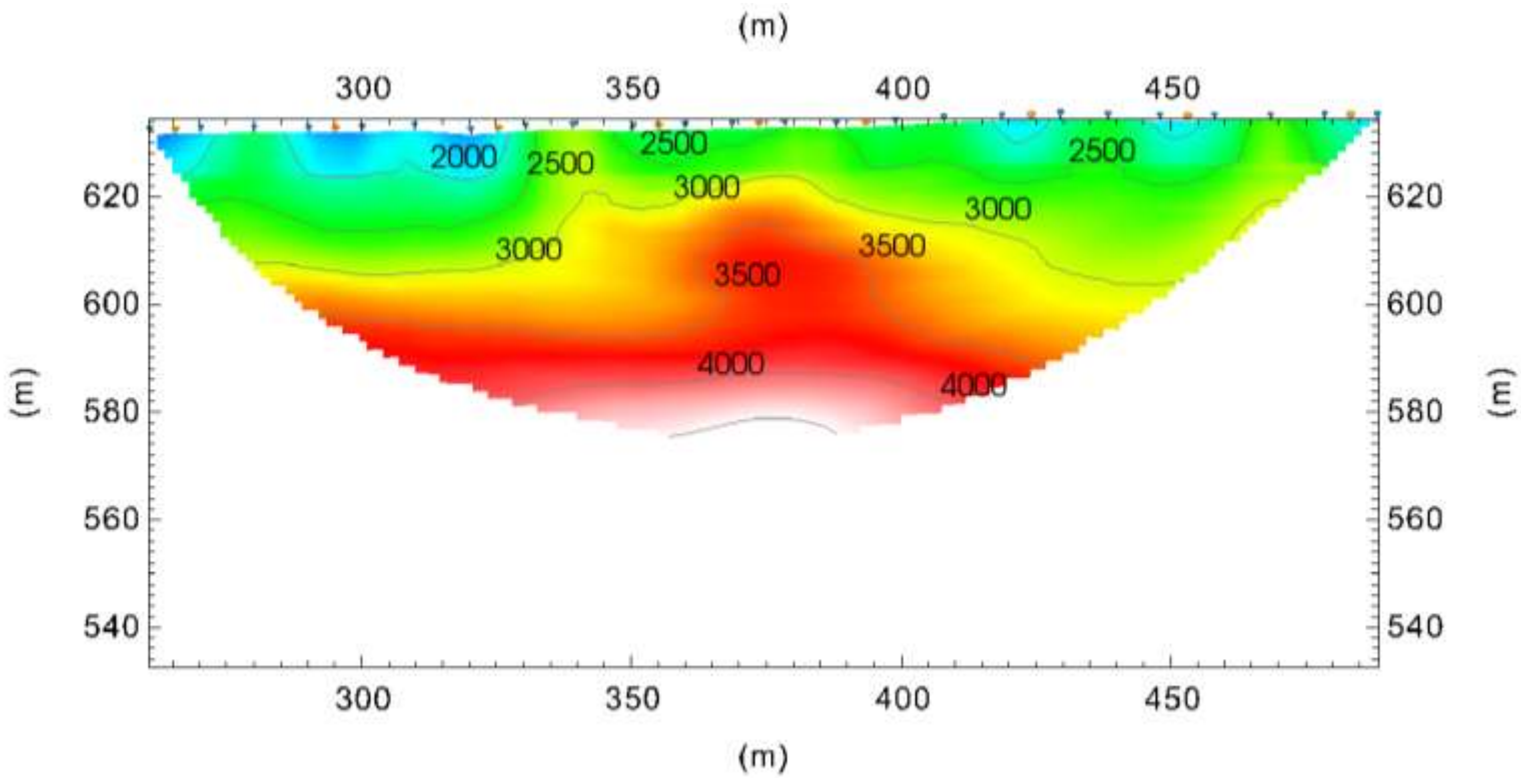


Discussions:

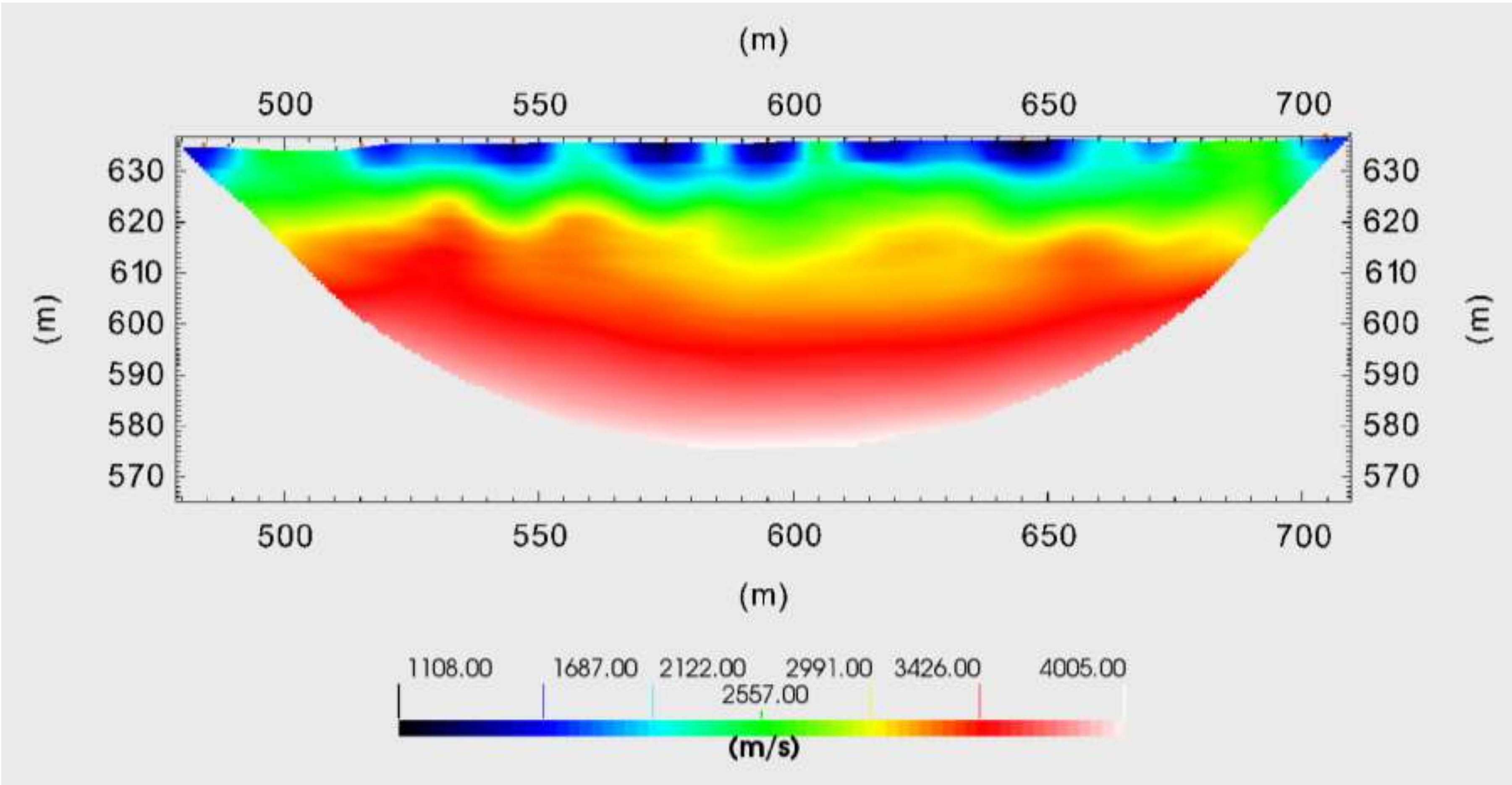
Seismic Source Used: Explosives

The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is shallow in central part of the profile.

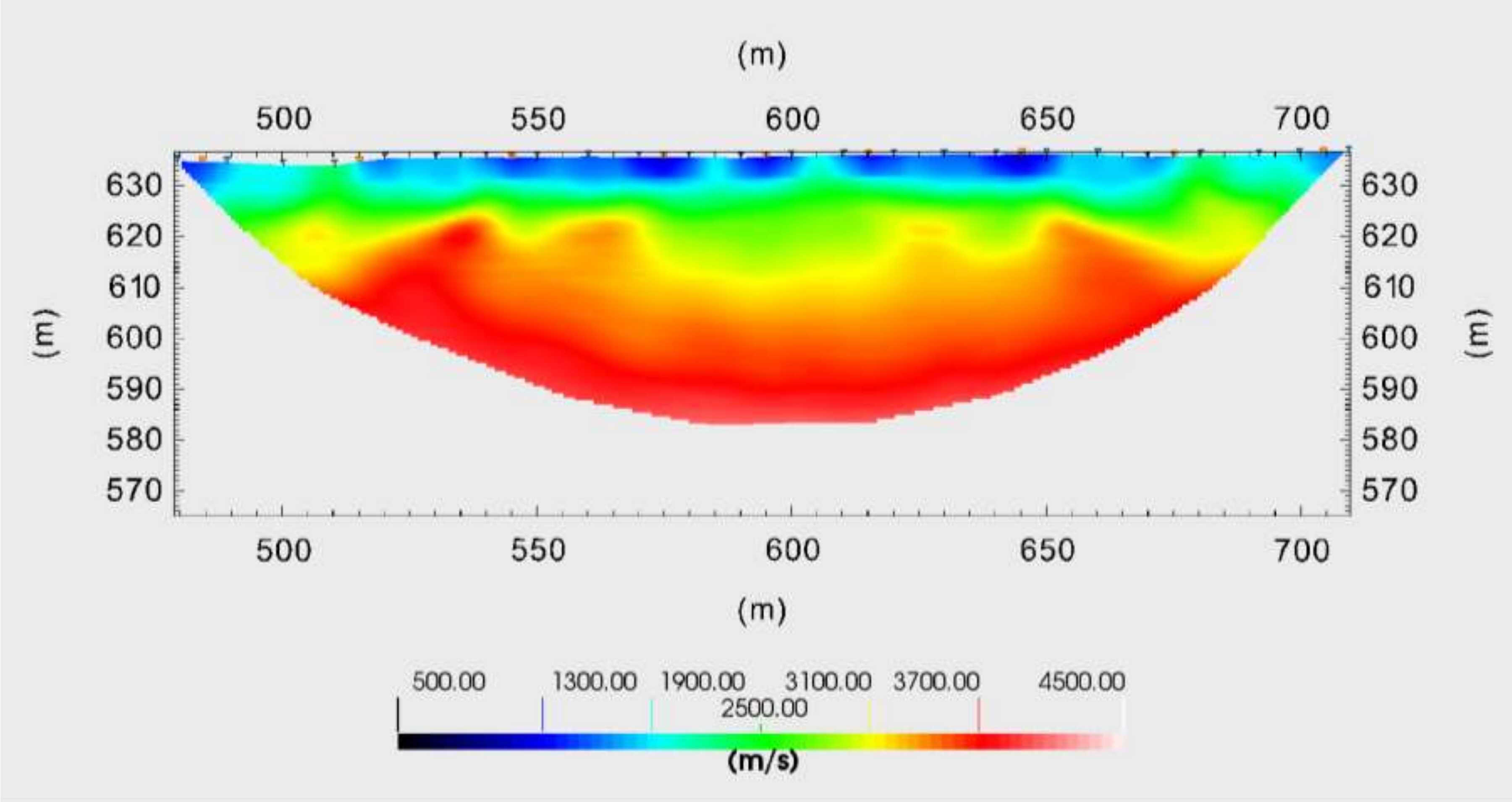
The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is very small at this bank. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extends upto RL 610-615m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3300m/s. Most small undulations are related to ray paths, which are eliminated when ray path smoothing algorithm is applied to data as under, leaving only the central part zone:



Right Bank- Profile-3: Unconstrained



Right Bank- Profile-3: Constrained

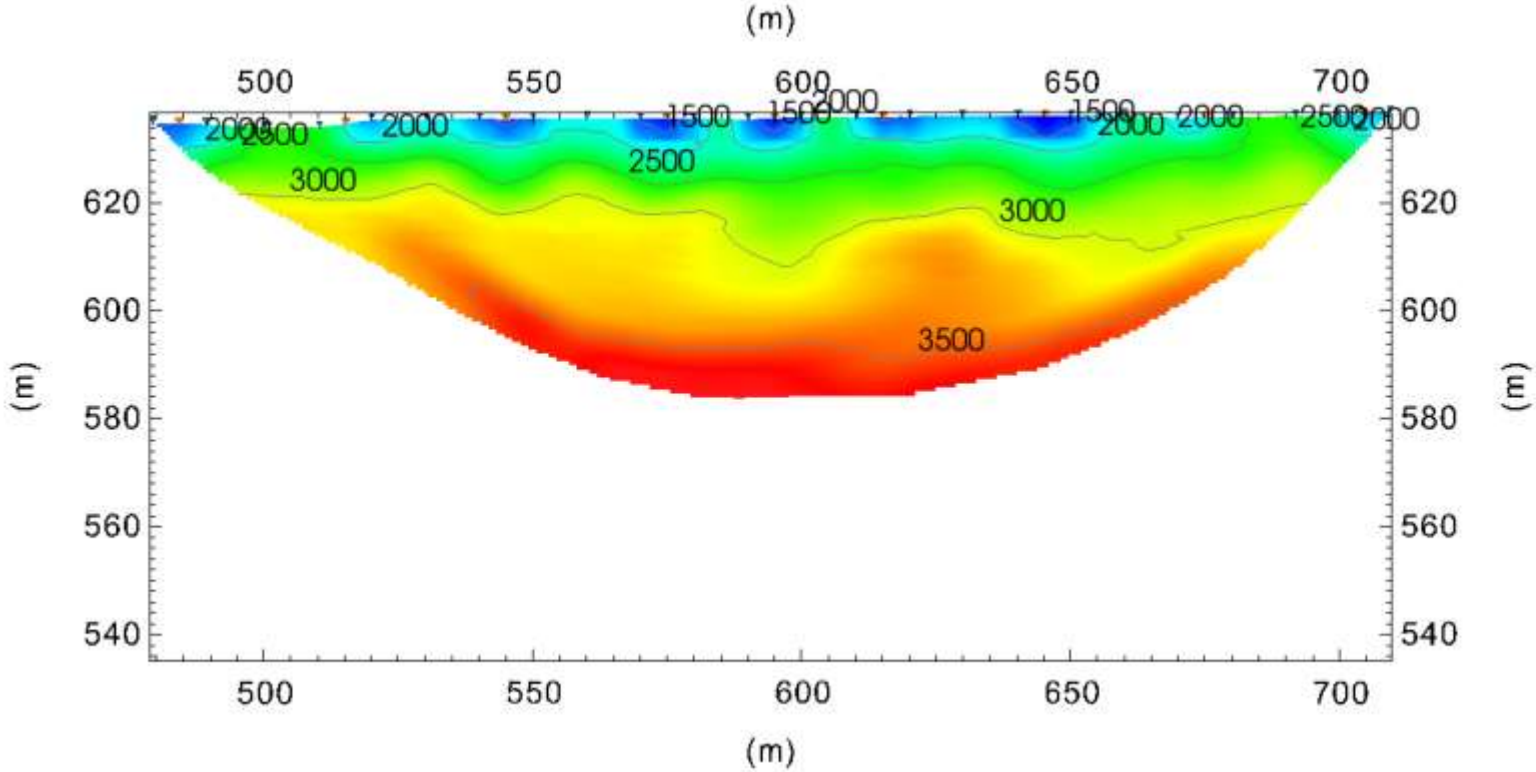


Discussions:

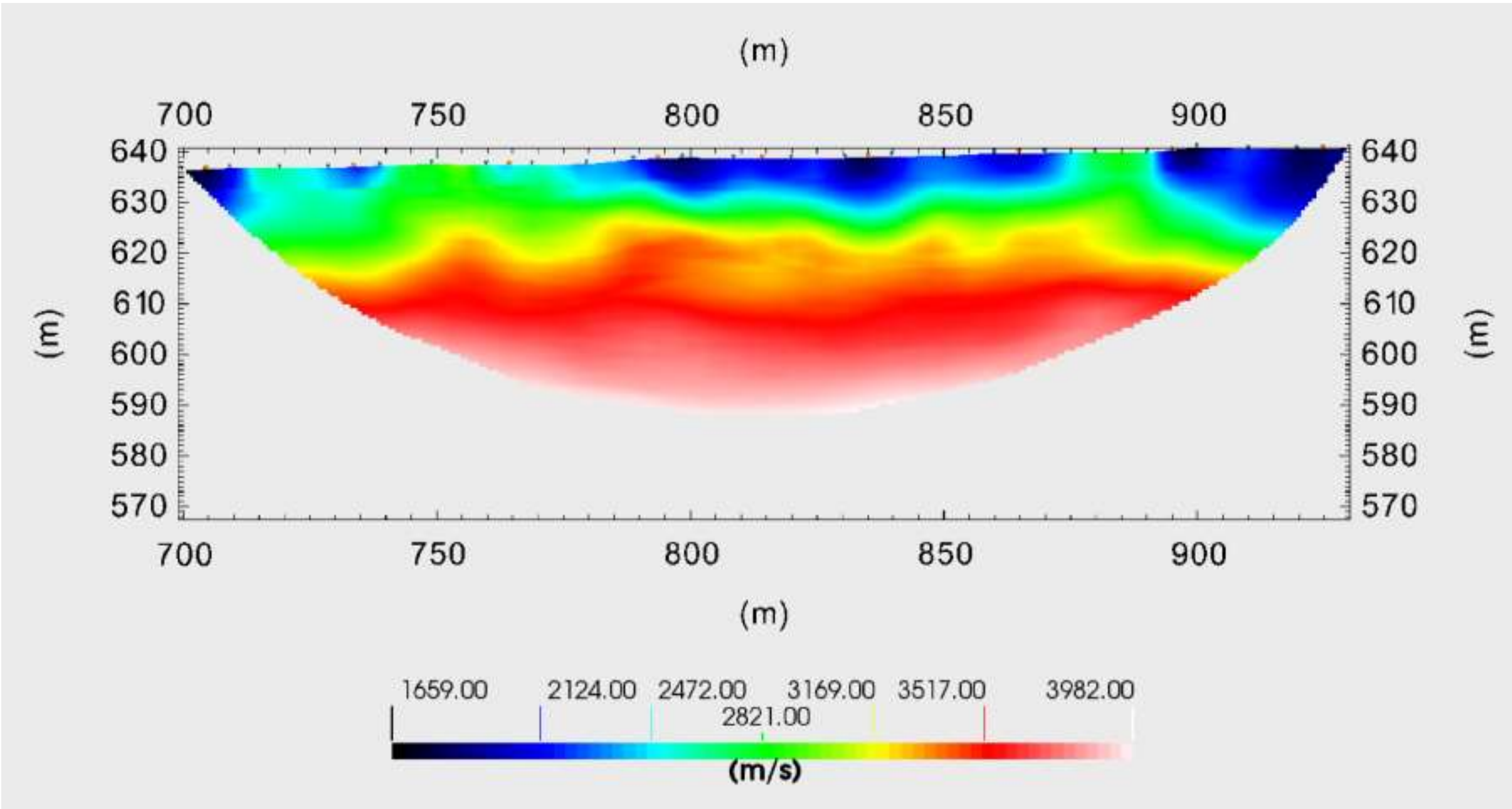
Seismic Source Used: Explosives

The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile.

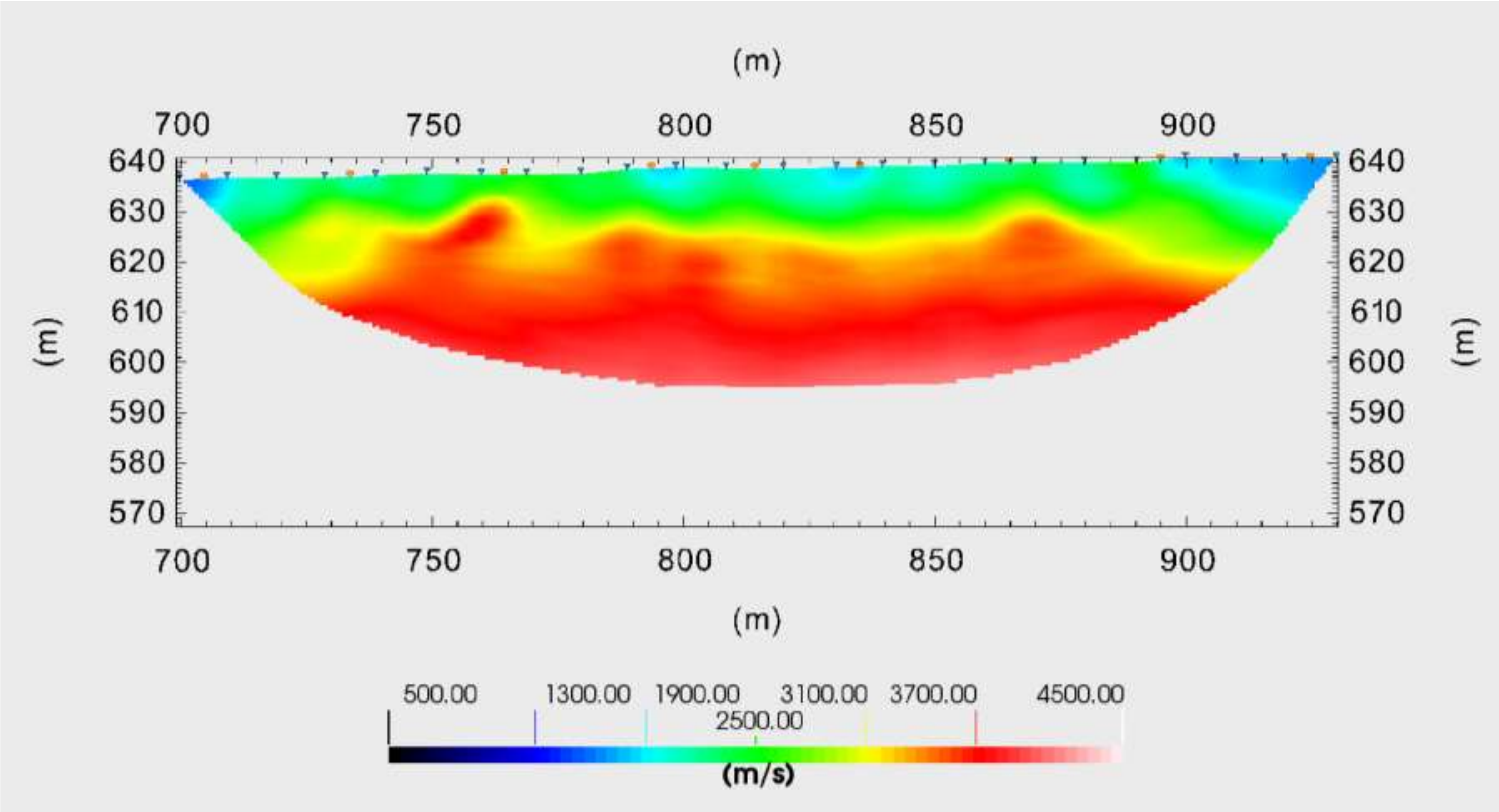
The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is very small at this bank. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extends upto RL 610-620m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3300m/s. Most small undulations are related to ray paths, which are eliminated when ray path smoothing algorithm is applied to data as under, leaving only the central part zone (slight deepening).



Right Bank- Profile-4: Unconstrained



Right Bank- Profile-4: Constrained



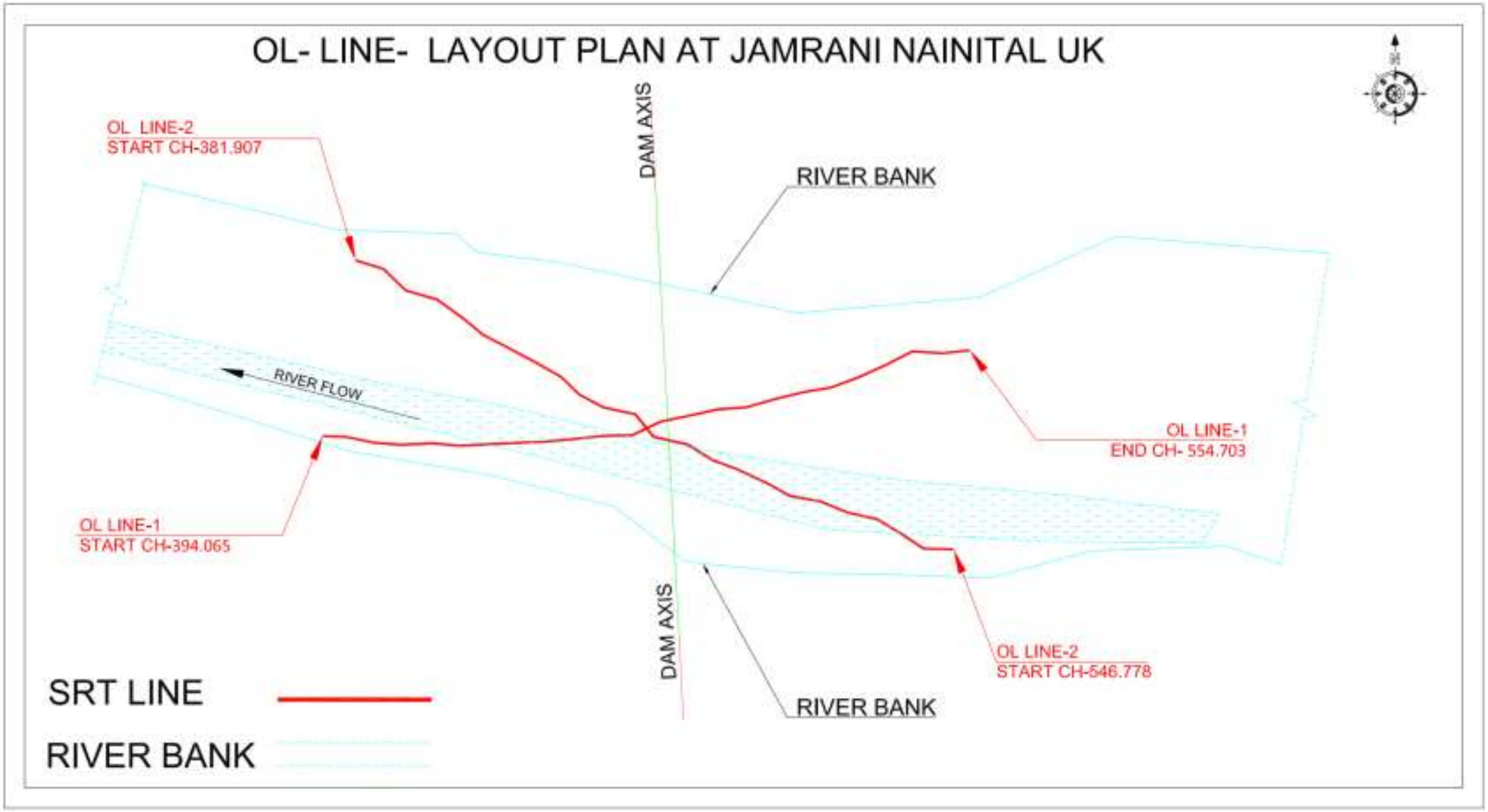
Discussions:

Seismic Source Used: Explosives

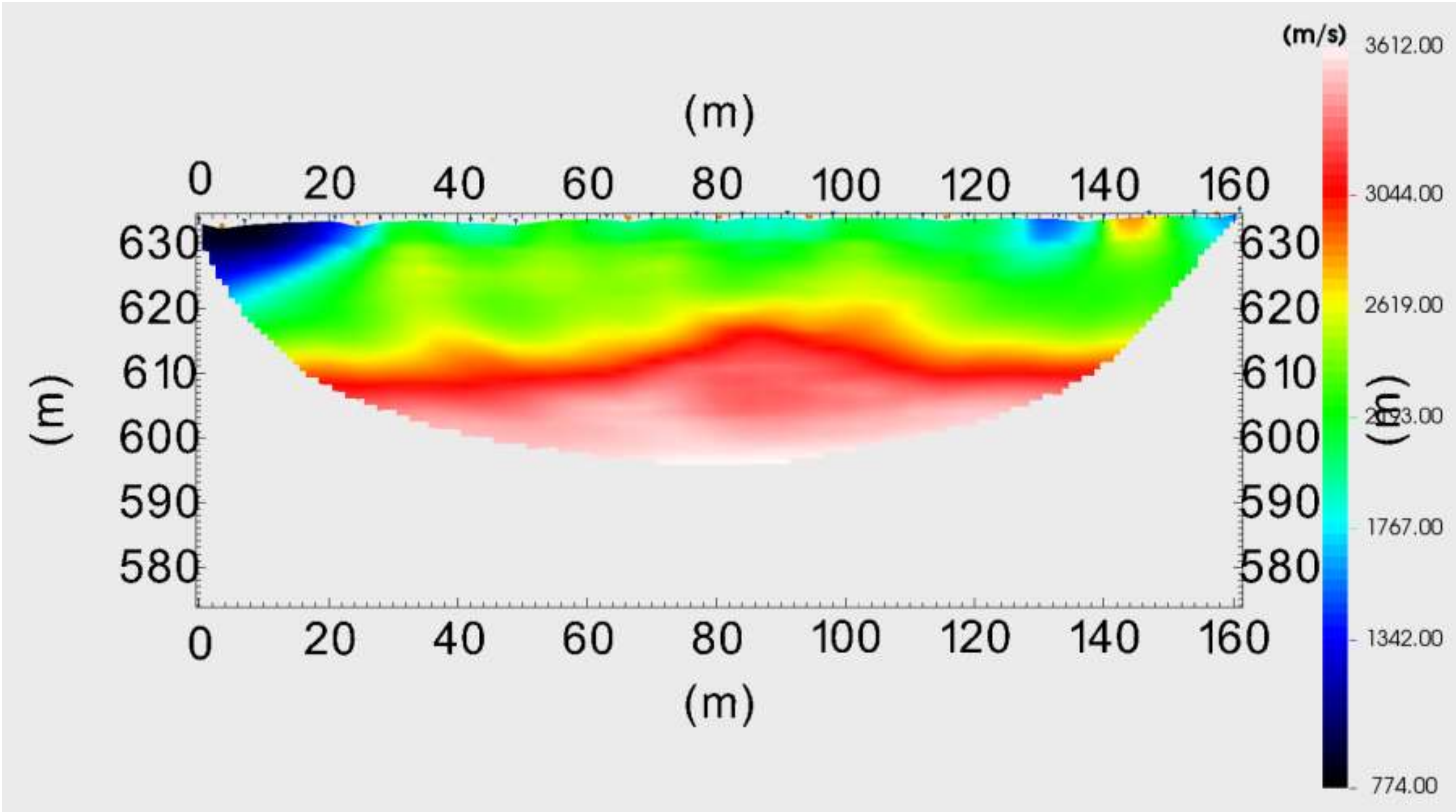
The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile.

The top layer (shades of blue) has low velocities corresponding to top overburden. The thickness of this layer is very small at this bank. This is underlain by a higher velocity layer (shades of green) which might correspond to compacted overburden material or weathered rock. The layer extends upto RL 610-620m. The last layer (shades of red after transition boundary in yellow) might correspond to rock with velocities exceeding 3300m/s.

Oblique Profiles Layout Plan:

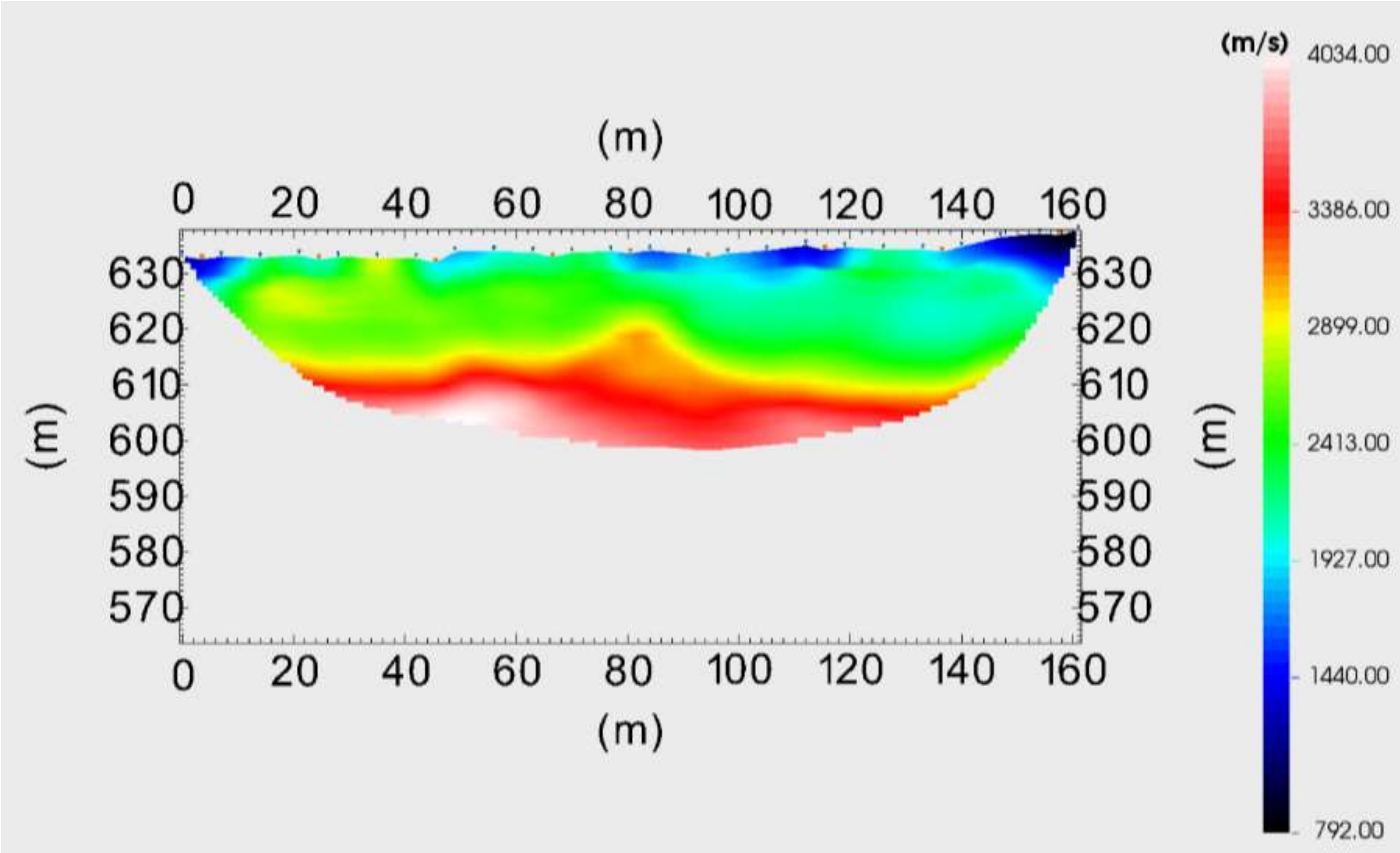


Oblique Profile-1:



Seismic source used- Explosives. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile.

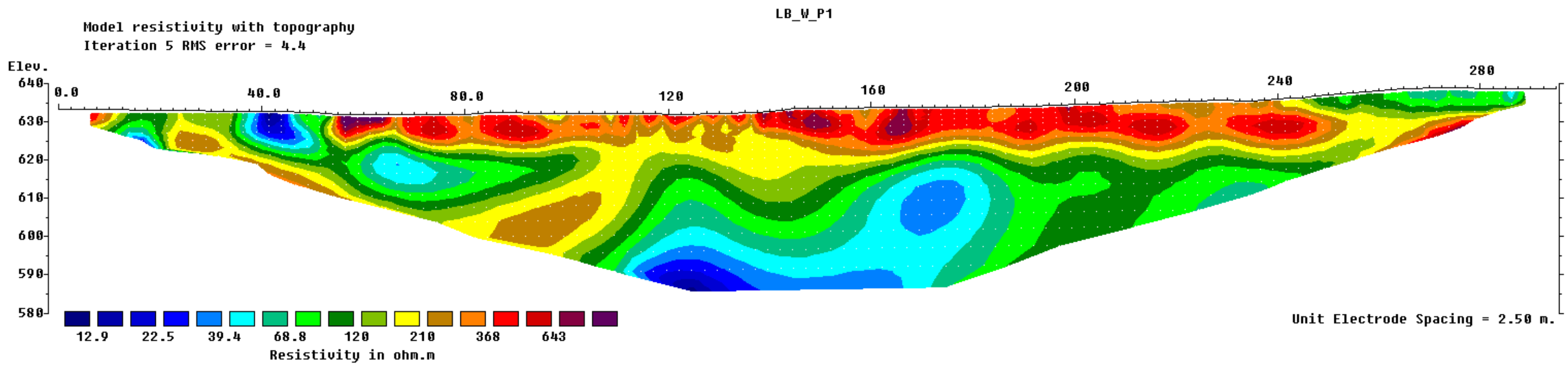
Oblique Profile-2:

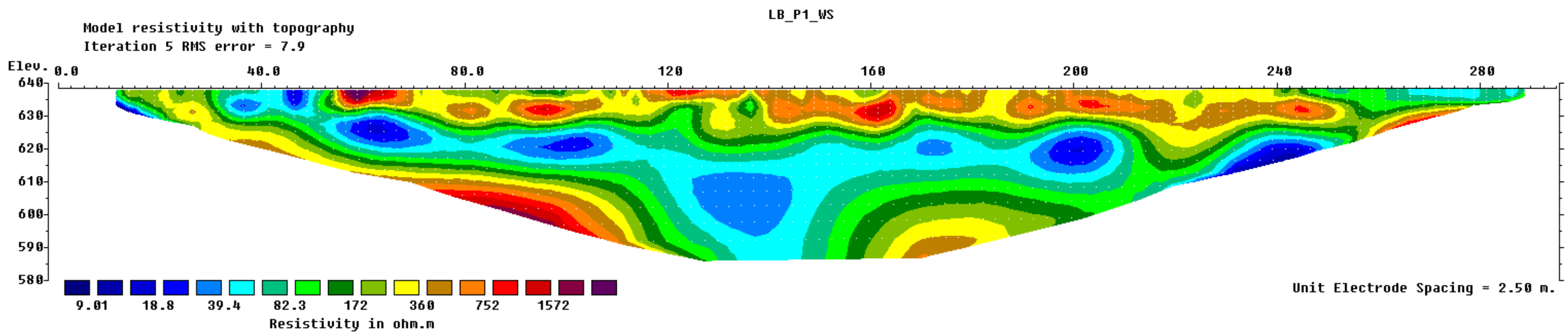


Seismic source used- Explosives. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile.

8 RESULTS- ELECTRICAL RESISTIVITY IMAGING

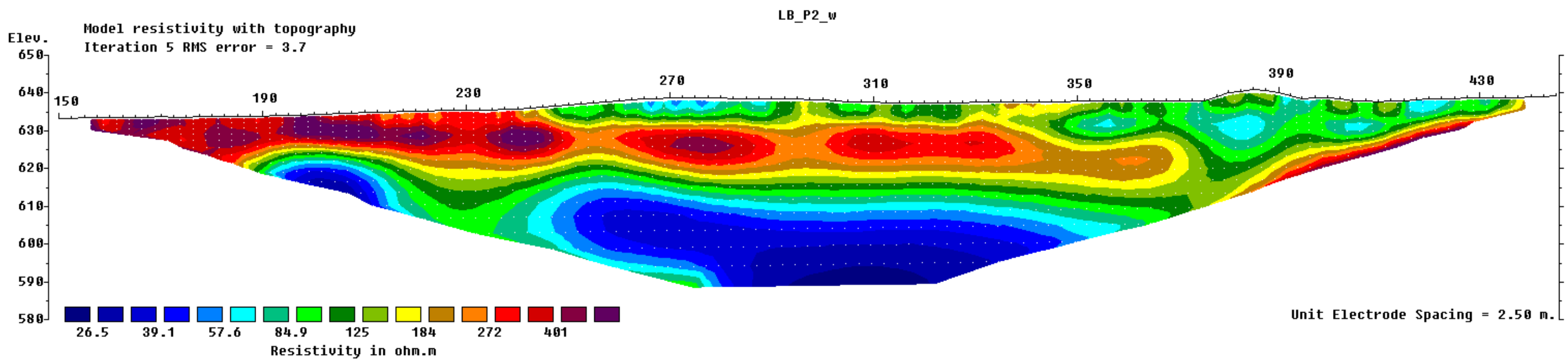
Left Bank- Profile-1:

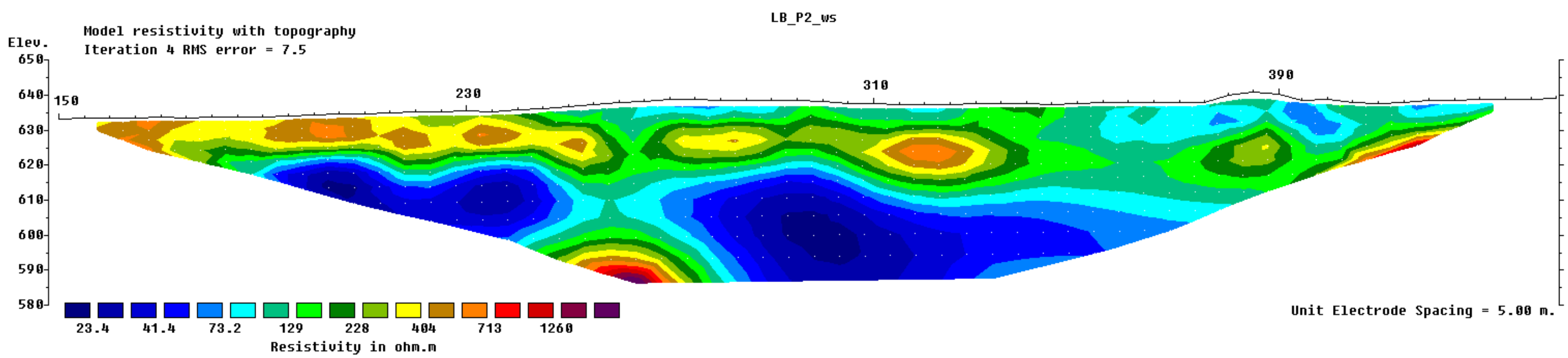




The resistivity profiles (wenner & wenner-schlumberger) shows a relatively high resistivity top strata (top boulder dry layer), and low resistivities in middle layer, indicating of higher water presence. WS profile shows high resistivity strata in deeper part of the profile, which is discontinued in middle of the profile. Results indicate secondary porosity in rock layer, leading to observed low resistivity values.

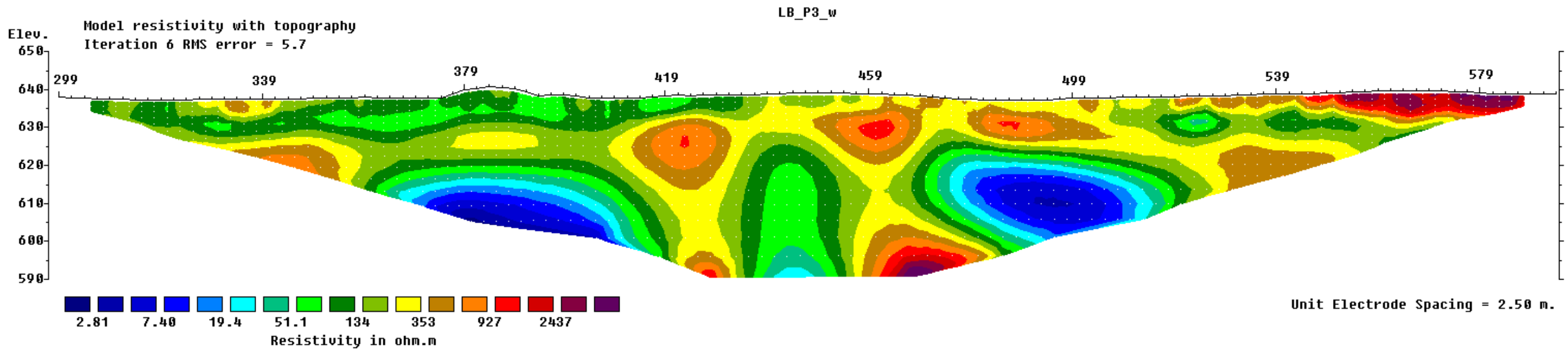
Left Bank- Profile-2:

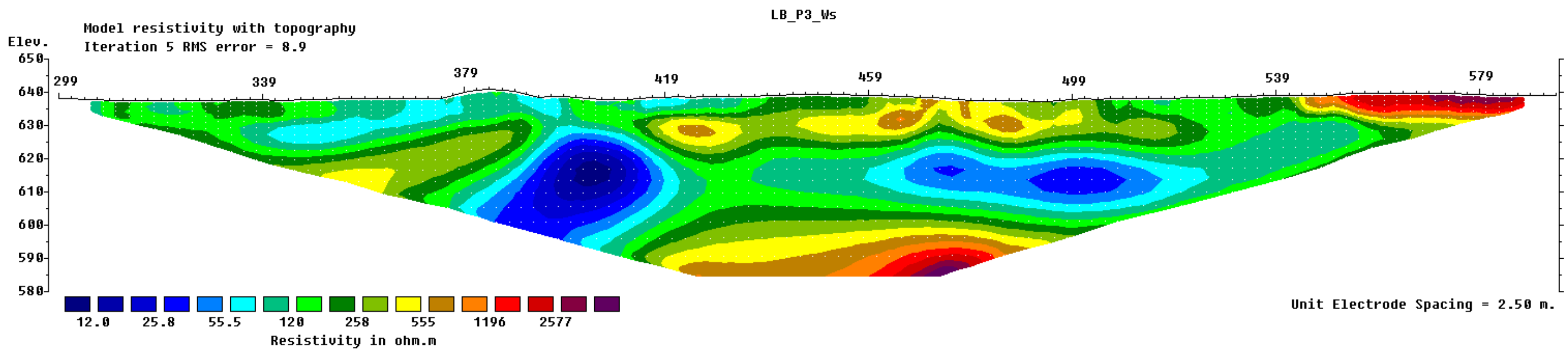




The resistivity profiles (wenner & wenner-schlumberger) shows a relatively high resistivity top strata (top boulder dry layer), and low resistivities in bottom layer, indicating of higher water presence. As per SRT profile this layer correspond to rock, and hence low resistivities indicate presence of water in secondary pore spaces in this layer.

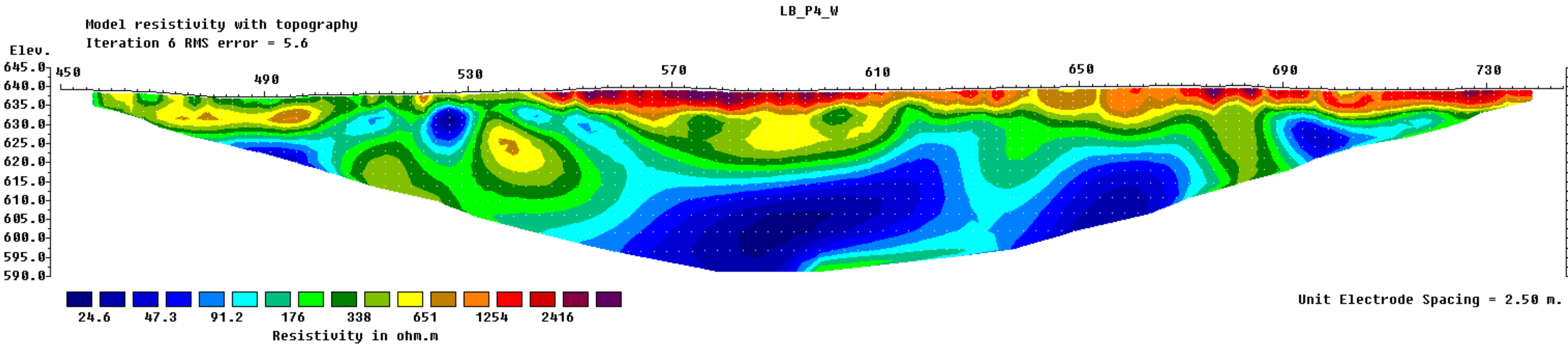
Left Bank- Profile-3:

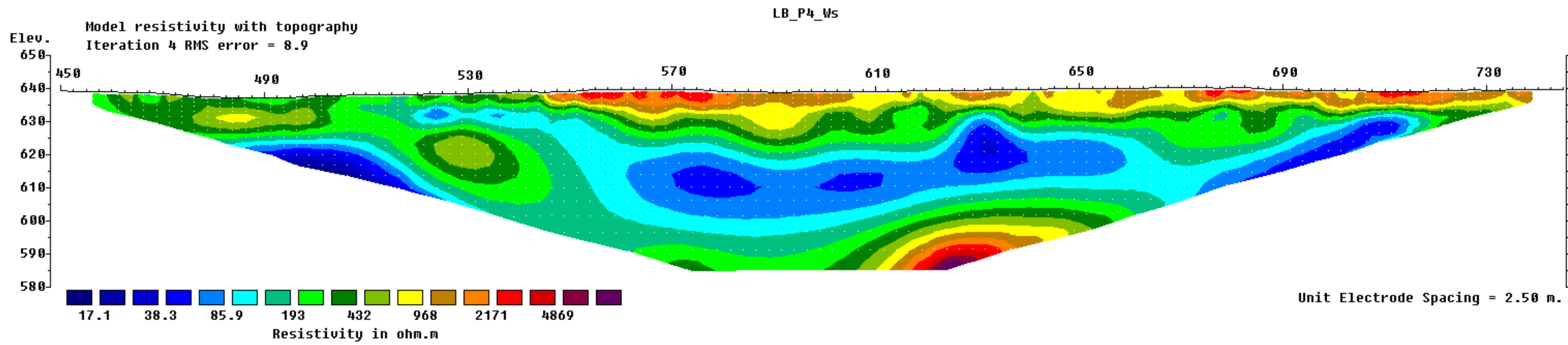




The resistivity profiles (wenner & wenner-schlumberger) shows low resistivities in middle layer, indicating of higher water presence. WS profile shows high resistivity strata in deeper part of the profile. The low resistivity zones falling within rock layer (as indicated in SRT results) might correspond to high degree of secondary porosity.

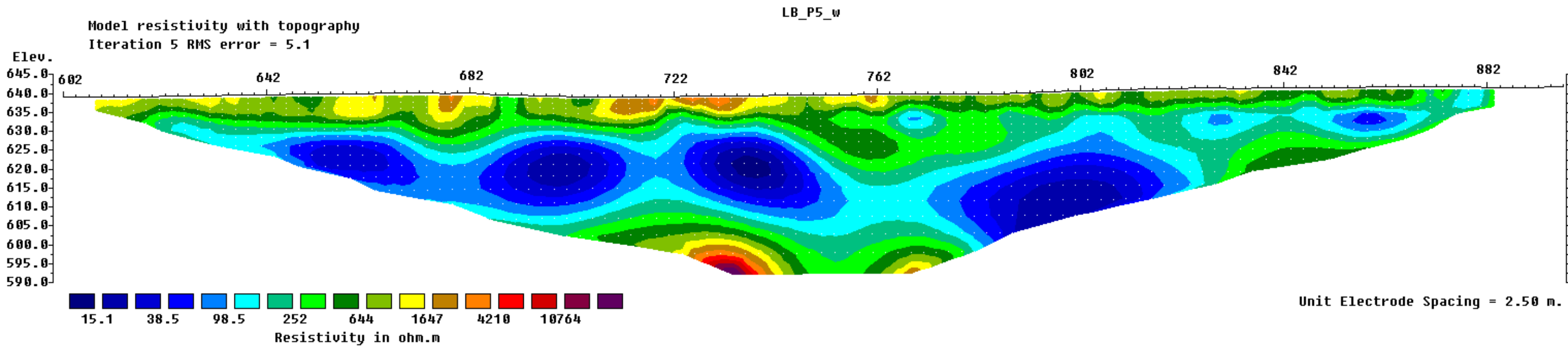
Left Bank- Profile-4:

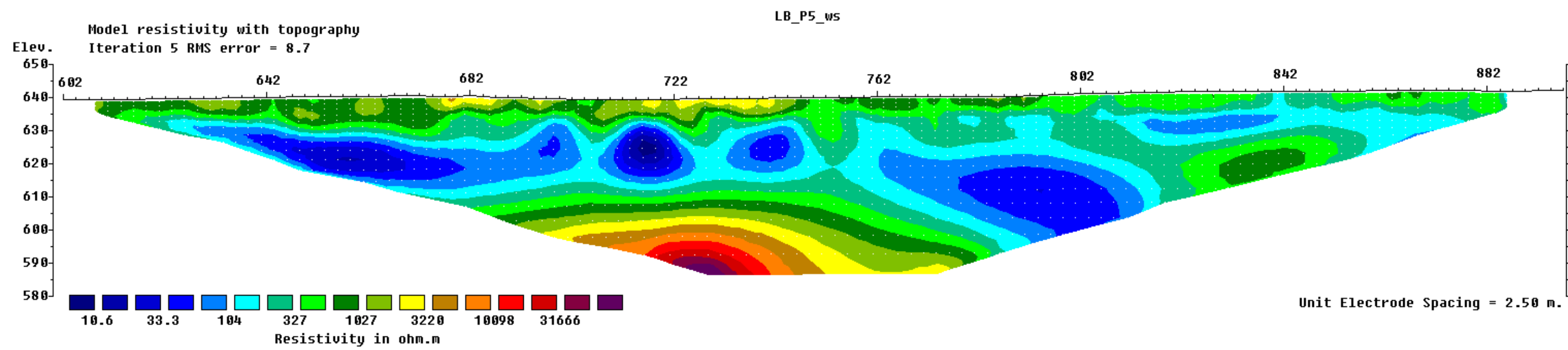




The resistivity profiles (wenner & wenner-schlumberger) shows low resistivities in middle layer, indicating of higher water presence. WS profile shows high resistivity strata in right side of deeper part of the profile. Low resistivities in the middle layer indicate presence of water in secondary pore spaces in this layer.

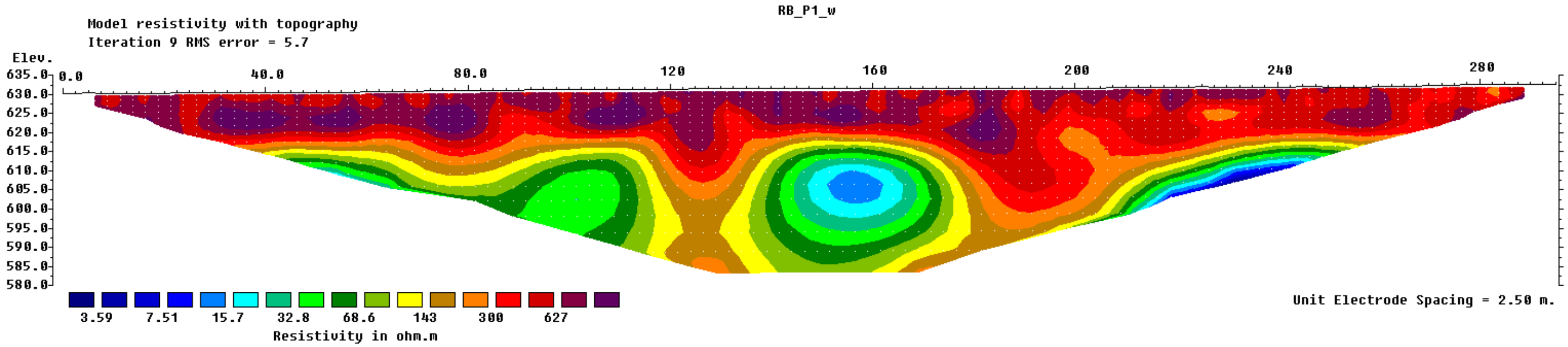
Left Bank- Profile-5:

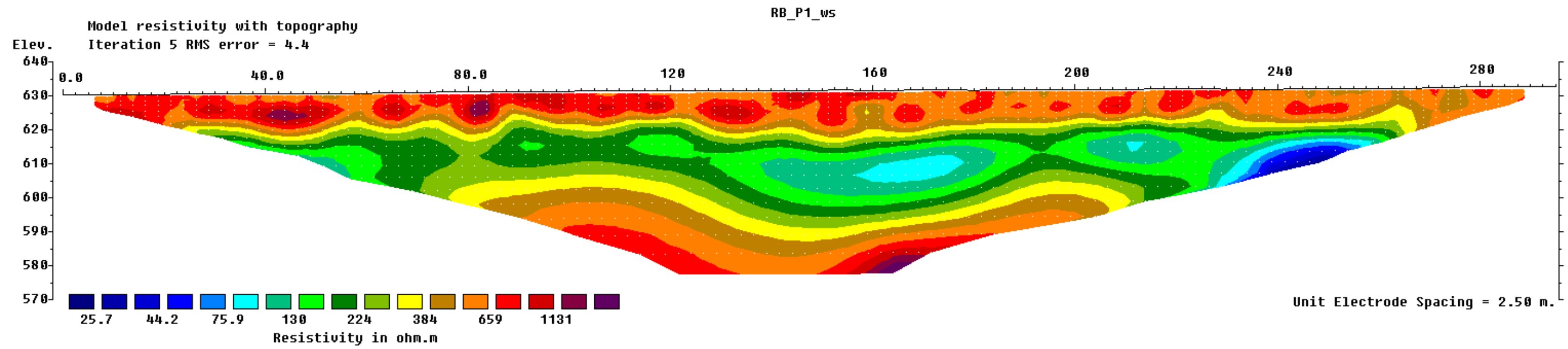




The resistivity profiles (wenner & wenner-schlumberger) shows low resistivities in middle layer, indicating of higher water presence. W and WS profile shows high resistivity strata in deeper part of the profile. Low resistivities in the middle layer indicate presence of water in secondary pore spaces in this layer.

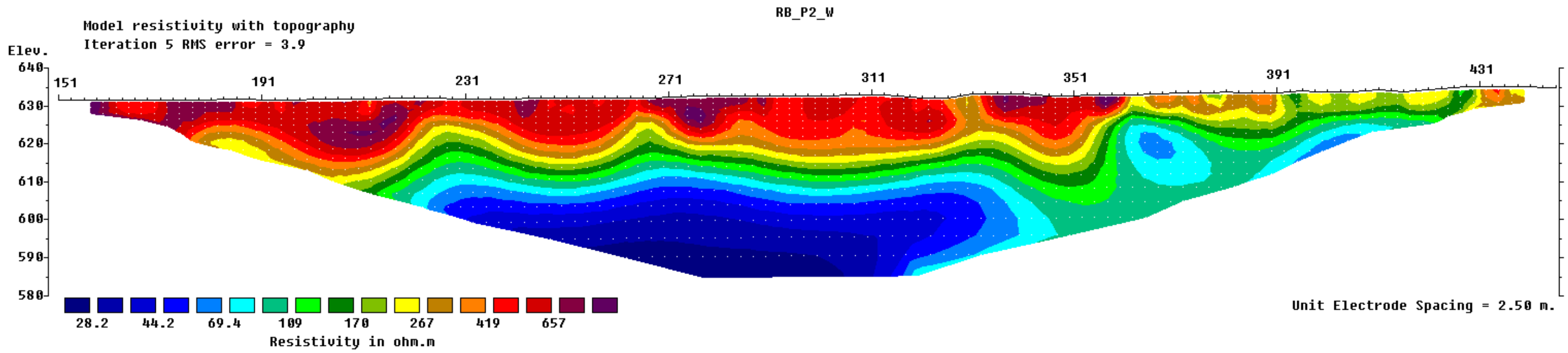
Right Bank- Profile-1:

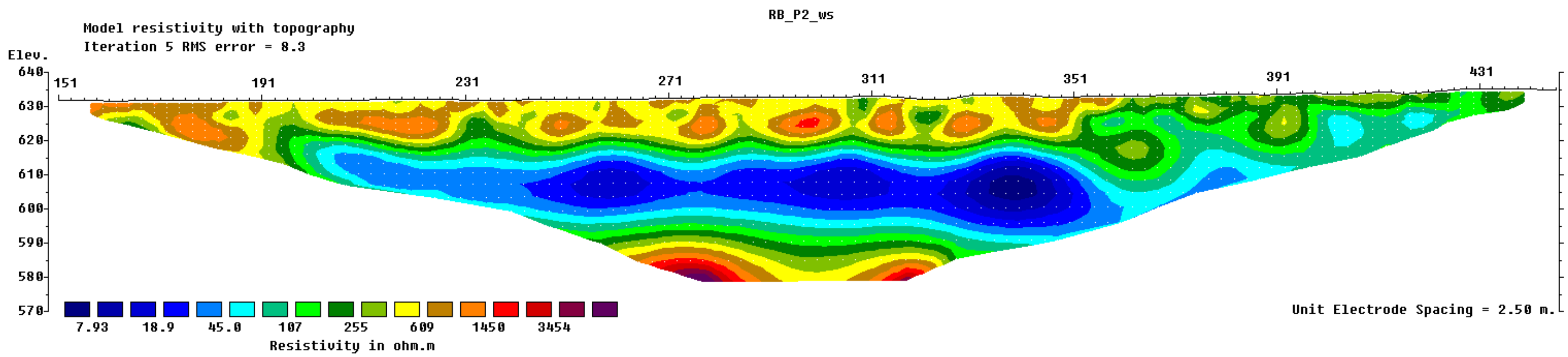




The resistivity profiles (wenner & wenner-schlumberger) shows low resistivities in middle layer, indicating of higher water presence. WS profile shows high resistivity strata in deeper part of the profile. Low resistivities in the middle layer indicate presence of water in secondary pore spaces in this layer.

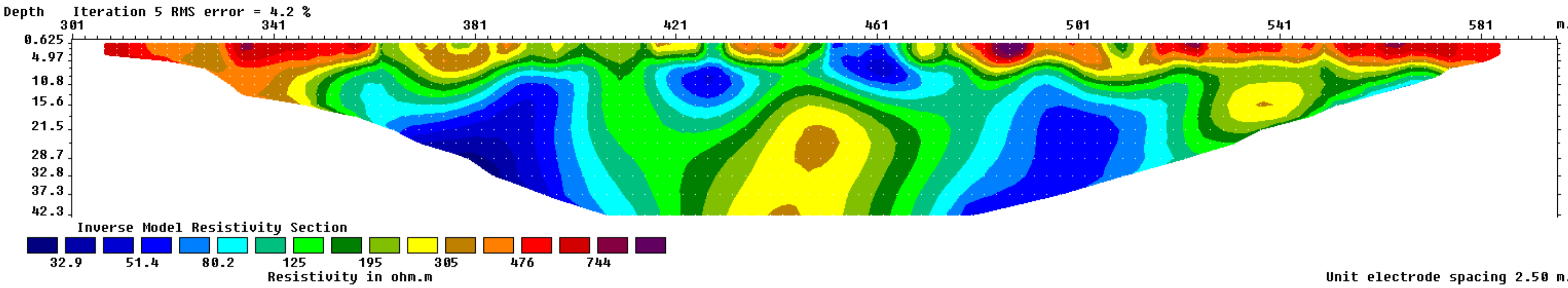
Right Bank- Profile-2:

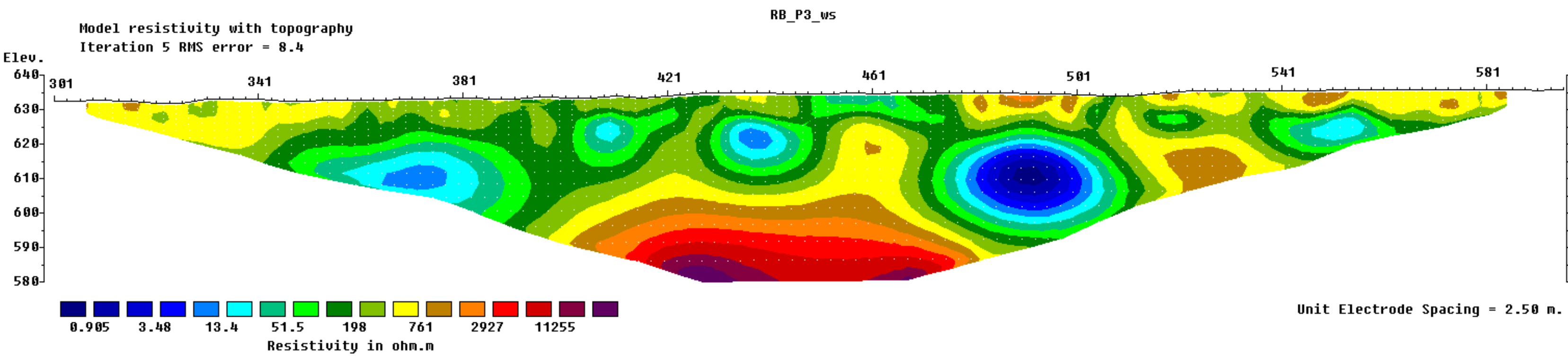




The resistivity profiles (wenner & wenner-schlumberger) shows low resistivities in middle layer, indicating of higher water presence. WS profile shows high resistivity strata in deeper part of the profile. Low resistivities in the middle layer indicate presence of water in secondary pore spaces in this layer.

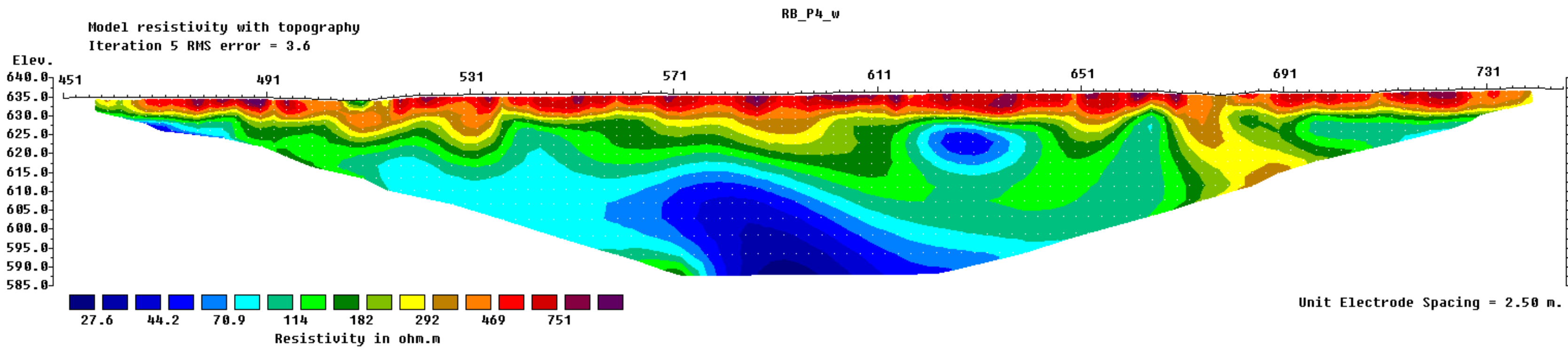
Right Bank- Profile-3:

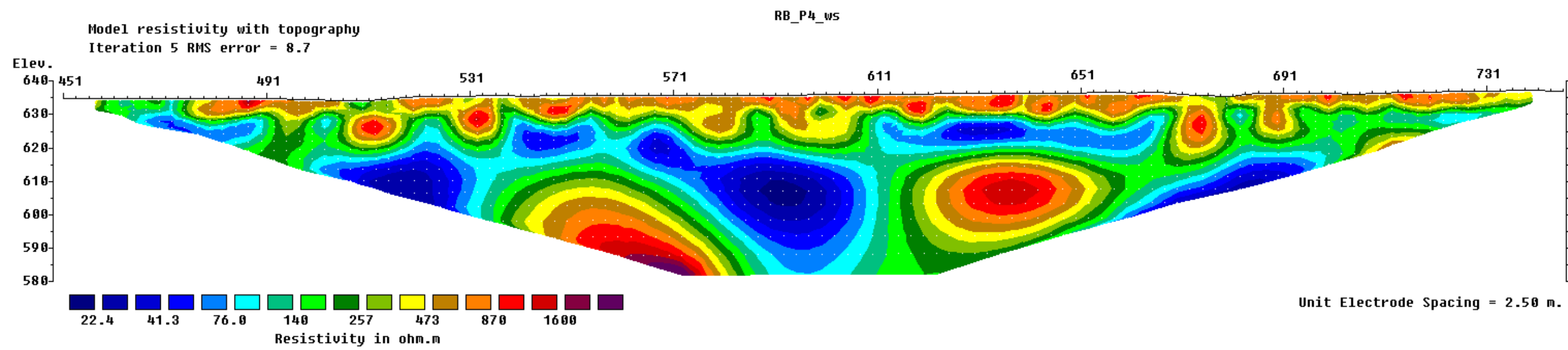




The profiles show low resistivity zones in middle layer with lateral heterogeneity. WS profile shows high resistivity strata in deeper central part of the profile. The low resistivity zones falling within rock layer (as indicated in SRT results) might correspond to high degree of secondary porosity.

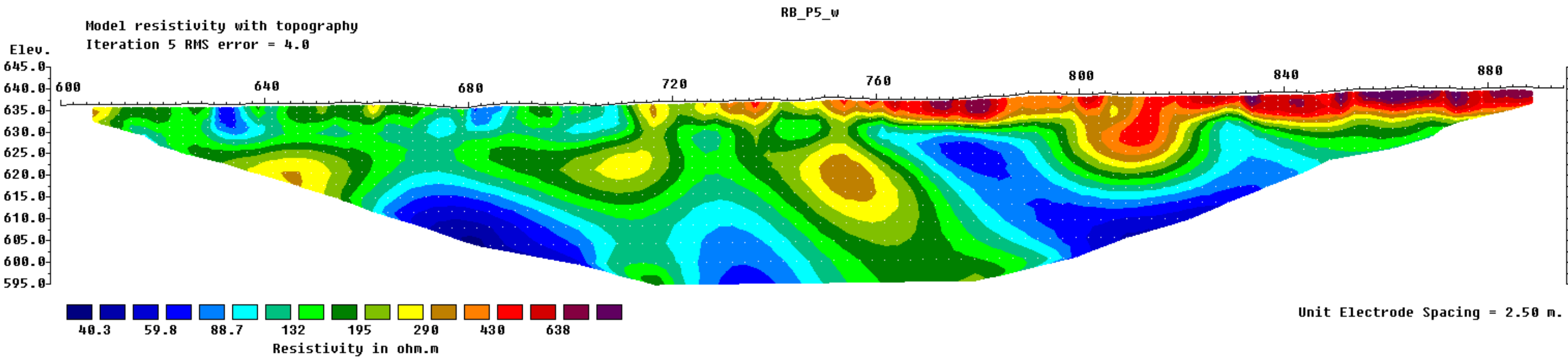
Right Bank- Profile-4:

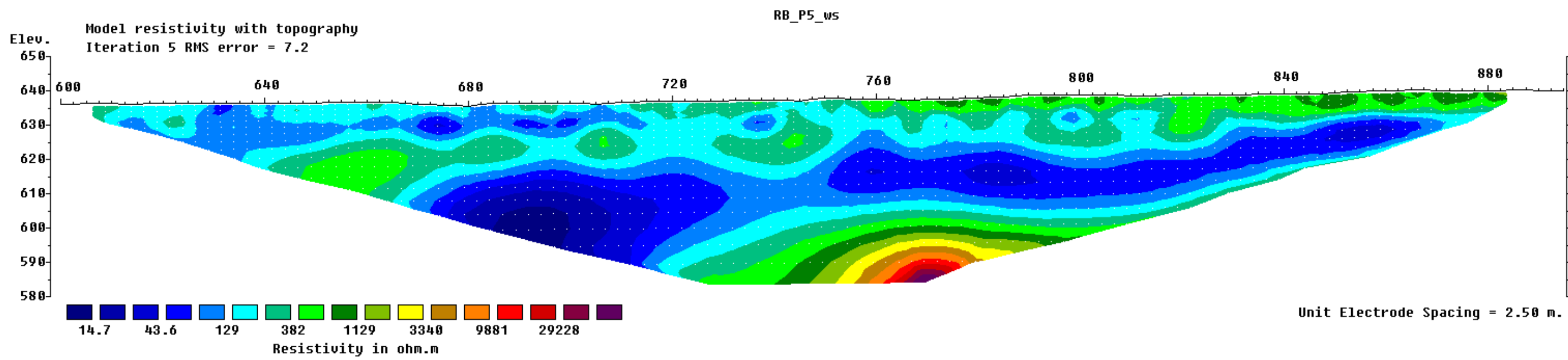




The profiles show low resistivity zones in middle layer with lateral heterogeneity. Since WS array is more sensitive for changes in lateral direction, there is a significant different between the profiles obtained under the two profiles. The low resistivity zones falling within rock layer (as indicated in SRT results) might correspond to high degree of secondary porosity.

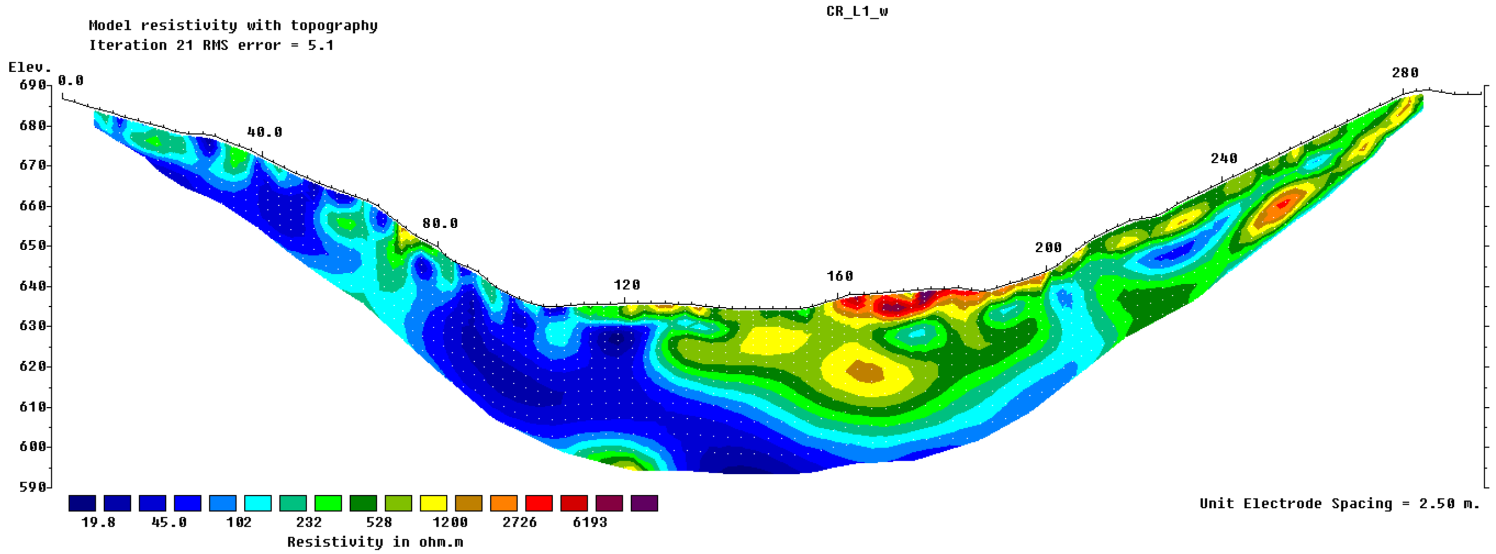
Right Bank- Profile-5:

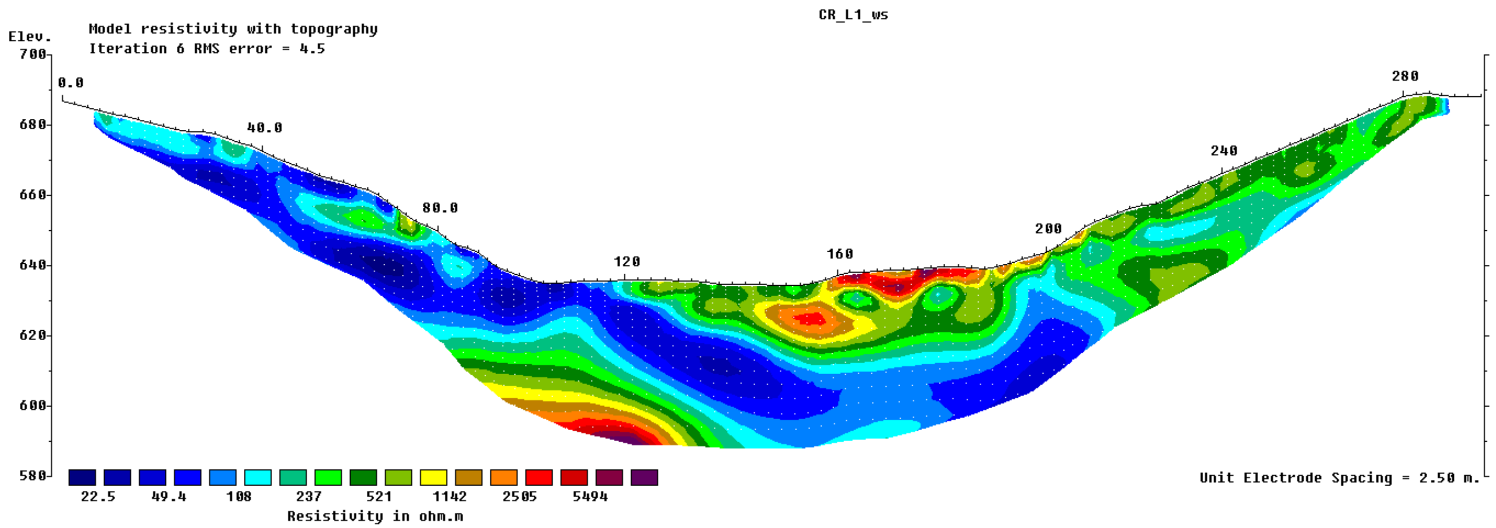




The profiles show low resistivity zones in middle layer with lateral heterogeneity. Since WS array is more sensitive for changes in lateral direction, there is a significant different between the profiles obtained under the two profiles. The low resistivity zones falling within rock layer (as indicated in SRT results) might correspond to high degree of secondary porosity.

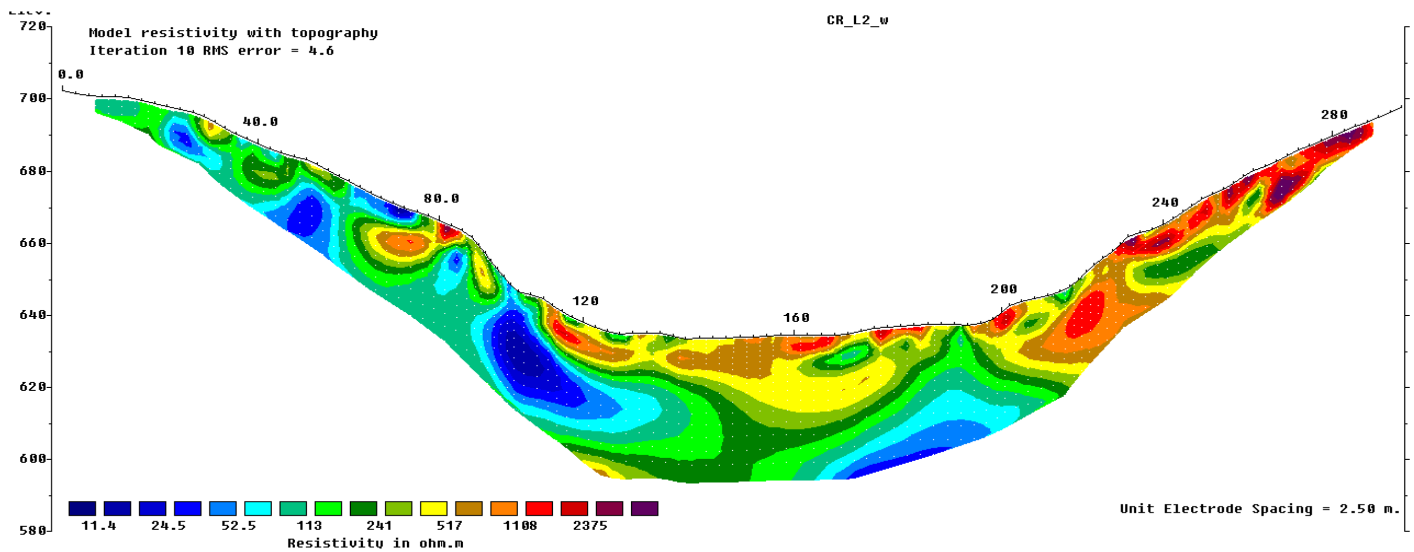
Crossline-Upstream:

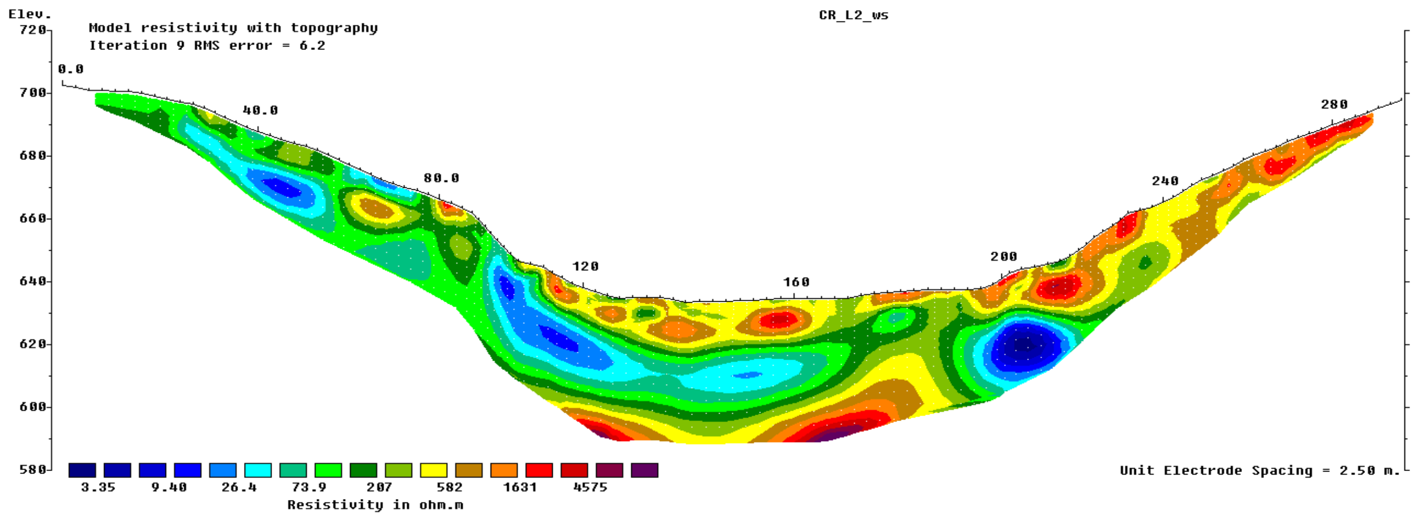




The profiles show lower resistivity values in middle layer of the profile.

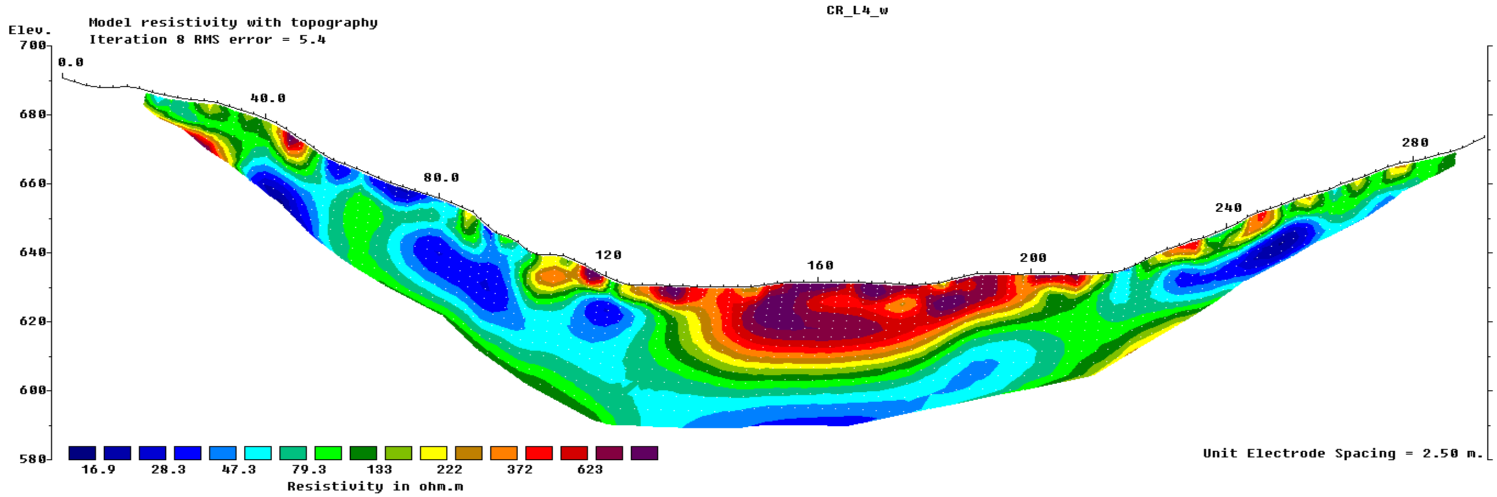
Crossline-Drift:

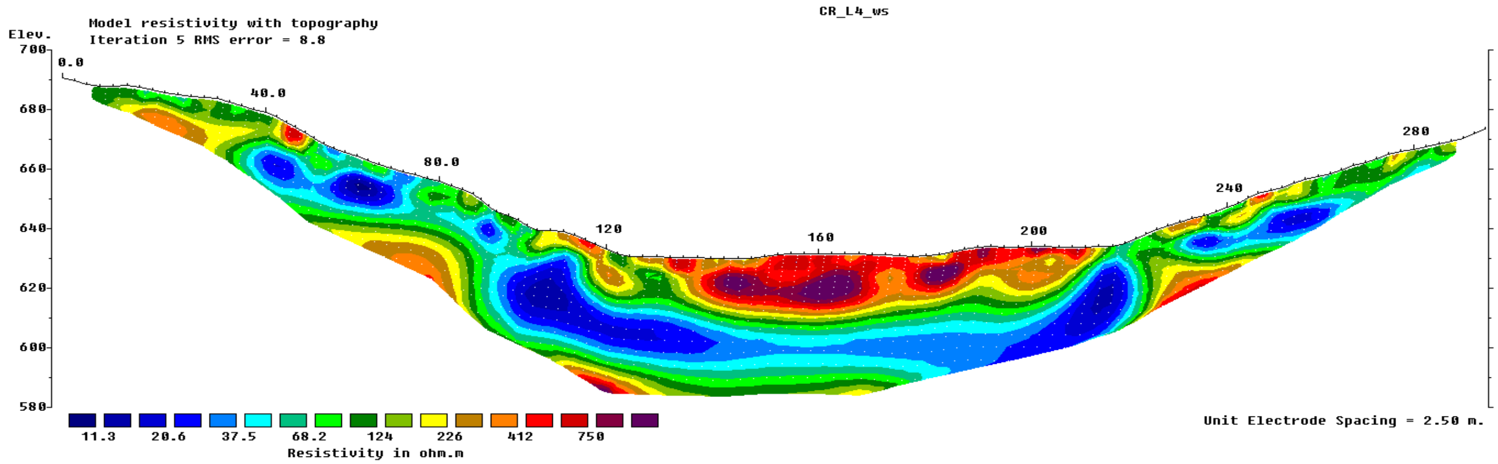




The profile shows presence of high resistivity layer at deeper part in WS profile

Crossline-Downstream:

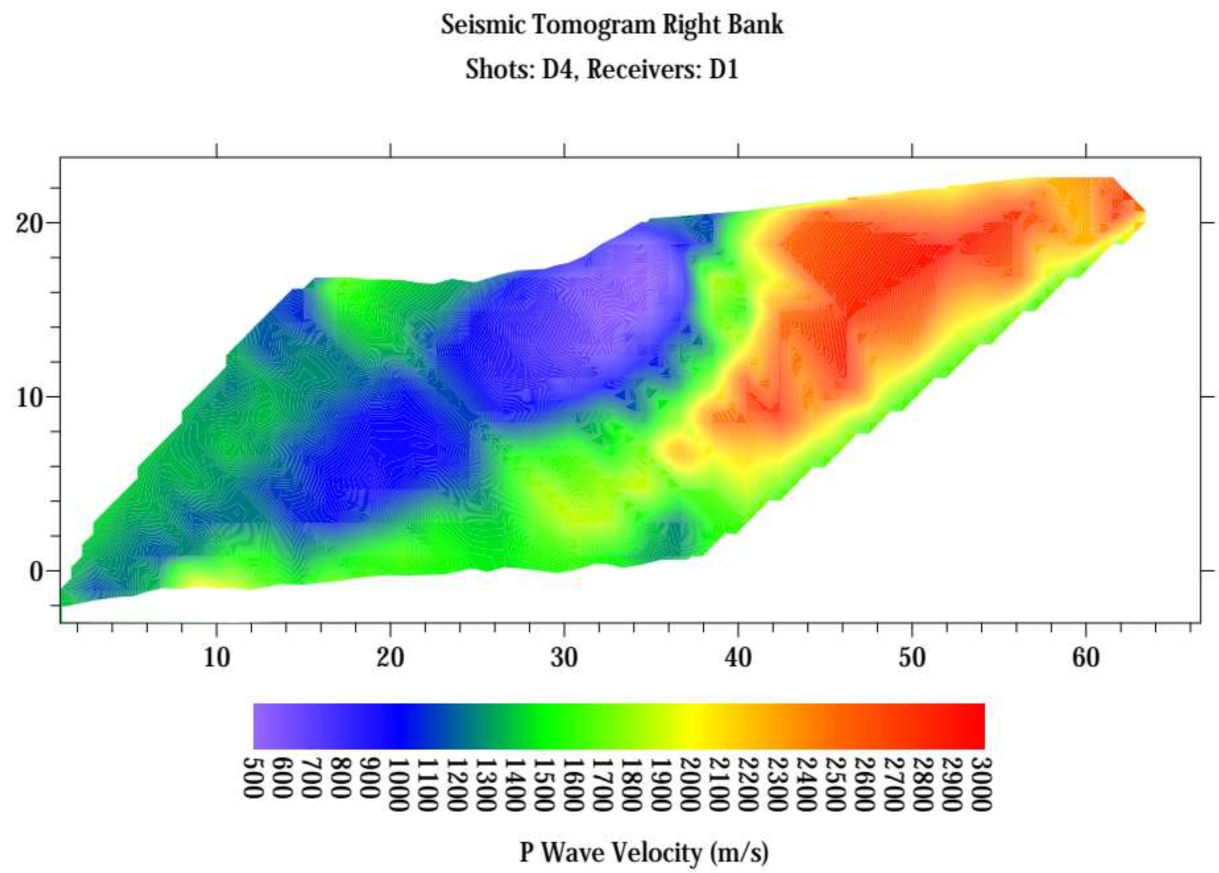




The profile shows a high resistivity middle top layer.

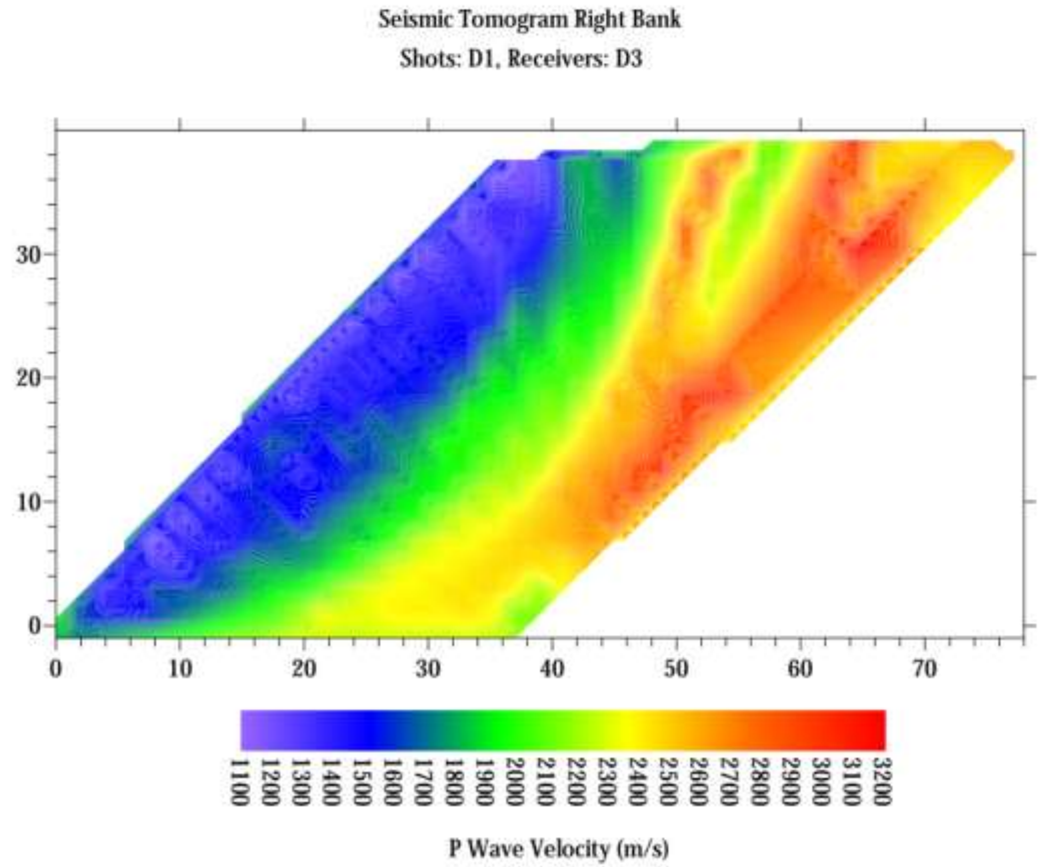
9 RESULTS- DRIFT TOMOGRAPHY

Right Bank: Source D-4, Geophone D-1



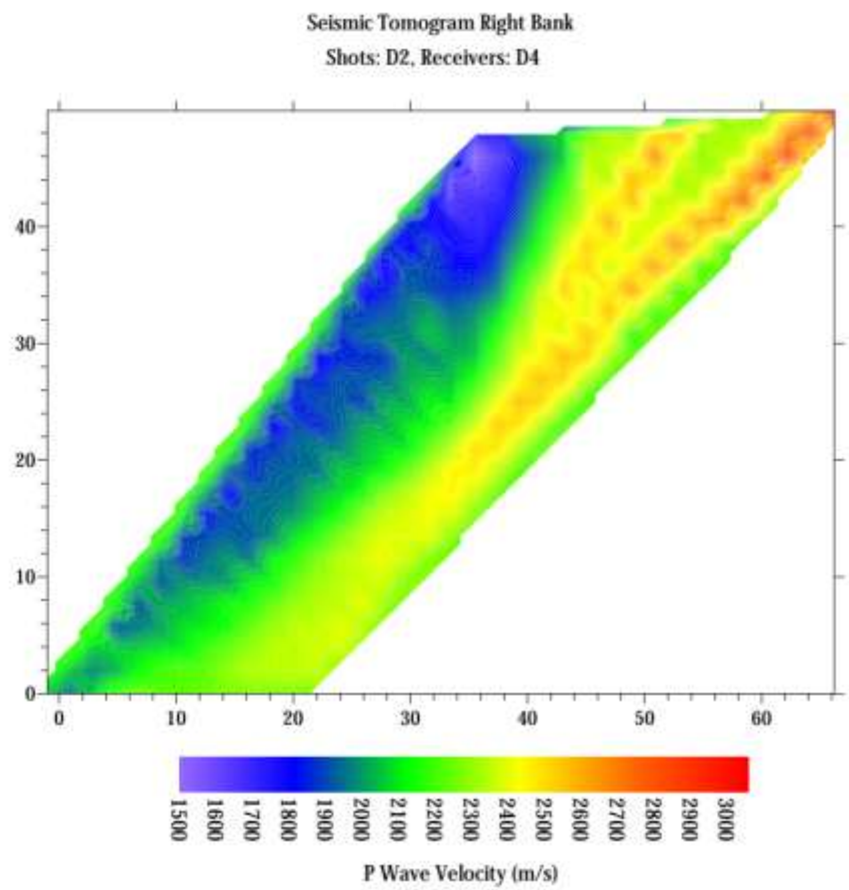
The tomogram shows high velocities in deeper part of drifts. Most of the area has a velocity in the range of 1900 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 500-800 m/s.

Right Bank: Source D-1, Geophone D-3



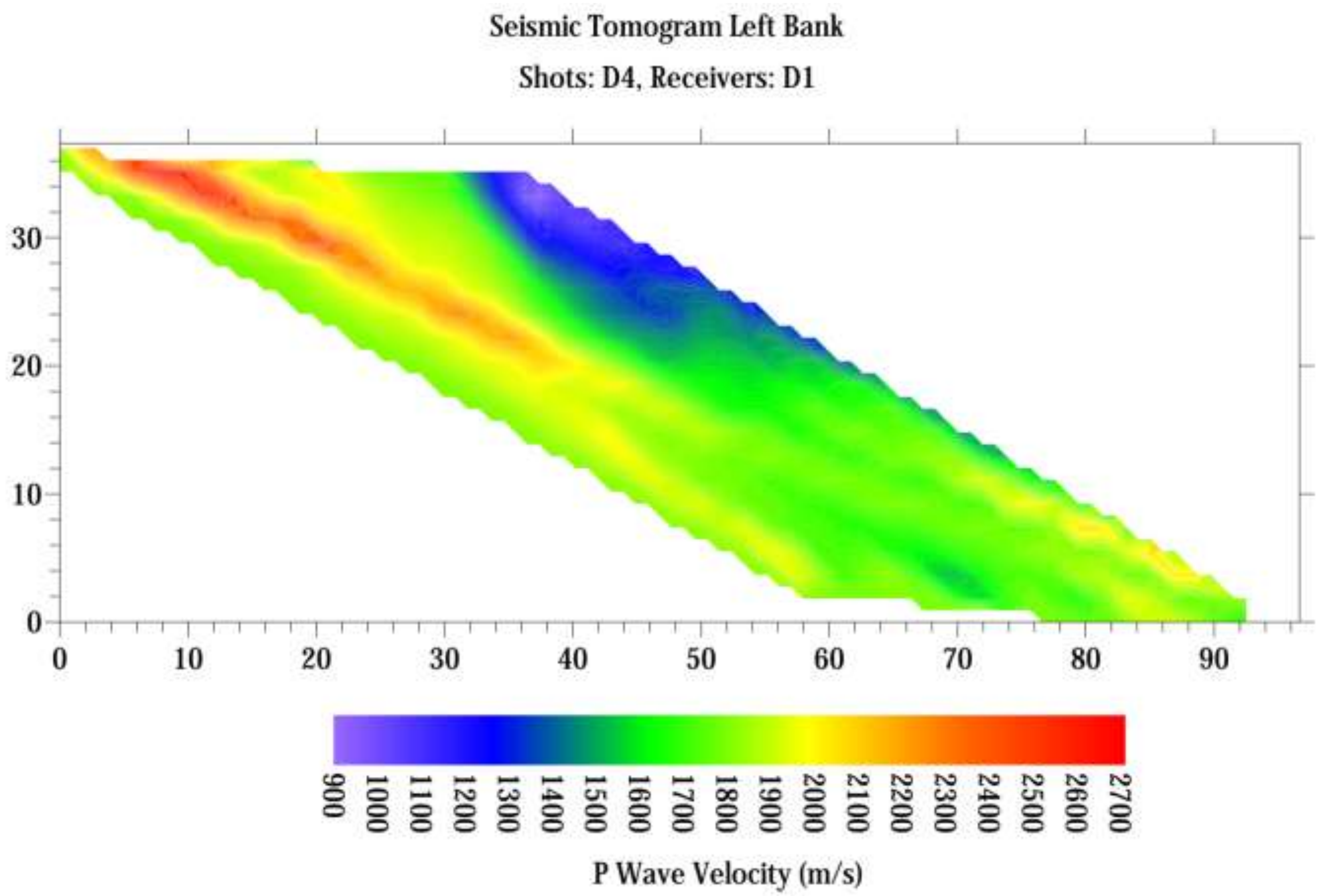
The tomogram shows high velocities in deeper part of drifts. Most of the area has a velocity in the range of 1900-2100 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 1100-1400 m/s.

Right Bank: Source D-2, Geophone D-4



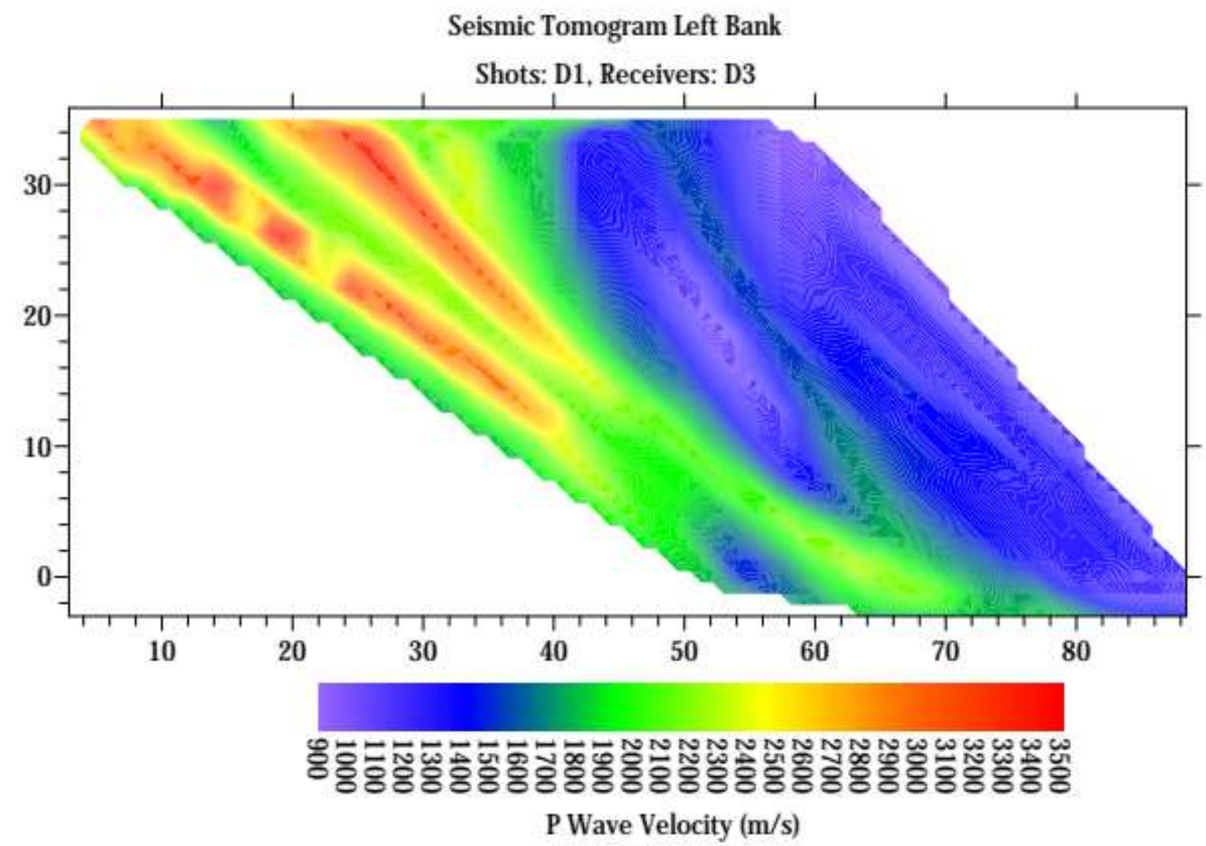
Most of the area has a velocity in the range of 2100-2300 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 1500-1700 m/s. Inclined features are created due to extremely slanted raypaths between the drifts.

Left Bank: Source D-4, Geophone D-1



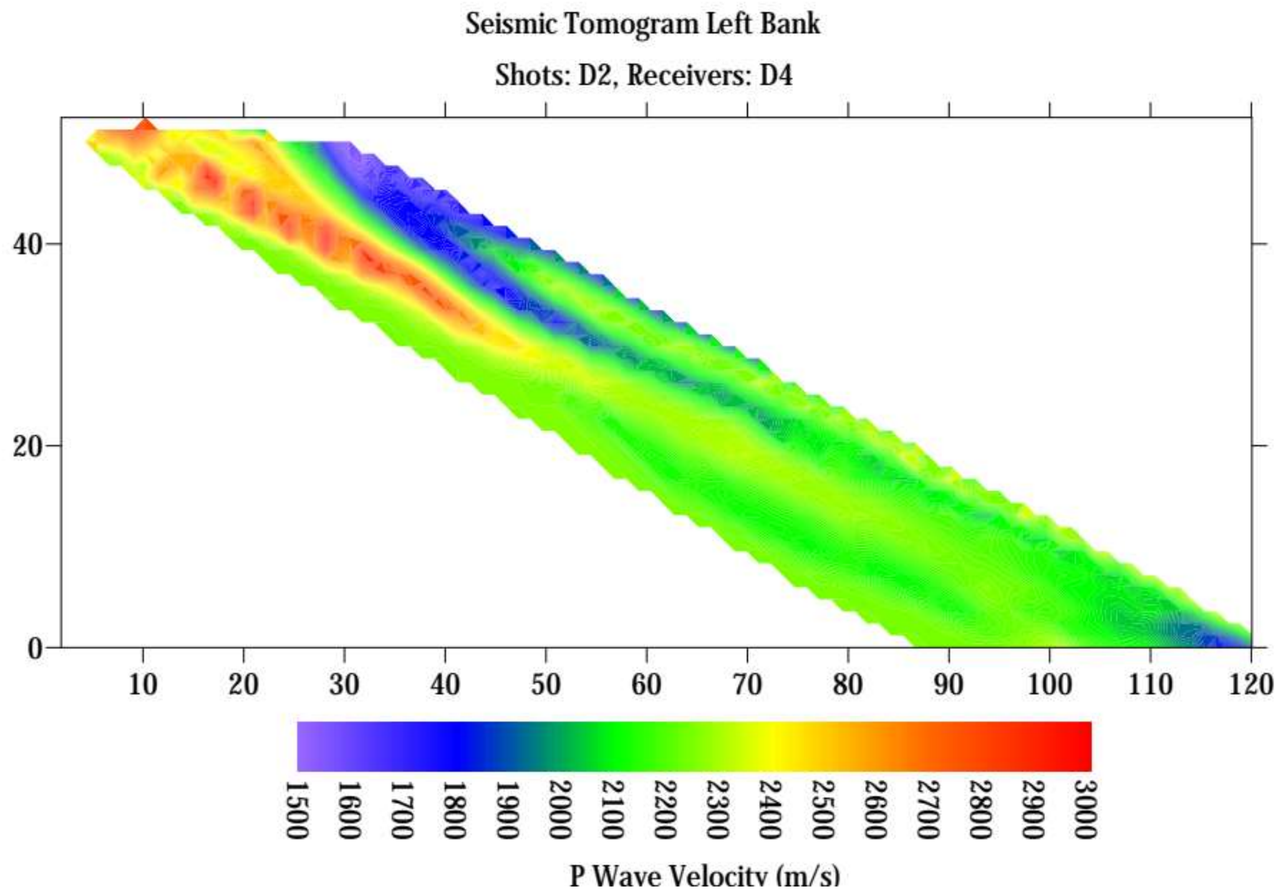
Most of the area has a velocity in the range of 1900 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 900-1200 m/s. Inclined features are created due to extremely slanted raypaths between the drifts.

Left Bank: Source D-1, Geophone D-3



Most of the area has a velocity in the range of 1900-2100 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 900-1200 m/s. Inclined features are created due to extremely slanted raypaths between the drifts.

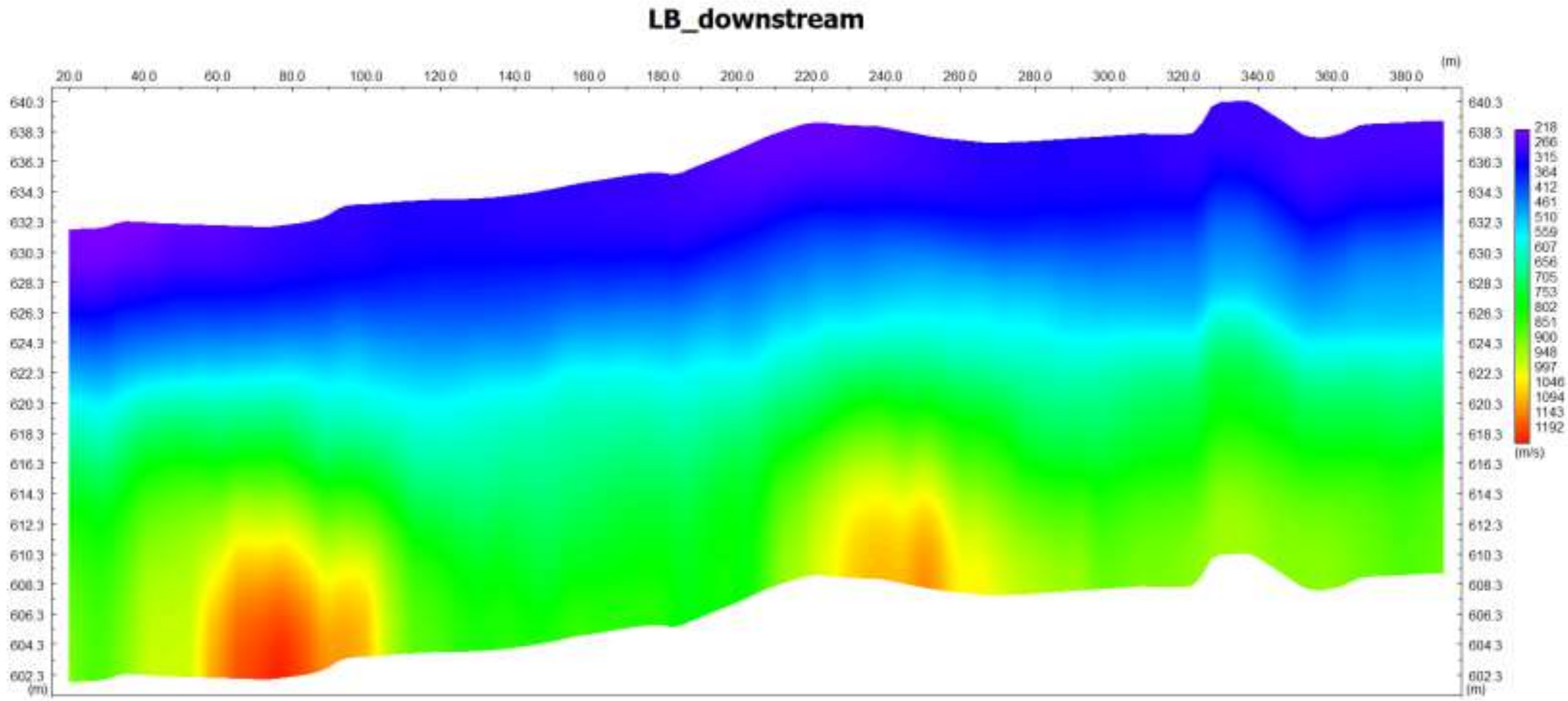
Left Bank: Source D-2, Geophone D-4



Most of the area has a velocity in the range of 2100 m/s relating to sandstone present in the area. Low velocity zones is observed having low velocities from 1500-1800 m/s. Inclined features are created due to extremely slanted raypaths between the drifts.

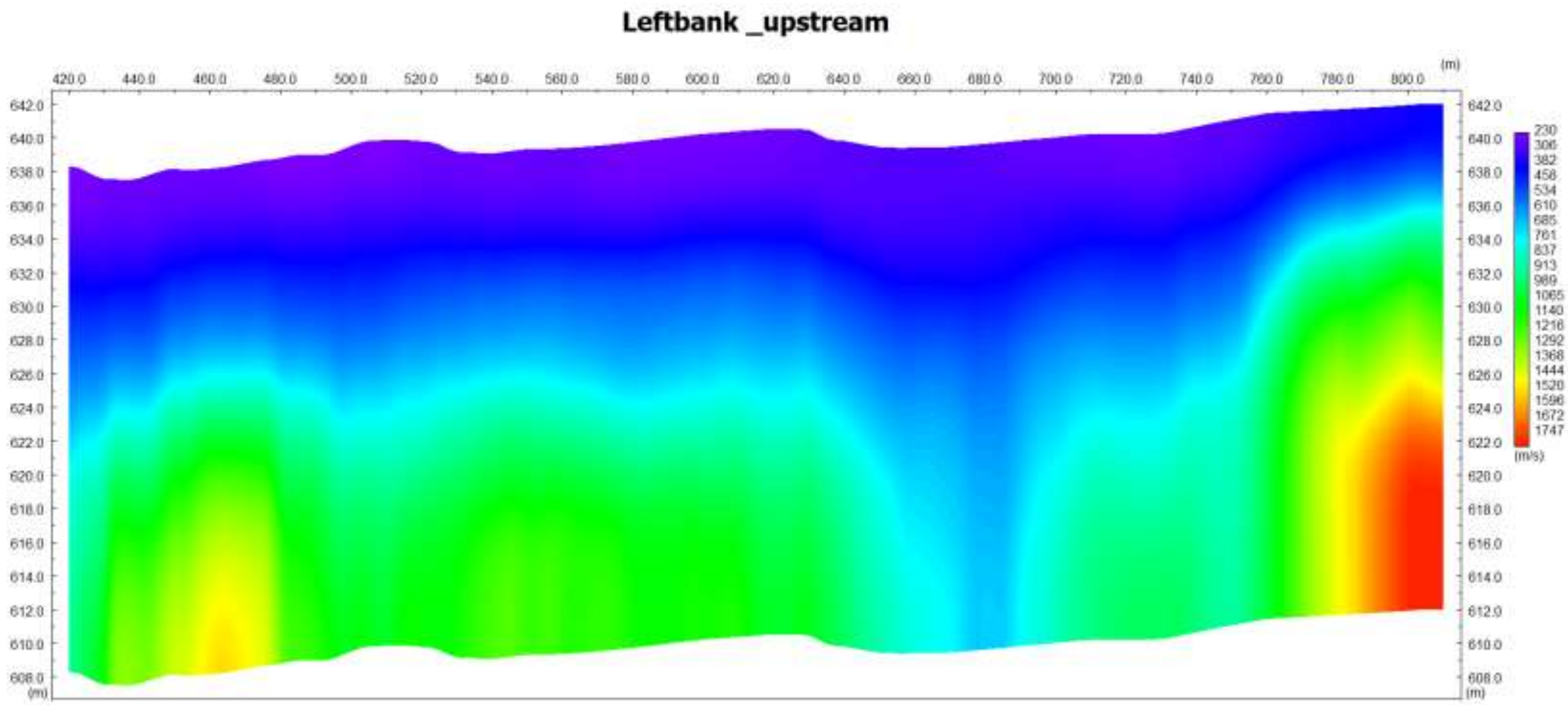
10 RESULTS- MASW

Left Bank: Profile-1



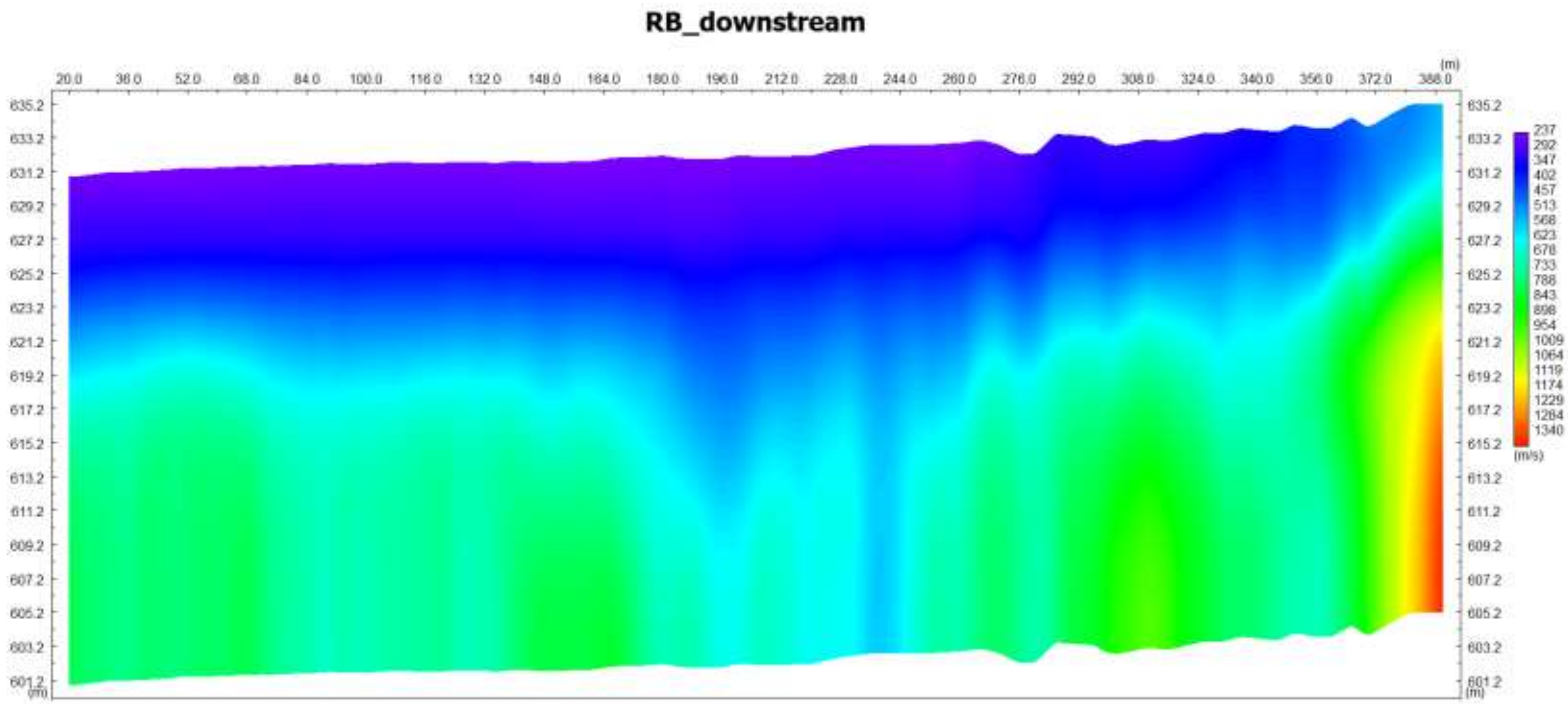
The distance 20 along the x-direction correlates with the 69.90m of actual chainage. An interface is observed around EL 620m. There are no lateral heterogeneties observed along this profile.

Left Bank: Profile-2



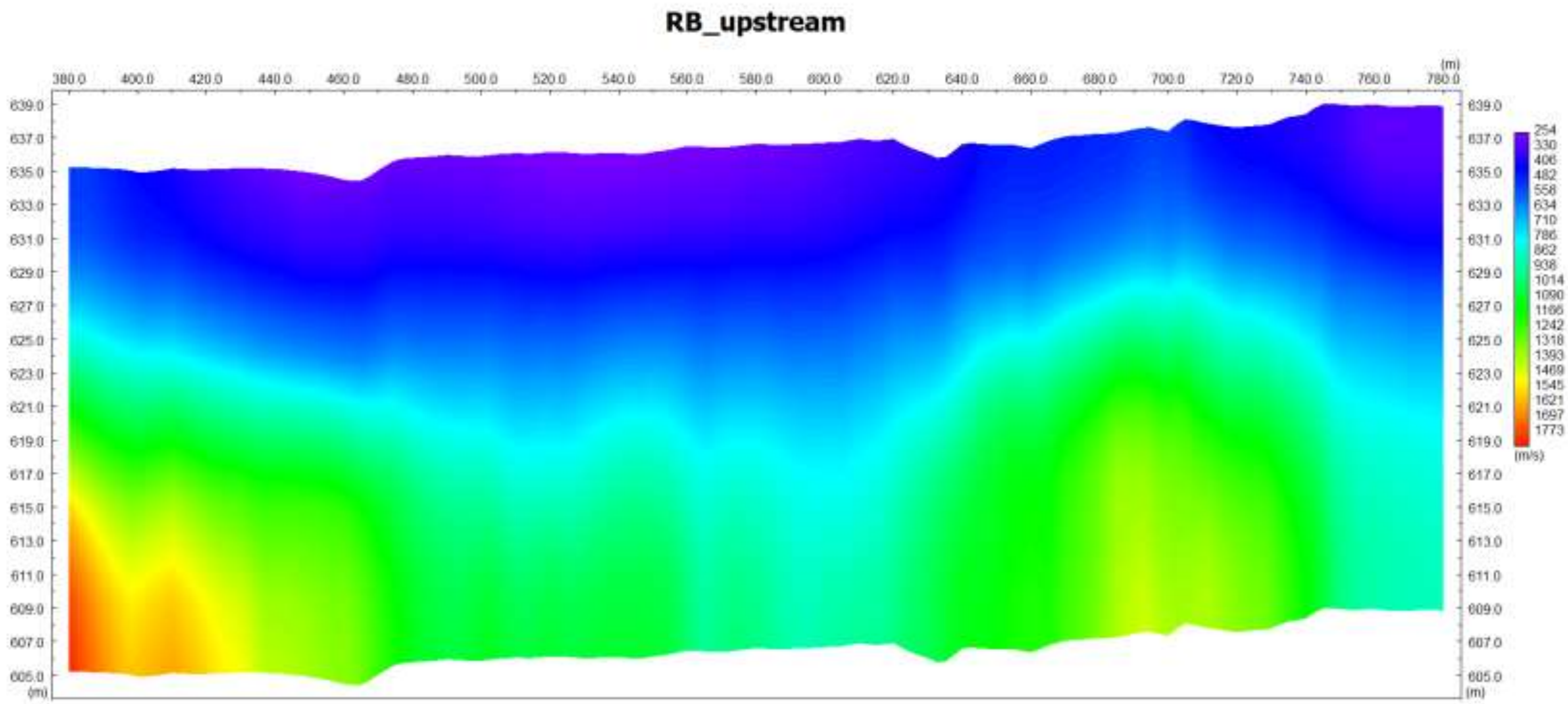
The distance 420 along the x-direction correlates with the 469.63m of actual chainage. An interface is observed around EL 624-636m. There is lowering of S wave velocities around chainage 680m. Slight deepening of bedrock interface was also observed at this location in SRT profile.

Right Bank: Profile-1



The distance 20 along the x-direction correlates with the 64.88m of actual chainage. An interface is observed around EL 621-630m. There is lowering of S wave velocities around chainage 196m

Right Bank: Profile-2



The distance 380 along the x-direction correlates with the 424.69M of actual chainage. An interface is observed around EL 625m with undulations. Slight lowering of interface in middle of profile matches very well with similar feature observed in SRT profile.

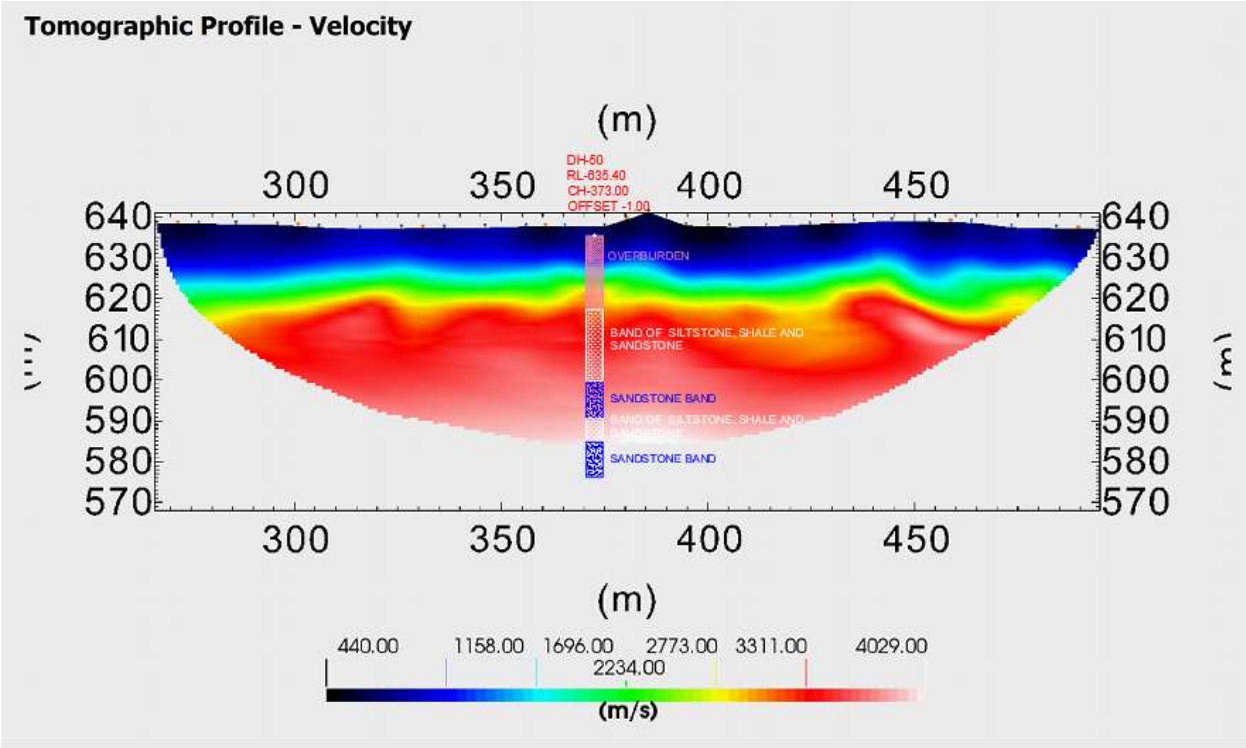
Vs30 is obtained based on profiles carried out at present ground elevation and have been enclosed as tables.

11 BOREHOLE CORRELATION

A number of boreholes were drilled in the project area, apparently a long time ago, and correlation of borehole data was attempted with geophysical results. Boreholes with small offsets were only considered for correlation, as even in such boreholes **there is considerable difference in BH ground levels when compared to present day ground levels**. This might be due to erosion/ deposition or sand mining activity in the area. **It's always recommended to have boreholes drilled after geophysical investigations, at recommended locations, to have a more meaningful correlation.**

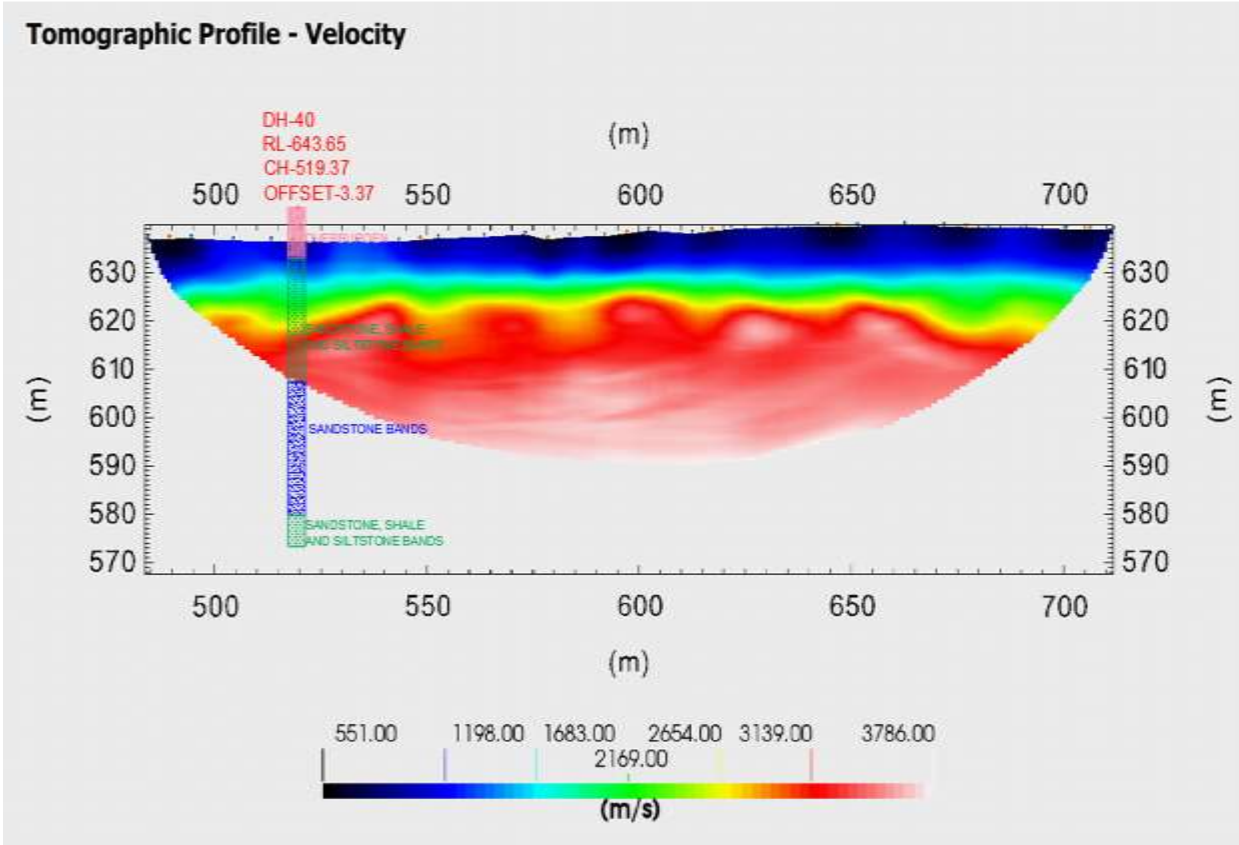
The correlation is presented hereunder for selected profiles on which boreholes fall with small offsets:

Left Bank- Profile-2:



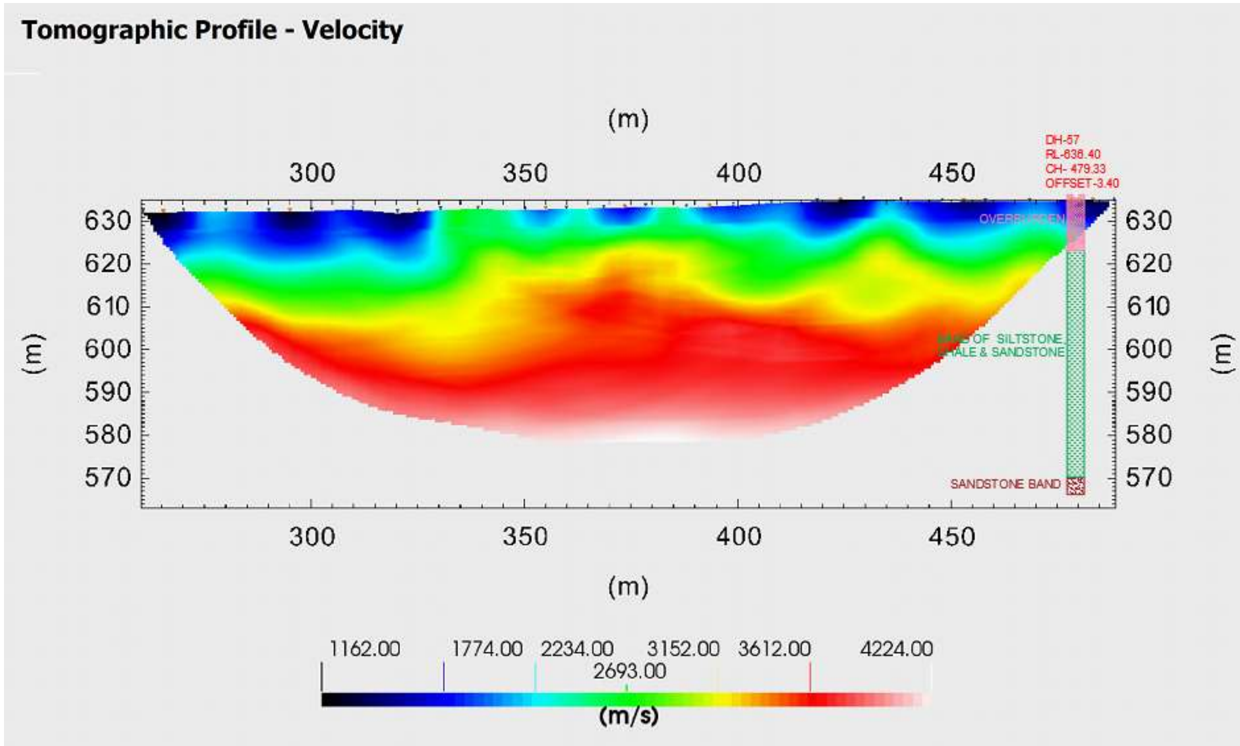
The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 610-620 with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip. **DH-50 falls along with line with very little offset and hence considered for correlation. There is a level difference between borehole level and present ground level. As per correlation, top two layers of seismic profile correspond to overburden, and band of siltstone, shale and sandstone correspond to 3100 m/s interface. The transition of this band to sandstone band doesn't show any separate interface indicating almost similar velocities.**

Left Bank- Profile-3:



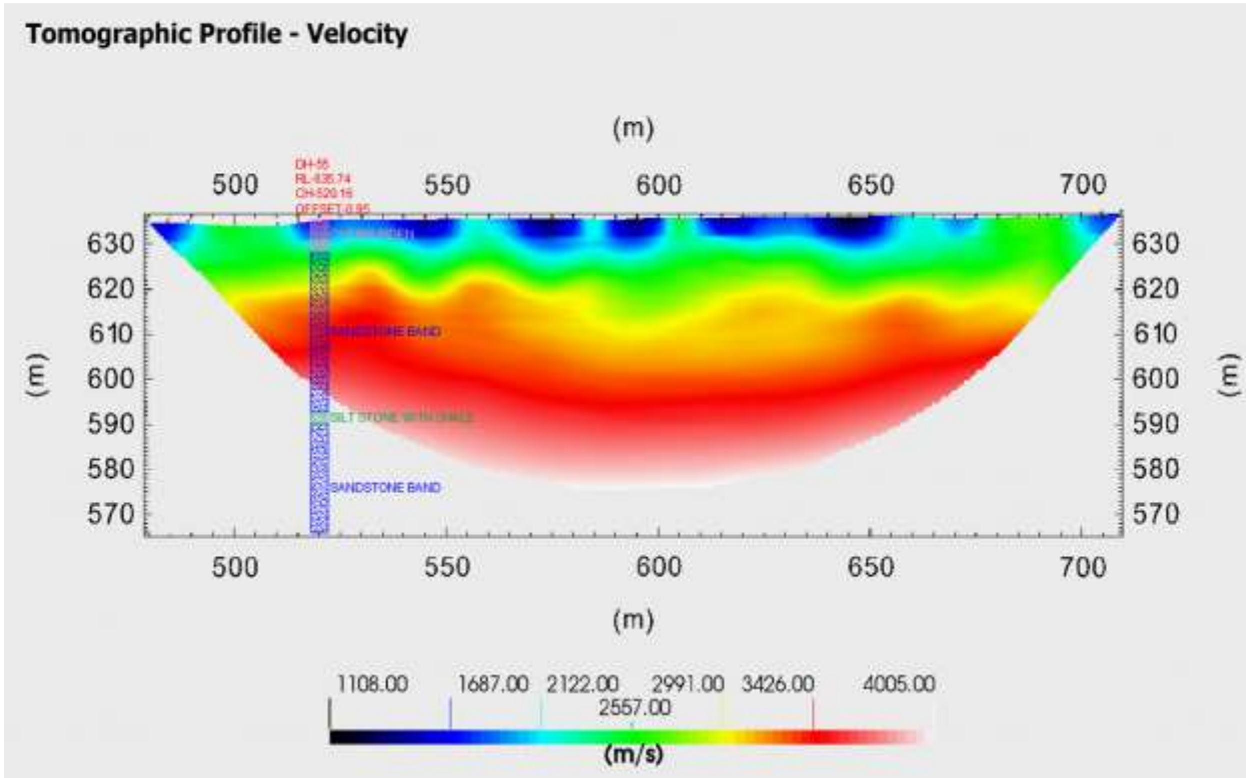
The layer analysis of left bank profiles show interfaced between layers with velocity of 2140m/s and 3100m/s. The sharp gradient in the tomographic profile of 3100 m/s is from yellow-red. The interface is at almost EL 615-620 with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is almost flat without any dip. **DH-40 falls along with line with very little offset and hence considered for correlation. There is a level difference between borehole level and present ground level. As per correlation, bottom two layers of seismic profile correspond to band of siltstone, shale and sandstone. Due to profound level difference between BH level and present day ground level, its advisable not to consider this borehole for correlation.**

Right Bank- Profile-2:



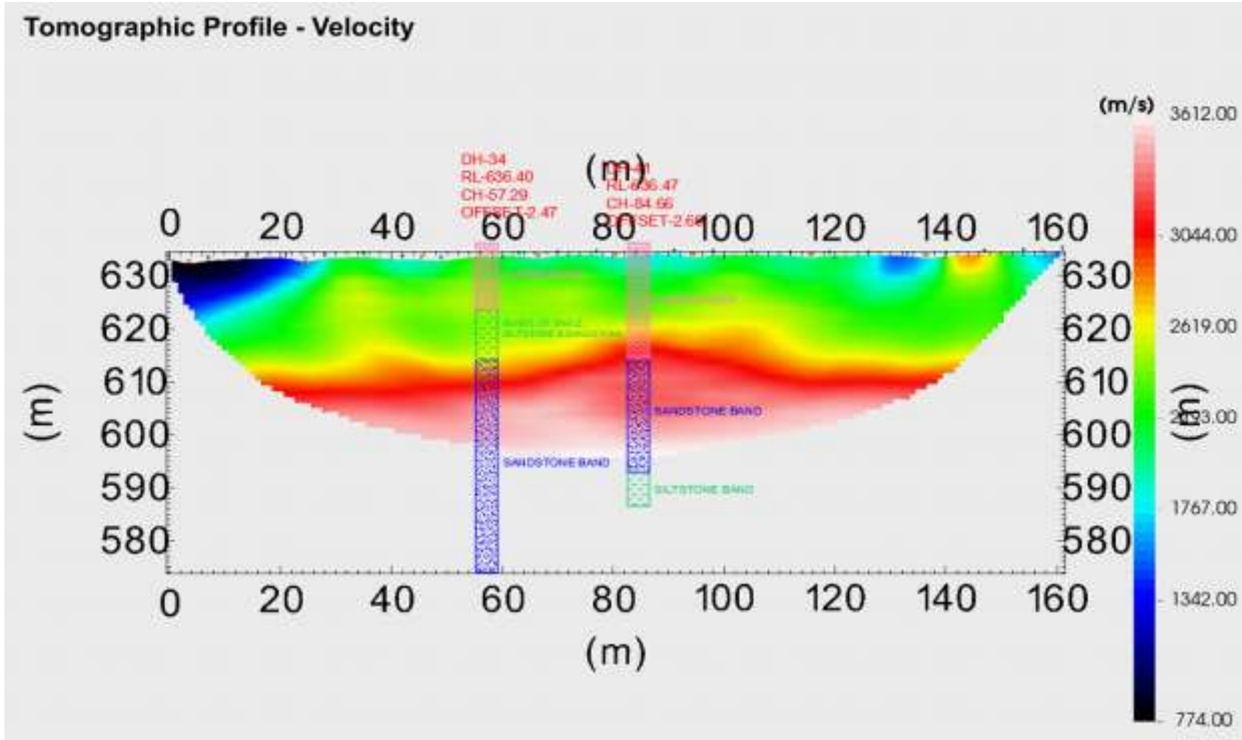
The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile. The interface is shallow in central part of the profile. **<u>DH-57 falls along this line with very little offset and hence considered for correlation. There is a slight level difference between borehole level and present ground level. The borehole falls towards end of the line and hence direct correlation is not possible. However, since model shows vertical stratification, borehole might be considered to fall anywhere along the profile. As per correlation, top two layers of seismic profile correspond to overburden, and band of siltstone, shale and sandstone correspond to 3300 m/s interface.</u>**

Right Bank- Profile-3:



The layer analysis of right bank profiles show interfaced between layers with velocity of 2140m/s and 3300m/s. The sharp gradient in the tomographic profile of 3300 m/s is from yellow-red. The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile. **<u>DH-55 falls along this line with very little offset and hence considered for correlation. As per correlation, the sandstone band shows relatively low velocity in this section, in the range of 2500m/s.</u>**

Oblique Profile-1:



The interface is at almost EL 610-620m with undulating topography of the interface. This might correspond to rock interface along this profile. **DH-34 shows an excellent correlation with the rock interface in tomography profile and sandstone band presented in borehole data.**

It's clear from the above, that seismic velocities are different from same description of rock type in drill log data possibly due to different degree of weathering, not captured in drill logs.

In the drift low velocities have been observed which are consistent with velocities measured on drift samples and reported in DPR available in public domain. P wave velocity 2126 m/sec were measured on samples collected from drift according to this DPR.

Higher velocities were found in samples of silt stone, as per project DPR, and were of the order of 4295m/s. The high velocity patches observed in drift tomography might correspond to this formation.

12 CONCLUSIONS

Integrated geophysical investigations were carried out at Jamrani using the following geophysical techniques:

1. Electrical Resistivity Imaging
2. Seismic Refraction Tomography
3. Multi-Channel Analysis of Surface Waves (MASW)
4. Seismic Tomography

The investigations have provided detailed insight of the subsurface conditions in the area.

Seismic refraction tomography results show rock interfaces along all profiles without any major anomalies like faults/ fractures/ shear zones.

Electrical resistivity profiles indicate higher water content (low resistivity) in lower layers corresponding to rock, indicating presence of secondary porosity.

Drift investigation carried out using seismic tomography provide detailed high-resolution information on seismic velocities of formation between drifts, including presence of low velocity zones close to slope surfaces.

13 Site Photographs - SRT

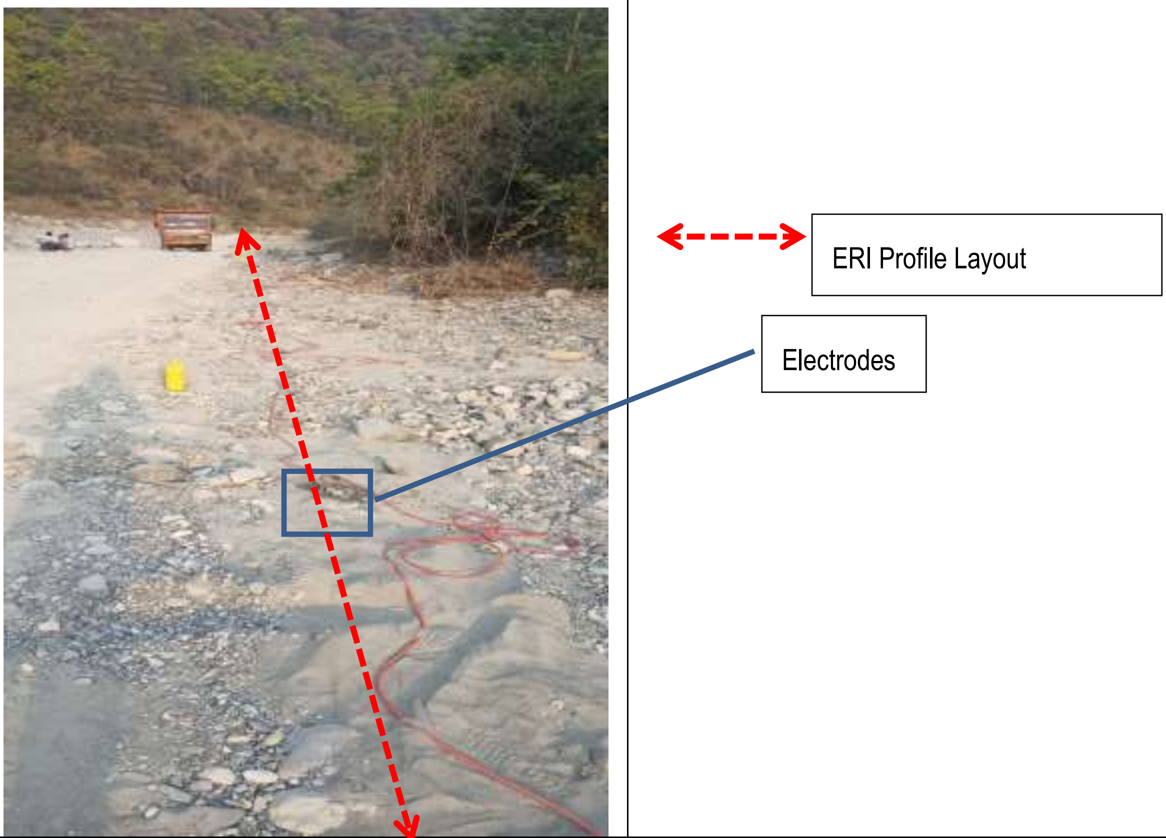
SRT Line Laying

Shot Point and Explosive used as Seismic Source

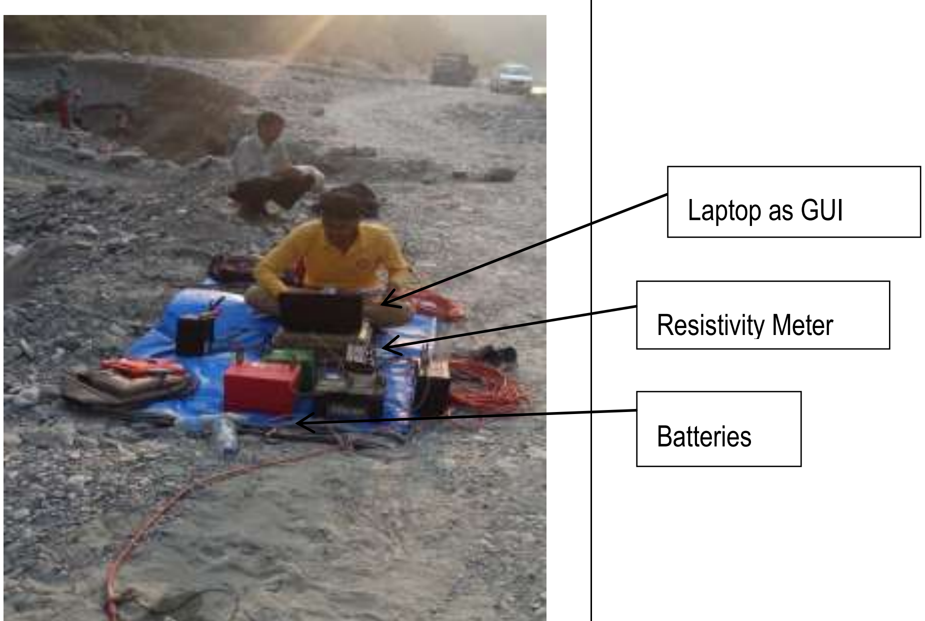
Shot Firing

MASW	
	
Sledge Hammer used as Seismic Source	Laying of MASW Profile
	
Planting of Geophones	Data Acquisition

Field Work ERT



ERI Profile Layout



ERT Data Acquisition

Field Work	Seismic Tomography in Drifts
	
Drilling of Holes for Fixing Expansion Bolts for Geophones	
	 
Customized DC to AC Convertor for operating drilling machine in drift as power supply was not available at project location	8 mm Expansion Bolt for Fixing Geophones

Shots in Drift

Placement of Geophones in Drift

Data Acquistion in Drift