An Evaluation between Time-term, Reciprocal Time and Refraction Tomography Analysis Methods for obtaining 2-D shallow Seismic Velocity Models over Synthetic Traveltimes

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ABSTRACT

Shallow seismic refraction is the principal geophysical method for environmental and engineering site investigations to image the shallow subsurface. We present an assessment of three inversion methods, namely Time-Term inversion, Reciprocal Time methods and Refraction tomography inversion by using commercial software (SeisImager™) by using a synthetic first-arrival-time dataset that was made by SeisImager. In this study, we have generated six velocity representative models and the Synthetic travel times were acquired from these models, also we were adding specific random noise to travel times, like to an estimated picking accuracy. Individual interpretation results have been presented in this paper followed by their comparative. These models are designed to represent different subsurface geological features. Refraction Tomography inversion performs well in many situations where conventional methods fail; also tomographic inversion has proved to be a useful technique in identifying subsurface voids Synthetic modeling. The inverted model is compared to the original synthetic model in order to evaluate the resolution and detection capability. From the interpreted results, it can be concluded that the velocity model from tomography inversion is a more accurate representation of the subsurface although results from time-term inversion can be used along with tomographic results during interpretation.

***Keywords*:** Seismic Refraction Tomography, interpretation, Reciprocal time, Time-Term, delay time, Inversion, Synthetic model.

I. INTRODUCTION

Seismic methods for near-surface characterization has developed in recent years and becoming more and more popular because of their cost-effectiveness for shallow targets. Seismic refraction method is considered to be paramount in engineering geophysics which used to investigating the subsurface layering and structure. These techniques are routinely used in many applications such as engineering, environmental, groundwater, hydrocarbon, and mineral exploration (**Khalil and Hanafy, 2008; Khalil et al. 2008; Bridle 2006; Yilmaz et al. 2006; Hodgkinson and Brown 2005**). Some using the method achieve valuable results, but others consider results misleading and confusing. This discrepancy may result from poor geophysical interpretations, but often geologists and engineers draw the wrong conclusions from the seismic results. Poor interpretations cannot be excused. They result from inadequate field surveys and the use of inadequate interpretation procedures.

Analysis of seismic Refraction data depends upon the complexity of the subsurface velocity structure. If the subsurface target is planar in nature, the slope-intercept method can be used to model multiple horizontal or dipping planar layers (**Telford et al., 1990**). The most traditional method in interpretation techniques is based on ray theory (**Cerveny and Ravindra, 1971**) called Intercept Time Method (ITM). It is the simplest of all methods practiced in refraction interpretation. The velocity of each layer is equal to the inverse of the computed slope of time-distance relationship belonging to different refractors. The Time-term inversion technique employs a combination of linear least squares and delays time analysis to invert the first-arrivals for a velocity section. If the subsurface target is undulating then layer based analysis routines such as the generalized reciprocal method (**Palmer, 1980 and 1981; Lankston, 1986 and 1990**). Reciprocal method or generalized reciprocal method (GRM) refraction analyses make simplifying assumptions about the velocity structure that conflict with frequently observed near-surface attributes, such as heterogeneity, lateral discontinuities, and gradients. Relative benefits of conventional approaches are discussed elsewhere (e.g., **Lankston, 1990; Palmer, 1980**). where Refraction Tomography(RT) is able to resolve velocity gradients and lateral velocity changes and may be applied in settings such as subsurface velocity structure is complex where conventional refraction techniques fail, such as areas of compaction, karst, and fault zones (**Zhang and Toksoz, 1998**).

In this paper, We evaluate performance and discuss three refraction interpretation techniques: Time-term inversion(TTI) Reciprocal time method(RTM), Tomography inversion (TI) by using **SeisImager™** Plotrefa software package, developed by OYO Corporation/2D (version 3.2). We also briefly compare every method results to other in order to demonstrate when this might give better results and when it might not for different subsurface geological features where we are supposed. The long-term goal of this study has been to assess the performance of these inversion methods for different conditions begins with fundamental models to complex models of synthetic traveltimes models.

II. SYNTHETIC MODELLING

The processing flow for SeisImager is simple which the data or synthetic data are simply imported into the software. A topography file can be imported but here it’s not necessary for analysis. Without a topography file, a flat surface is selected at a specified elevation. There are many ways of creating the initial model. We have used inversion algorithm for generating different models by specifying a velocity range, shot point number, dimensions, and a number of layers. When we are complete specific models we can convert synthetic traveltimes to observed data. This basically tricks the program into thinking that the synthetic data is actually real data, allowing us to treat it as such. This is a necessary step if we wish to invert this synthetic data and compare the resulting model to the original input model. This forward/inverse modeling can be very useful in checkup the capabilities of the various interpretation techniques on various types of seismic models.

We can follow the following steps to creating synthetic models:

1. Create desired velocity model and use the Raytracing menu to calculate the synthetic traveltimes.
2. Add a reasonable level of random noise to our data.
3. Convert the synthetic data into real data and applying available inversion methods of these real data then compare the initial model to the calculated model.
4. The new synthetic data will now be displayed along with the “observed” data.

Synthetic traveltimes are used for this assessment in order to have a true model with which to compare the available methods results. Six synthetic models are tested in this paper. They include Three constant velocity layers over a half space (Model 1), Stair Step (Model 2), Fault (Model 3), depression (Model 4 and 5), Karst topography (Model 6) Figure (1-6). For all six models (10) shots into (48) geophones were used in the synthetic model. For all models, the geophone spacing is (5m). A topography file can be imported but is not necessary for analysis. Without a topography file, a flat surface is selected at a specified elevation. There are several ways of creating the initial model; the common way is to use a time-term inversion algorithm contained in the code to generate a simple layered model. This layered model is then converted to a grid model. This is a useful method for simple data where distinct slopes can be associated with particular refractors. The alternative is to create a pseudo gradient model by specifying a velocity range, dimensions and number of layers but there is no control over the grid spacing in SeisImager. SeisImager uses a nonlinear least squares approach for the inversion step and wavefronts propagation methods for the travel time modeling (**Geometrics and OYO, 2003 and Zhang and Toksöz, 1998**).

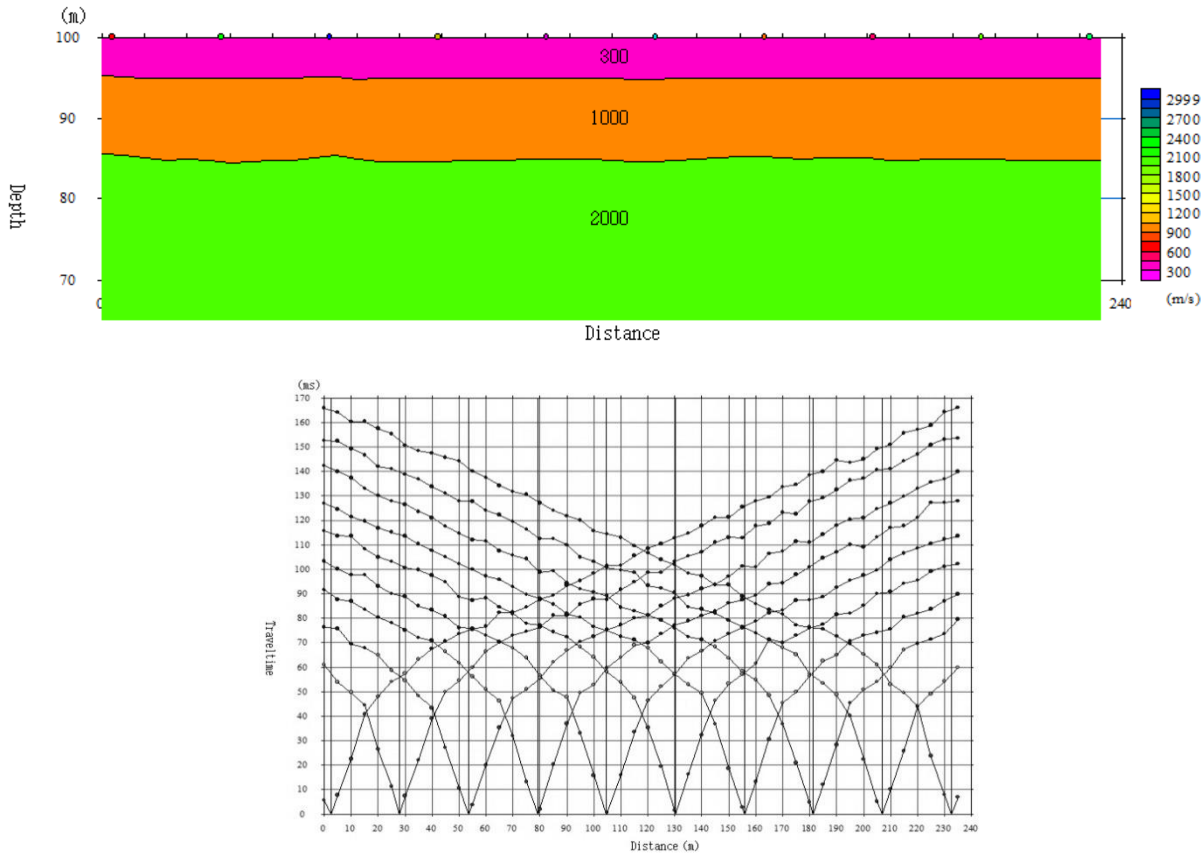

Figure1. The velocities models and Synthetic traveltimes for three constant velocity layers (**Model 1**)

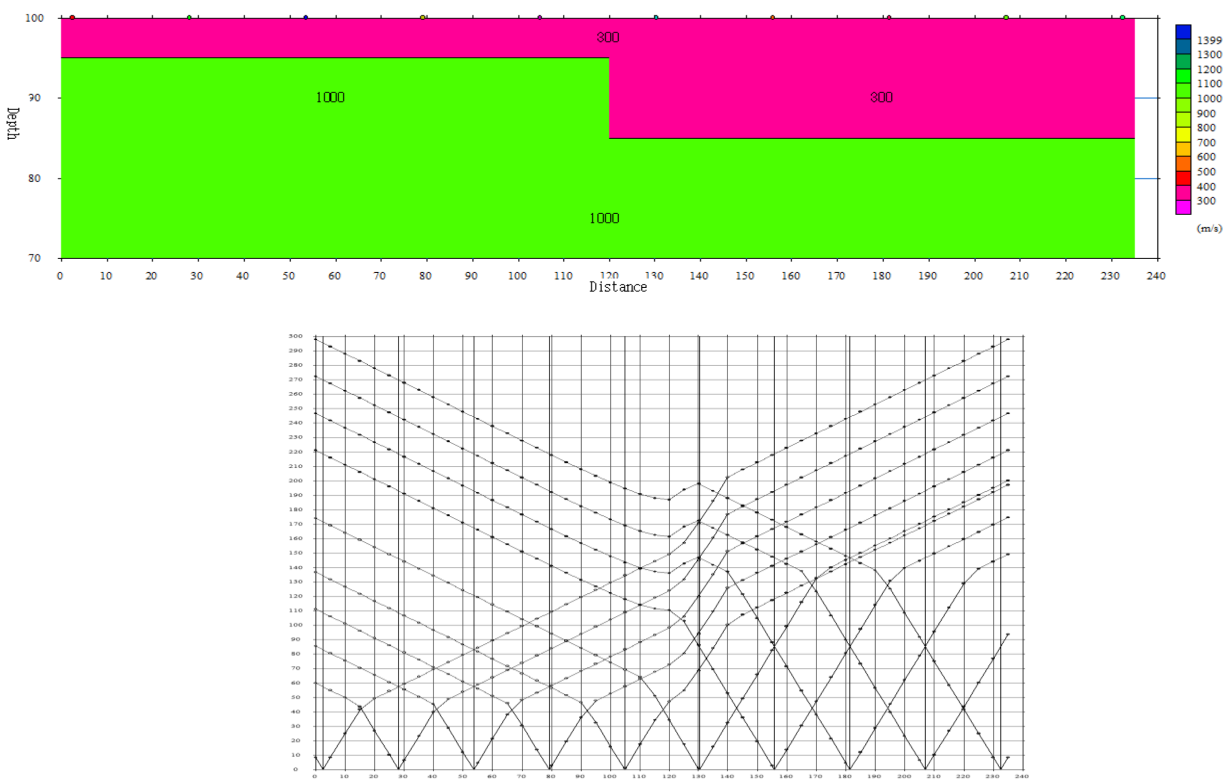

Figure2. The velocities models and Synthetic traveltimes for Stair Step (**Model 2**)

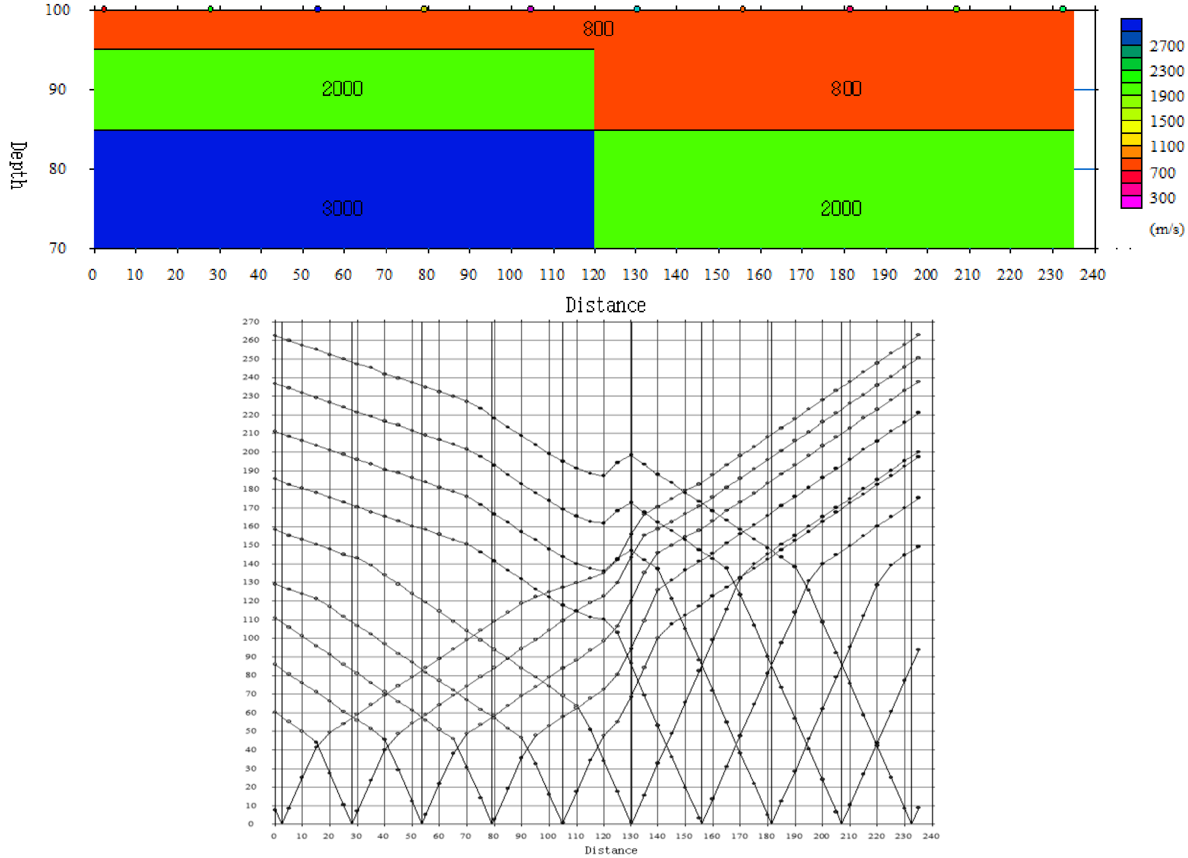

Figure3. The velocities models and Synthetic traveltimes for Fault structure (**Model 3**)

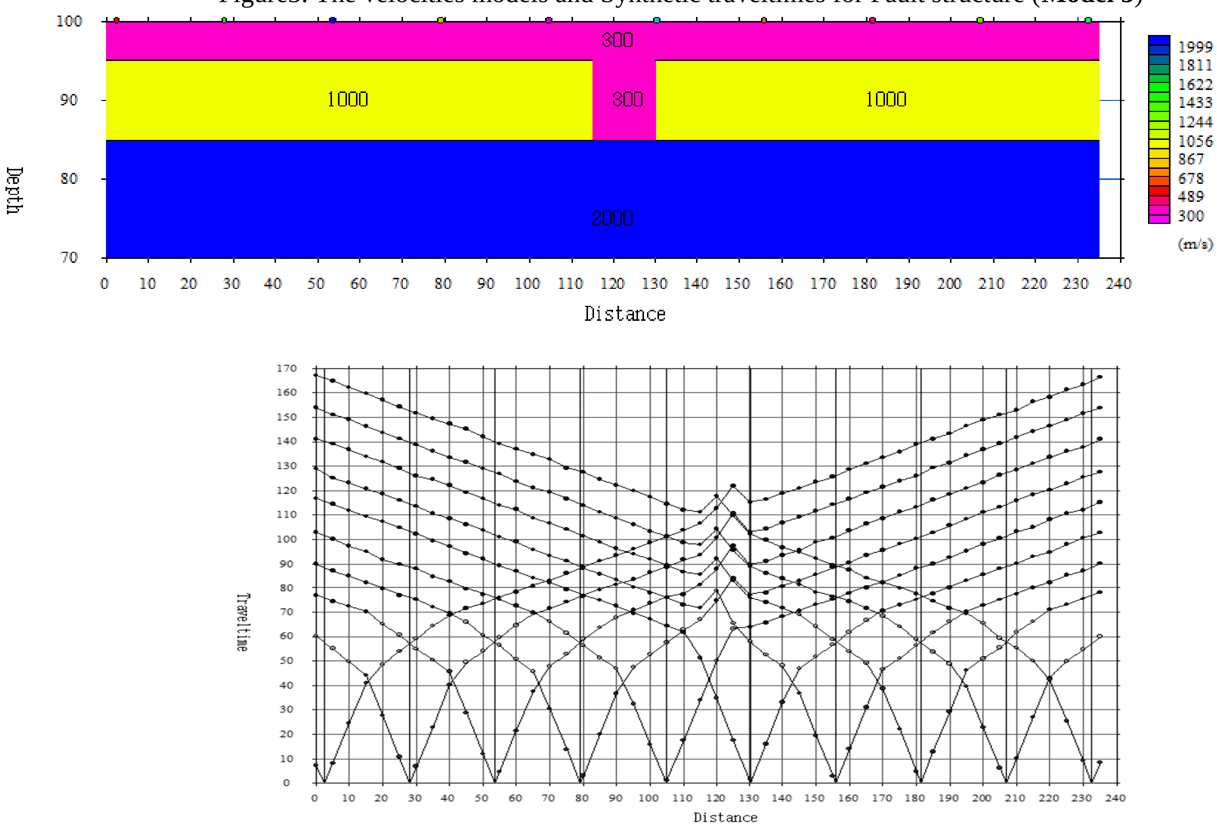

Figure4. The velocities models and Synthetic traveltimes for Narrow depression landform (**Model 4**)

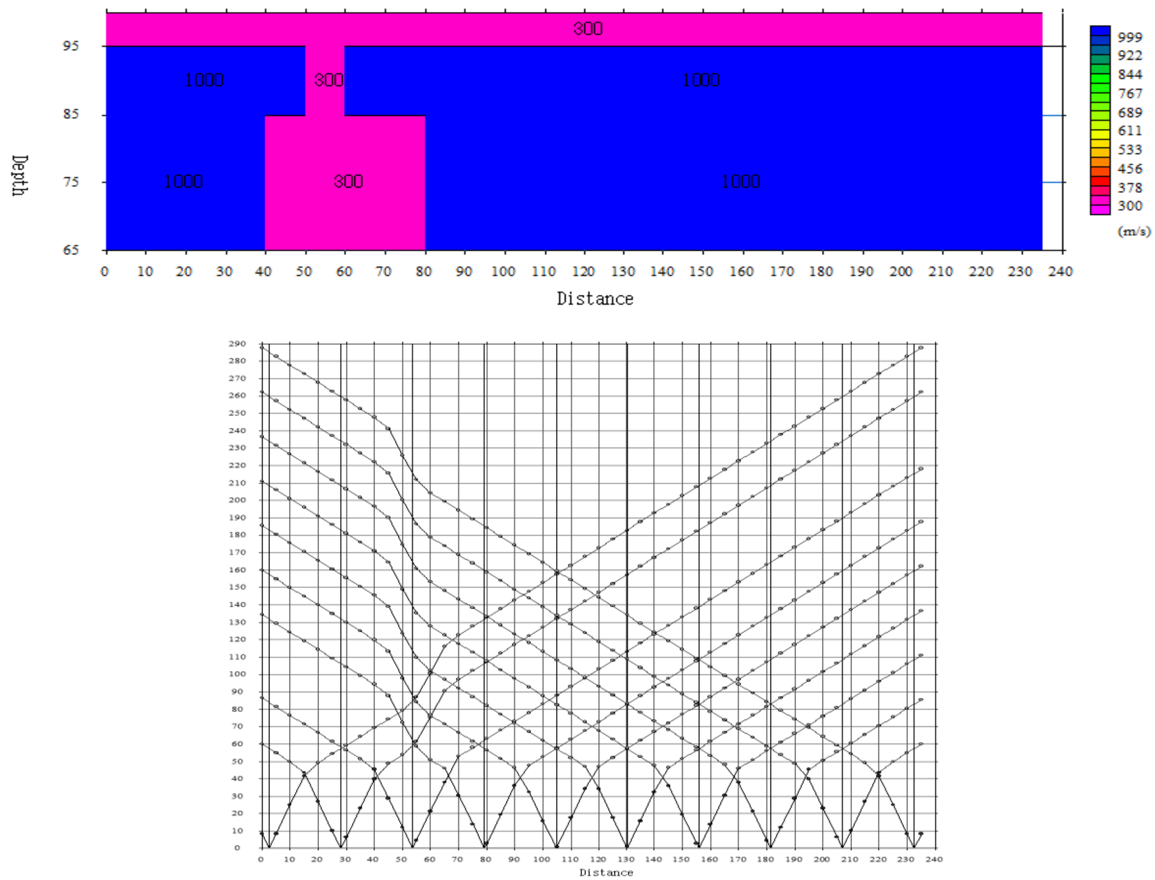

Figure 5: The velocities models and Synthetic traveltimes for depression (wide) landform (**Model 5**)

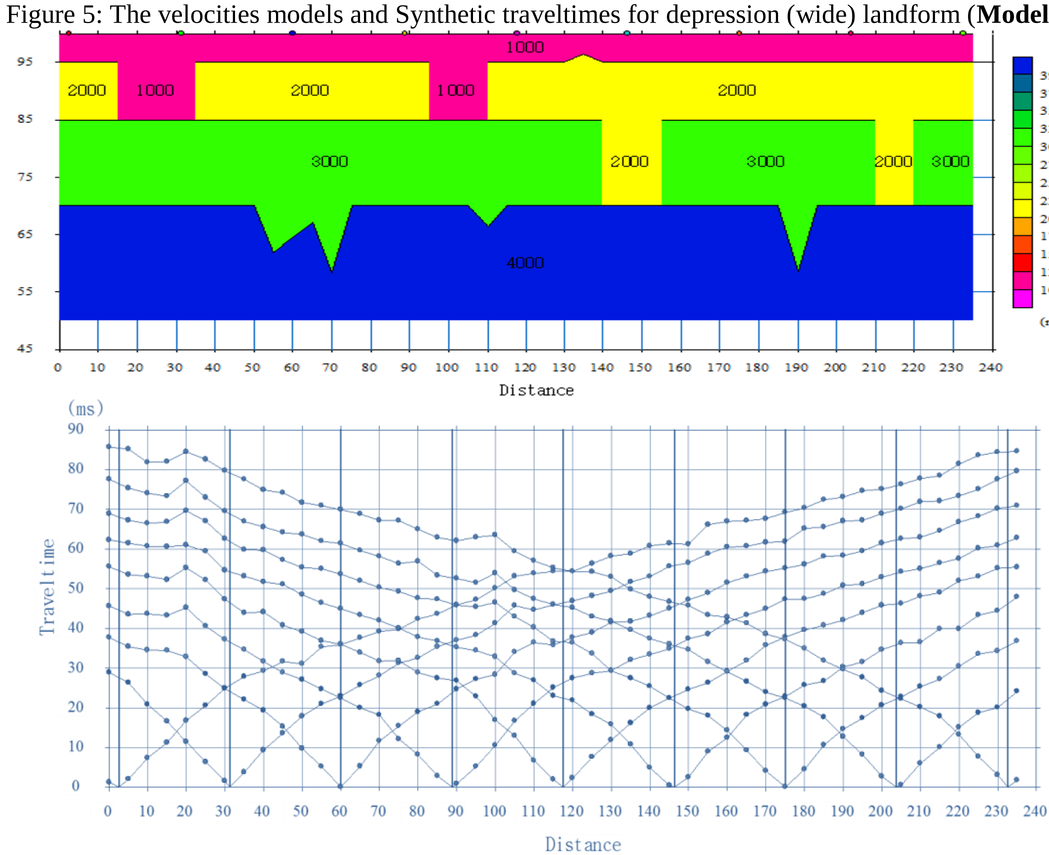

Figure 6: The velocities models and Synthetic traveltimes for Karst topography (**Model 6**)

III. Interpretation Techniques

The interpretation of seismic refraction data at present is most conveniently carried out using commercial software packages on personal computers. There are wide ranges of good software is available for the plotting, automatic picking, and interpretation of such data. The synthetic traveltimes data creating and processing was performed by using SeisImager/2D™ packages. The inversion of the travel time data was carried out in Plotrefa™ application which is a part of the SeisImager/2D Refraction Data Analysis packages. This application allows us to use three types of inversions, namely time-term inversion (TTI), reciprocal method and tomographic inversion, which have been performed and these results from the three types of inversions for all the models are discussed in this paper.

A. Time –term inversion technique

The Time-term inversion (simple travel-time) technique is a simple travel-time inversion. This method has several advantages in spite of its simple travel-time approximately; the first one is the computational stability. A sophisticated travel-time inversion based on the ray-tracing method is sometimes so sensitive to small-scale structure changes because of its high-frequency approximation. Such instability never happiness in the time-term method because of its simple travel-time calculated. The second advantage is the computational fastness due to the linear observation equations. Moreover, this method is quite robust for estimating a refraction velocity. The Time-term technique employs a combination of linear least squares and delay time analysis to invert the first-arrivals for a velocity section. It is a good approach for lower-budget, simple refraction surveys, in which refractor detail is of lesser importance than gross velocities and depths. The answer usually does not need to be a detailed one, and minimizing the time between fieldwork and the deliverable to the client tends to trump all (**Geometrics and OYO, 2009**).

This technique is a quick and easy way to estimate refractor depth. This inversion method assumes the subsurface to be vertically stratified and does not account for the lateral changes in during inversion. The depths to the top of the underlying layers are calculated from the point of travel time vs. offset plot, where the slope (1/Velocity) changes. This method only requires layer assignments for each of the first break arrivals. The time-term inversion is based on a few simplifying assumptions, which may be valid in our cases; it assumes discrete constant velocity layers as well as a horizontal refractor. The general flow of the time-term inversion is displayed in the flowchart (Figure 7).

A simple time-term analysis allows a two- or three-layer interpretation by using Plotrefa program, once all of the layers have been assigned; we are ready to invert the data for the velocity section. The inversion error will be displayed, and it is simply a measure of the quality of the Least- squares inversion. Generally, a matrix inversion error of (1.5%) or less is Acceptable. If it is larger, you might want to re-examine your picks and/or layer assignments.

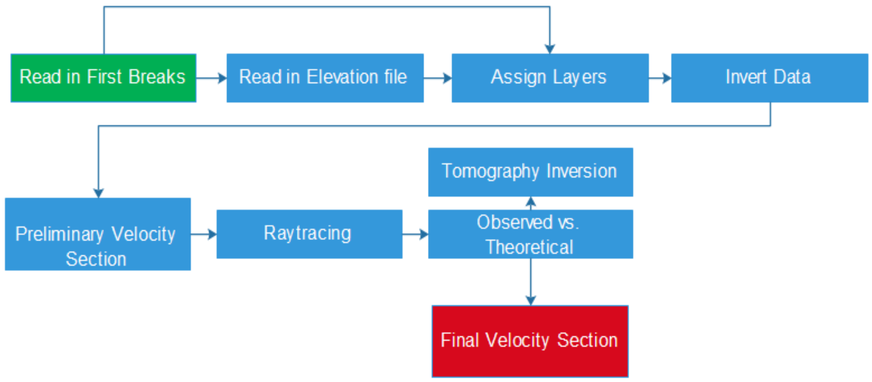

Figure 7: General flow chart of a Time-Term technique

B. Reciprocal Time (Delay- time) Method

The Reciprocal time method(RM) or The Generalized Reciprocal Method (GRM) (**Palmer, 1980**) is capable of mapping highly irregular refractors using reversed profiles and is relatively insensitive to dip up to (20)degree. It is also able to resolve lateral variation in the refractor velocity (**Palmer, 1986, 1991**). This is especially important in engineering (where low velocity may indicate low rock/soil strength) and groundwater studies (where it may indicate high porosity) (**Reynolds, 2003**). In 1980, Palmer introduced the concept of (GRM). It is the advanced version of the reciprocal method (RM) as it can be utilized for delineating ruffled refractors, present at any depth. Here, refractor velocity and depth are computed using travel-times of two geophones, located at a variable distance. Two geophones lead to improved interpretation and optimum separation is estimated by the response of velocity analysis function (**Leung, 1995**). The interpreted result with means of geophones spaced at an optimum distance tends to smoothen refractor and provide least linear velocity variation. This method has many Advantages and limitations, which are that refraction seismic is generally very effective at determining bedrock depths since bedrock usually has a higher velocity than the overburden. In addition, this method is able to provide fairly detailed lateral variations in depth since the depth beneath each geophone can also be found. While the Limitations are the probably the most restrictive limitation is that each of the successively deeper refractors must have a higher velocity than the shallower refractor. However, for determining bedrock depths, this is probably not a significant limitation since, as mentioned above, the bedrock usually has a higher velocity than the overburden. The Reciprocal method (RM) is a powerful technique for solving more complex refraction problems. It works best with highly redundant data (many shots), 24 channels or more per shot, and requires a far greater degree of input from the interpreter compared with the time-term method in same software. The general flow of a reciprocal time inversion is shown in the following flowchart (Figure 8).

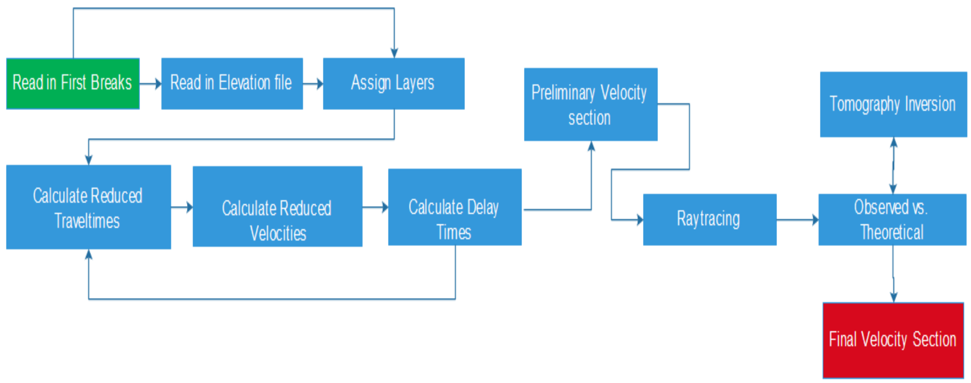

Figure 8: Flowchart for Reciprocal Time inversion.

C. Refraction Tomography Inversion (RTI)

Tomographic inversion (TI) is the 3rd interpretation technique provided by Plotrefa. This method an interpretation technique which requires an initial velocity model, to begin with (**Zhang and Toksöz, 1998**). This method starts with an initial velocity model (generally generated by a time-term inversion), and iteratively traces rays through the model with the primary purpose of reducing the RMS error between the observed and calculated traveltimes to produce a velocity model devoid of small-scale artifacts. Tomographic inversion (TI) is generally best used when velocity contrasts are known to be more gradational than discrete, when strong horizontal velocity variations are known to exist and in extreme topography. All of these cases can lead to erroneous results with the previous two interpretation techniques, depending on the severity. The typical flow of a tomographic inversion is shown in the flowchart (Figure 9).

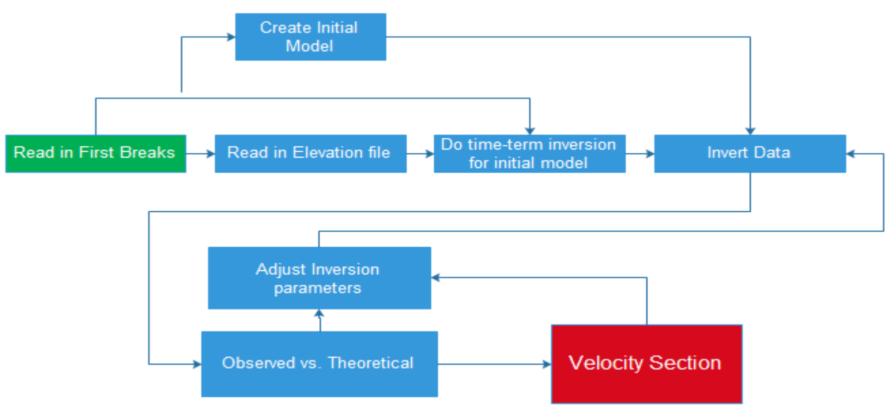

Figure 9: Flowchart depicting steps performed in tomography Inversion (TI).

A topography file can be imported but is not necessary for analysis here. So without a topography file, a flat surface is selected at a specified elevation. There are two ways of creating the initial model; the first one is to use a time-term inversion algorithm contained in the application to generate a simple layered model. Then this layered model is converted to a grid model. This is a useful method for simple data where distinct slopes can be associated with particular refractors. The alternative is to create a pseudo gradient model by specifying a velocity range, dimensions and number of layers but there is no control over the grid spacing in SeisImager/2D. The application uses a non-linear least squares approach for the inversion step and wavefront propagation methods for the travel time modeling **(Geometrics and OYO, 2003 and Zhang and Toksöz, 1998**). According to **Zhang and Toksöz (1994)**, this approach has the effect of inverting for travel time curves as a whole instead of individual travel times and helps reduce non-uniqueness, another benefit of this approach is that the average slowness is effective at finding the shallow velocity structure and the apparent slowness is better at finding the deeper structure. During the inversion, the first little iteration is inverting average slowness only. Then, once the shallow subsurface is constrained the inversion switches to a joint inversion of average slowness and apparent slowness. In this way, minor imprecisions in the shallow subsurface are less likely lead to larger errors at depth. The wavefront propagation method for traveltimes calculation determines the time required for the wave to travel from the source to each adjacent node. The node that has the shortest traveltimes path leading to it then acts as the source, and the process is repeated until the whole model is traced (**Zhang and Toksöz, 1998**). Below the Table1 have summarized refraction interpretation techniques for mapping subsurface.

Table 1: Illustrating Refraction interpretation Techniques for mapping subsurface.

Interpretation Method	Application
ITM (intercept time)	Picking and Travel time curve illustration
Travel Time (Time-term) Inversion) (**TTI**)	Velocity model using ITM
Reciprocal time (**RT**)	Calculation of depth & velocity
Tomography Inversion (**TI**)	Velocity model using Tomography

IV. RESULTS AND COMPARISON OF TTI, RM, AND TI

To compare the time-term inversions (TTI), Reciprocal time (RT) method and tomography inversion (TI) techniques are not easy. Pros and cons of these interpretation techniques depend mainly on geological settings at each particular locality and on the type of model needed.

The results of various interpretation techniques will be shown together for each model. The results for **Model 1** (three constant velocity layers) are shown in (Figure. 10). The layers boundary is distinct in all techniques. The deep layer boundary is inaccurate on all of the results, although it can be inferred close to the true depth on all three. This model is better suited to conventional analysis techniques Time-term Inversion (TTI) and Reciprocal Time (RT) than it is to Tomography inversion (TI). The **Model 2** (stair step) results show a smoothed stair step shape (Figure 11) in (RT and TI) and the results show generally flat layers to the left and right of the offset, while the time –term inversion(TTI) model shows better-suited analysis techniques. The **Model 3** (fault structure) the results of (TTI and TI) The resulting velocity tomograms were able to clearly delineate faults. The **Model 4** (Narrow depression landform) the results of (TTI and TI) show a smoothed version of the depression with a high-velocity artifact under the depression (Figure. 13), and this smoothing is a slightly pronounced result. Most of the artifacts are outside of the ray coverage, suggesting that the artifact is the result of the tomography algorithm updating the velocity at the center of the model only where there is adequate ray coverage. The **Model 5** (Wide depression landform) the Tomography inversion (TI) find the general shape of the boundary, and even show the large feature located between 40 and 80 meters (Figure. 14). The only significant difference between (TTI and TI) techniques is in the depth of the boundary. It appears to be a little deeper in the result that the true model or the other two results. Unfortunately that the **Model 6** (Karst topography) (Figure 15) none of the (TTI and RT) could find the narrow low-velocity Pinnacles in Model 6 While the results of (TI) are accurate and are too similar to determine which of the best mimics the true model. However, the results of all techniques discussed above indicate that the tomography inversion (TI) appears to provide optimum results.

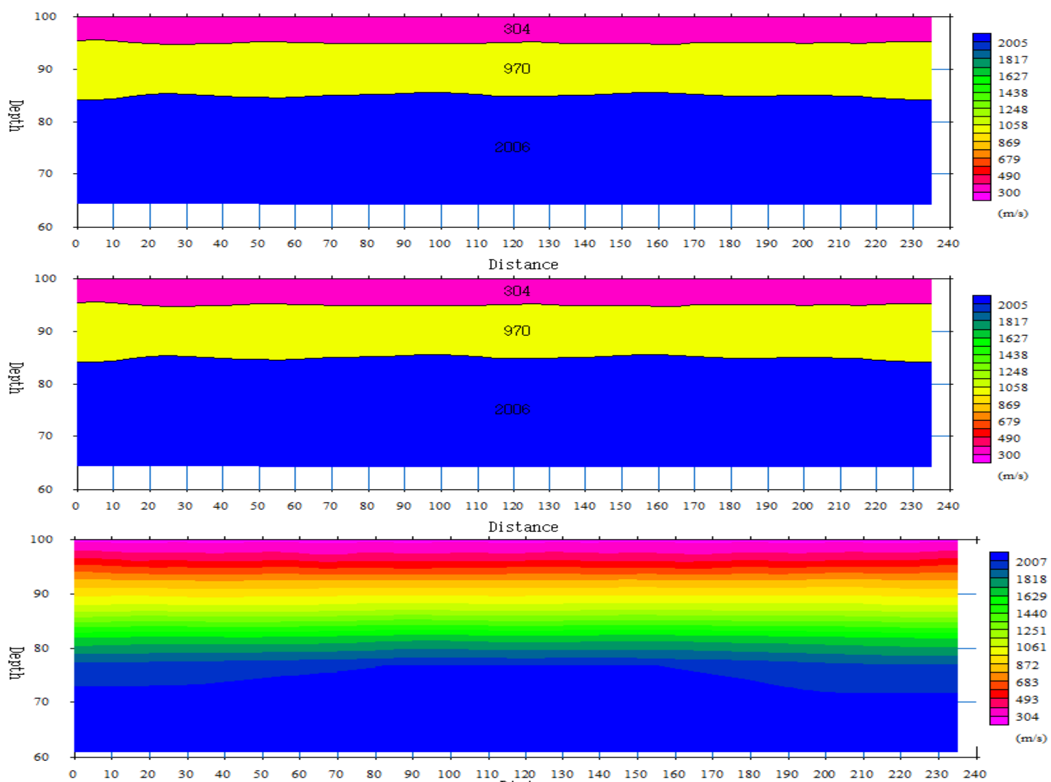

Figure 10: Comparing velocities models (**Model 1**) for three constant velocity layers obtained from 1. TTI, 2.RM, and TI

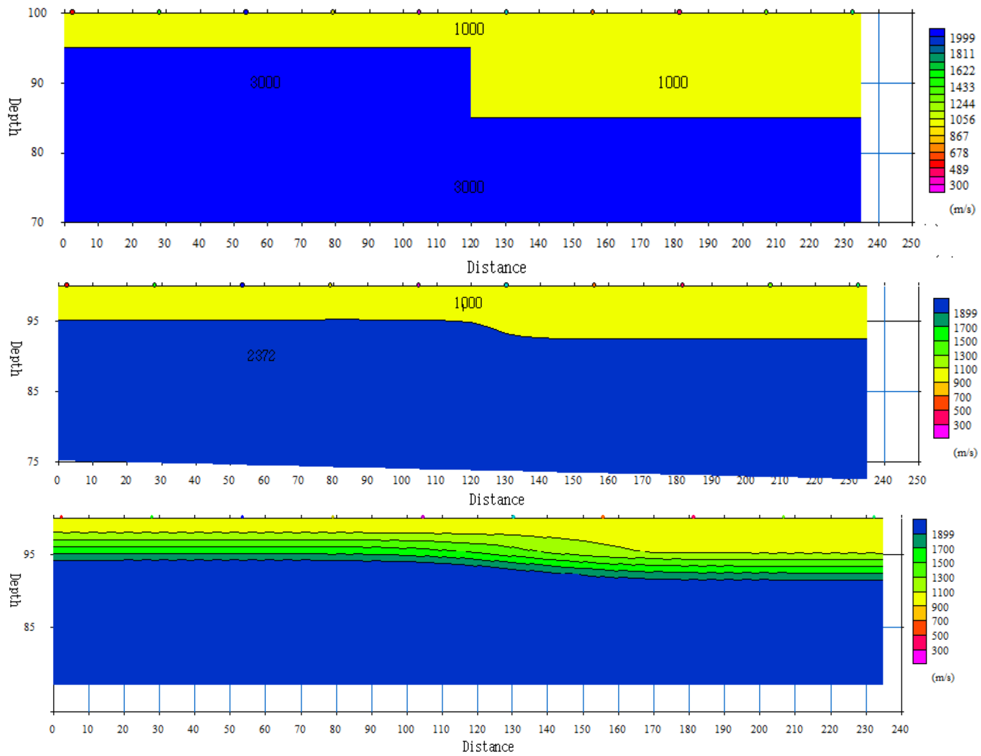

Figure 11: Comparing velocities models (**Model 2**) for Stair Step obtained from 1. TTI, 2.RT, and TI

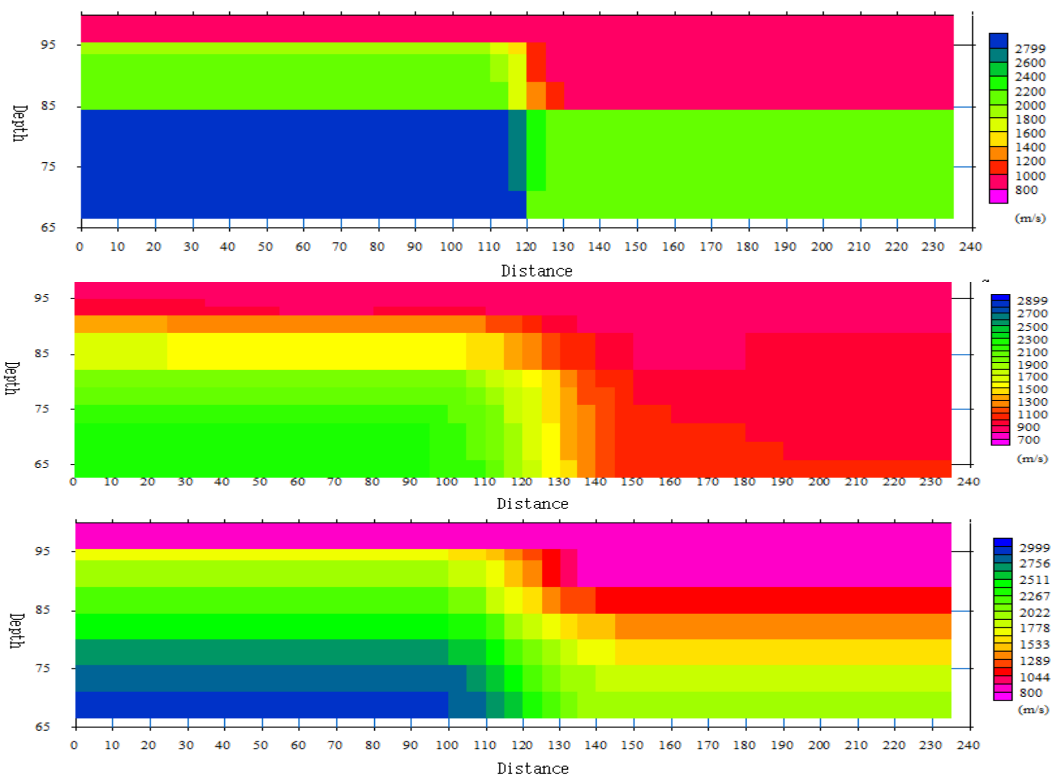

Figure12: Comparing velocities models (**Model 3**) for Fault structure obtained from 1. TTI, 2.RT, and TI

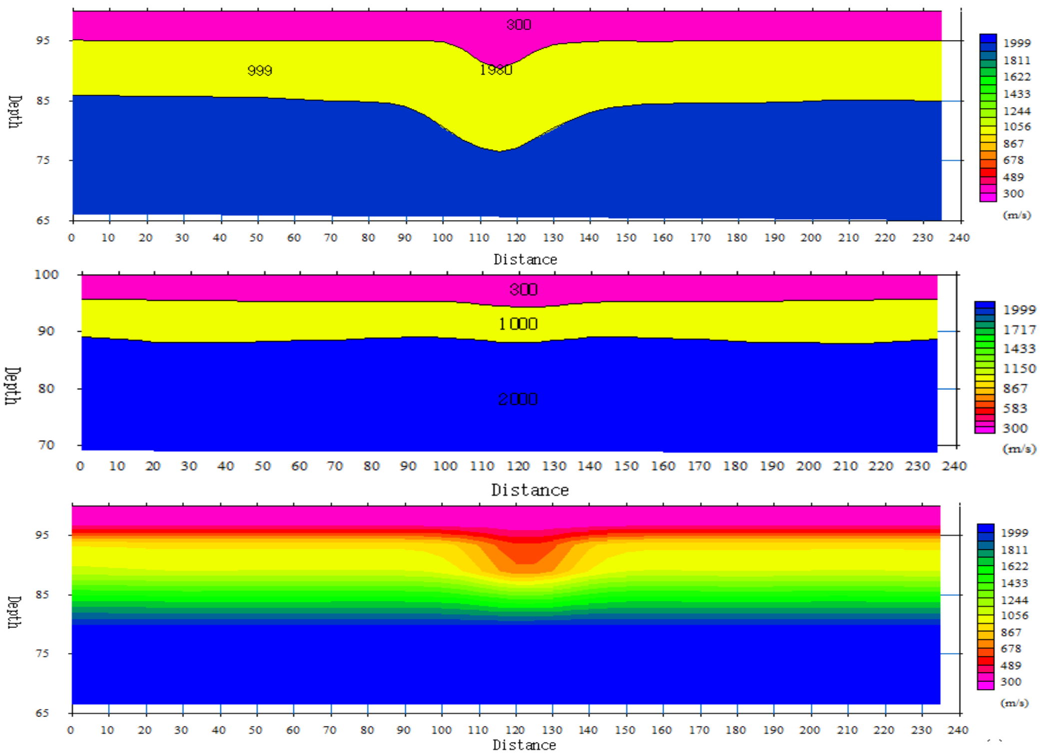

Figure14: Comparing velocities models (**Model 5**) for depression (wide) landform obtained from 1. TTI, 2.RT, and TI

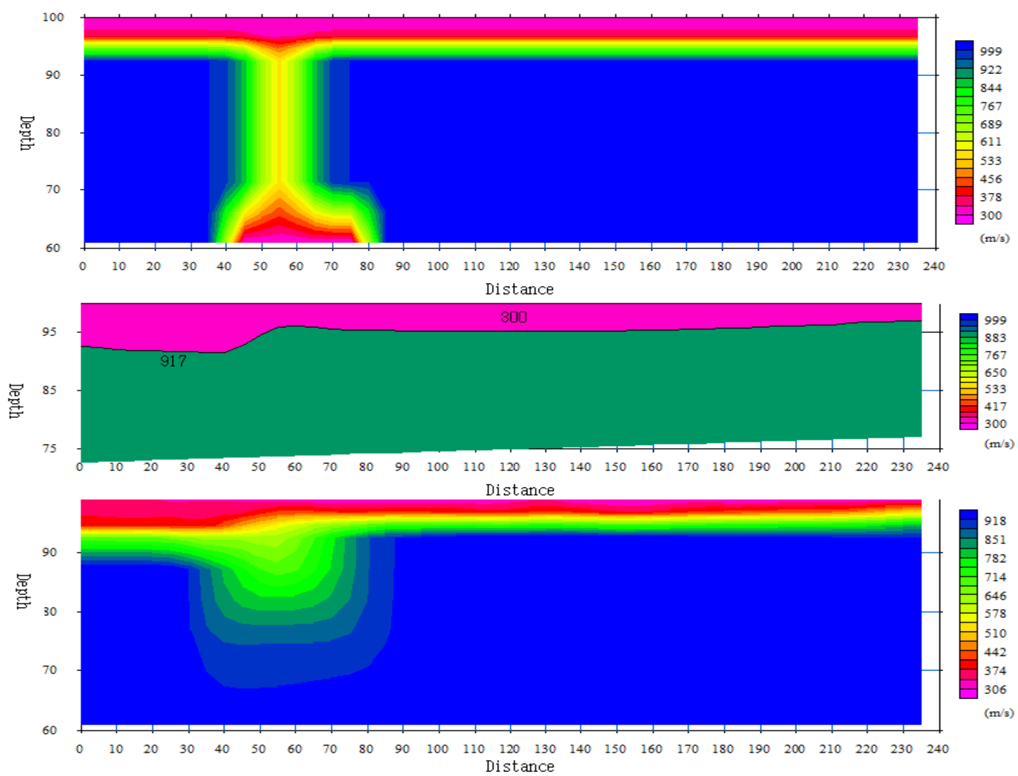

Figure13: Comparing velocities models (**Model 4**) for depression landform obtained from 1. TTI, 2.RT, and TI

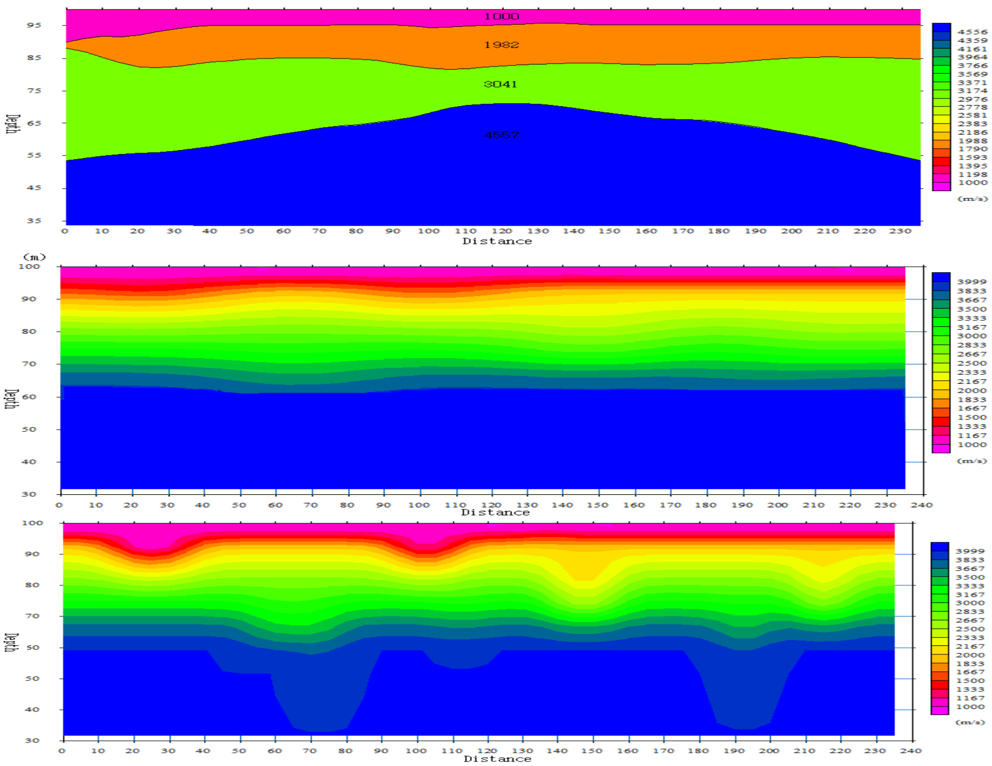

Figure15: Comparing velocities models (**Model 6**) for Karst Topography obtained from 1. TTI, 2.RT, 3.TI

V. CONCLUSION

Each method has its own strengths and weaknesses. Reciprocal and delay time methods provided preliminary information such as depth and velocity of refractors. The reciprocal method is one of the most widely layered-based interpretation methods used in the shallow refraction. Reciprocal methods use reverse shots (thus reciprocal) for the determination of depths and velocities of seismic layers and are therefore capable of resolving changes of velocities and depths of layer interfaces (2D models). Tomography was successful in smoothening lateral variations considerably and velocity model provided by it. Time-Term (delay time) method is a useful geophysical tool for subsurface reconnaissance and environmental studies. However, it fails in the determination of lateral velocity variation and identification of thin layer. Seismic refraction tomography is a method of interpreting seismic refraction is well suited for subsurface investigation of areas dominated by complex shallow structure, velocity gradients, and variable topography. The advantage of the time-term method over the tomography is in the higher resolution of depths end velocities of interfaces enabled by a simple linear inversion of data. The drawback is that the time-term method cannot handle gradient models, and hence its usage is limited to media where velocities are constant in the vertical direction in individual layers. Refraction tomography techniques are often able to resolve complex velocity structure (e.g. velocity gradients) that can be observed in bedrock weathering profiles. Layer based modeling techniques such as the RM is not able to accurately model the velocity gradients that can be observed in weathered bedrock. Among all the methods discussed, Tomography appears to provide optimum results, accurate depth section and precise velocities for different layers marked the operation of tomography. Its essence lies in the fact that it can tackle the discontinuities of refractor bed.

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