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Top to bottom interactive velocity analysis using travel-time ellipses and first break times from walkaway vertical seismic profiling data: a synthetic study

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Abstract: An interactive velocity analysis method is introduced in this paper and its efficacy was tested on various walkaway vertical seismic profile (WVSP) modeled data sets. In WVSP surveys, interval velocity profiles are determined fairly accurately along the VSP borehole using first break (FB) travel time picks from the zero-offset VSP (ZVSP) data. However, the accuracy of these vertical velocities fades away quickly as the source (S) distance (offset) from the VSP borehole increases due to possible horizontal changes in the geology or dips of the horizons. If the layer boundaries are not known, a simple type of ray tracing approach using a horizontally layered model may not be sufficient to accurately calculate the first arrival travel times from a S to a receiver (R). Introduced herein is an interactive velocity determination method to overcome the problem of finding layer interfaces in the events of unknown layer dips. Starting from the interval velocities of the ZVSP data, the algorithm successfully searched for and found travel time ellipses from the S to R and determined the boundaries of the layers where the interval velocities changed. The algorithm calculated the S to R travel time ellipses, searched for the best matching ellipse to the travel time pick from the data, and found the layer interface between the S and R (S-R) pair. Using the multiplicity of the S-R pairs, pseudo-ellipse images of the interfaces were created. The method was tested on several synthetic modeled data sets where it successfully expanded the interval velocity structures laterally from the borehole. Both direct as well as refracted wave arrivals were used in the evaluations.

Key words: WVSP, VSP, velocity analysis, first breaks, travel-time ellipses

1. Introduction

Vertical seismic profiling (VSP) is a commonly used technique in seismic exploration. In a VSP survey, a seismic source (S) is placed at the surface and the receivers (Rs) (usually geophones) are located in a borehole. The geometry of the VSP survey makes it look like a method to fill in the gap between surface seismic and borehole geophysical measurements. Since the seismic waves travel in a one-way path into the earth and the first arriving energy can be captured in the borehole, the travel times obtained from the first breaks (FBs) make an ideal case to determine the interval velocities along the VSP borehole in the form of a velocity-depth [$V_i(z)$] profile. It is a routine process to obtain check shots in seismic surveys for $V_i(z)$ control. The $V_i(z)$ from the FBs is a valid measurement at or near the borehole. Unfortunately, as the S offset from the borehole increases the vertical velocity, the $V_i(z)$ loses its accuracy, especially if the layers have dips or undulating interfaces. This is where the method proposed herein finds its importance. The algorithm maps the interfaces or boundaries between the velocity layers as the S moves away from the borehole. Since the algorithm uses not only the direct waves but also the refracted wave arrivals, long distances from the borehole seemed to be mapped correctly, and some examples of them are shown in the following test examples. The algorithm introduced herein is not a velocity analysis program, rather it is a method to find the extension of the interfaces between the velocity layers determined at the borehole.

Much work has been done in this area of determining velocities from the first arrivals and numerous researchers have presented their work on this subject. Using offset VSP data, which are a part of the walkaway VSP (WVSP) survey, Lines et al. (1984) showed how to estimate dips of the layers where the dip is determined iteratively by applying the method proposed by Crosson (1976). This method is similar to what was applied herein. The search-stop criteria were the travel times picked from the field data to match in both methods. The conversion factor was an assigned time interval (named epsilon). The method herein differs from their method in the sense that it does not make a dip assumption nor iterate for it. It automatically calculates the

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interface and creates a pseudo image of it using the S to R travel time ellipses. The amplitudes from the data were not used at this point, only the travel time ellipses were used in the analysis.

Balch et al. (1980) and Balch and Lee (1984) mentioned some methods by which the velocity fields are determined between wells. Mueller et al. (1979) discussed seismic tomography as a method to map the distribution of the velocities and also the absorption coefficients or amplitudes between the wells. Bois et al. (1972) presented the effects of ray path curvatures in the velocity calculation process between a cross-hole or two wells. Lytle and Dines (1980) described a two-layer model study using an iterative ray-tracing approach with increasing noise levels where they concluded that the resolution deteriorated quickly as the noise level in the travel times increased. Schneider (1990) and Schneider et al. (1992) discussed the application of cross-well tomography and showed the inverted velocity and amplitude or attenuation fields calculated from mathematical synthetic and physical modeled data sets. Guney (1990) presented results from straight ray tomography for velocity fields in his thesis study. Stewart (1983, 1984) talked about the inversion of travel times for velocities. Dines and Lytle (1979) showed results from computerized geophysical tomography, and Lytle and Dines (1980) presented results from interactive raytracing between boreholes. The general overview of the VSP technique can be obtained from Hardage (1985).

The structural base of the algorithm herein came from Erdemir (1997) and Erdemir and Balch (1999), where a similar approach was applied on both cross-hole physical modeling data as well as WVSP field reflection data sets and their results were presented. Both shot and R domain data sets were used in those studies.

The test results from the current investigation showed that the bottom boundary of a layer with a depth of 200 m was traced, identified, determined, and mapped as far as 1550 m away from the VSP borehole using the FB times from Ss with up to 2000-m offsets from the well head where the FBs were picked on the Rs below the layer.

The method was versatile when the velocity changed horizontally. In a dipping layer model test, the method successfully determined the layer boundaries where the changes in velocity occurred in both horizontal (x) and vertical (z) directions.

As also mentioned by Balch and Lee (1984), the method herein also requires that the velocities are known at the well confidently, and along the full borehole profile. Because an initial velocity model with horizontal layers is created at the well, if the velocities down to some depths are not known, an average velocity value approximation will be performed, which may cause loss of resolution in the areas where the velocities are not measured. The iteration process starts from the nearest S offset and continues by increasing the offsets from the well head. The travel time ellipses are created for each S and R (S-R) pair using the S velocity from the top of the layer and the R velocity from below the layer. If a layer boundary physically exists there and it continuous toward the S from the R, the algorithm creates a pseudo image at the interface between the mentioned layers. There is no iteration performed, it is a direct imaging of the interface using ellipses created from the travel times.

2. Methodology

This interactive velocity determination method was based on the studies of Erdemir (1992), Balch and Erdemir (1994), Erdemir (1997), and Erdemir and Balch (1999). In those studies, however, interval velocities were determined using the reflections coming from WVSP data sets. The method was expanded herein to find the interfaces of the velocity layers in the region between a S at the surface and Rs in a VSP borehole using the criteria of matching the first arrival times of the transmitted waves. Since each S-R pair is examined individually, unusual shapes of the interfaces between the two velocity layers can be traced and mapped without difficulty as long as the interface passes through the borehole. The analogy of the method is similar to the technique mentioned by Balch and Lee (1984) and Lines et al. (1984).

The algorithm starts with construction of a velocity-depth [V_i (z)] profile using the interval velocities obtained from zero-offset VSP (ZVSP) data at a VSP or check shot borehole. From the V_i(z), a flat layer velocity model is created. The interfaces selected at the borehole are next traced away to determine how far they expand laterally from the borehole and what shapes they are. This searching, exploring, and mapping is done for each S-R pair starting near the offset shot and continuing on in the farther offsets. The S interval is chosen depending on the complexity of the subsurface geology. If the geology is not complicated and does not change much laterally, a larger S interval may be used. A 500-m S interval was used in the current study, which seemed sufficient to produce accurate and satisfying results.

In summary, the method is composed of two main parts, as follows:

2.1 Part I: Initial model building

a) A WVSP survey or offset VSP data acquisition is assumed, and the FB travel times are collected from all of the WVSP data.

b) Interval velocities [V_{int}(z)] are calculated from the FB travel times of the ZVSP shot gather data.

c) A flat layer velocity model is created from the V_i (z) data. This is the initial velocity model to be used in the analysis. The user has to decide the resolution of the velocities at this stage.

2.2. Part II: Interactively building a velocity field

The top to bottom interactive velocity analysis method (TBIVAM) is applied at this stage:

a) The first layer (L_1) velocity is set as V_1 and the L_2 velocity is set as V_2, which are known at the borehole. Two ray propagation fields are calculated; the first is from the S down into the medium using V_1, and the second is from the R to every grid point in the medium. The interface is assumed to be anywhere between the S-R locations. From the one-way propagation travel time files, possible S to R travel time paths are produced, which yield travel time ellipses. The V_1-V_2 layer boundary is not known on either side of the borehole yet. It is assumed that the S sends waves with V_1, which are the down-going waves traveling to the R. The down-going wave after passing through the interface reaches the Rs (R_{L2}) in L_2 with V_2. There is a special path from the S to R_{L2}, in which the down-going ray travels and reaches R_{L2} with the travel time T_{L2} (where L# represents the layer unit number). If the path is determined correctly, then the V_1-V_2 layer boundary can be located in the path. However, since the layer boundary is not known, the exact ray path cannot be determined. This uncertainty was solved by assuming that every grid point between the S-R could be a boundary point, and they could be anywhere between the S-R locations. Thus, all possible ray paths from S to R are calculated and plotted in the form of travel time ellipses. The assumption here is that if there is a boundary between the S-R pair, one travel time ellipse should correspond to the FB travel time which is obtained from the field data. The algorithm searches through the ellipses and selects the one which corresponds to the pick time. Now, one ellipse is found, but the uncertainty still exists since the interface point could be anywhere along the chosen ellipse. The ellipses from other Rs from L_2 are also calculated and plotted together in the same file hoping that the ellipses would land along the boundary and reinforce each other creating a maxima time location, which will yield a portion of the boundary, as mentioned by Erdemir (1997) and Erdemir and Balch (1999). This is true if a boundary exists there. If there is no clear velocity change along the first arrival travel path of the S-R pair, there should not be a boundary separating the two velocities and the ellipses should not provide a solution. As more ellipses from other Rs are included in the combination plot, the interface starts to build up and a pseudo image of the interface is created along the interface at the correct location where a maxima time area is created. The procedure is repeated for other selected S locations along the WVSP profile to enable a lateral continuation of the interface between the upper and lower velocities (V_1-V_2). Larger S offsets yield longer distances of the interface from the R borehole.

b) Once the boundary (L_{12}) between V_1 and V_2 is determined, the bottom boundary of L_1 is now known, which means that L_1 is confined from the surface to the top of L_2. L_1 is then fixed with V_1 on both sides of the borehole. For L_2, the analogy is as follows. Two models are created; one is for the S side and the other is for the R side, as done previously. In the S side model, a two-layer velocity model is created where the known L_1 is used and the region below it is flooded with V_2, the L_2 velocity. For the R side, a constant velocity model is created with V_3. The Rs in L_3 (R_{L3}) are selected for the R side calculations. The S to the R_{L3} travel time ellipses are created using the new models. For each S-R_{L3} pair, the correct ellipse is selected and extracted from the ellipses file after matching the picked FB travel times. The ellipses from all the selected Rs are then plotted together to form the boundary between the L_2 and L_3 interfaces (L_{2-3} interface). If there is an interface there, the ellipses will form a maxima time location or surface on the boundary. After the procedure is repeated and completed for the selected Ss along the WVSP profile, the maxima time points on the ellipses are picked and connected along the interface via interpolation.

c) The above procedure is repeated for deeper layers until the last layer is mapped and the last interface is determined.

d) The interval velocities are assigned to the layers to create a velocity field file.

e) A check procedure can be followed-up if necessary, by forward travel time calculation using the model of the new velocity field and comparing the FB travel times from the new model to those coming from the exact model or the field data, but this step was not performed in this investigation.

The above procedures are summarized in Figure 1 as a flow diagram. In the following sections, the procedure was applied on different models and its efficacy and accuracy are shown and further discussed in their respective sections.

3. Applications of the algorithm

3.1 Flat layer model

The algorithm was first tested on a flat layer model to see if it could successfully determine the layer boundaries without any issues on a relatively simple model. The velocities were chosen arbitrarily for the model. Moreover, to determine from how far away the layers could be resolved from the VSP borehole, the model was extended extra horizontally.

The built model is shown in Figure 2. It has four layers, with velocities V_1 to V_4. A WVSP survey was simulated on the model. The S, R, and borehole locations are indicated in Figure 2. The model has a 5000-m width and 1000-m depth in horizontal (x) and vertical (z) directions. Grid spacing is 10 m in both the x and z directions. A finite

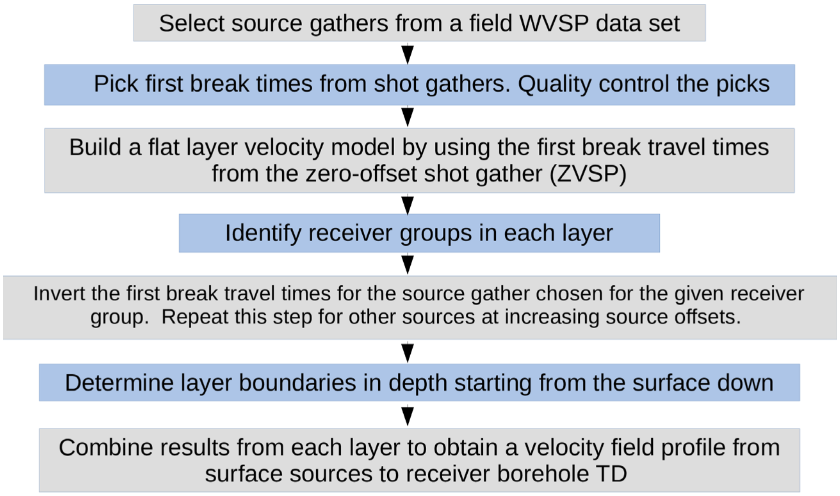

Figure 1. Flow chart of the top to bottom interactive velocity analysis algorithm (TBIVAM).

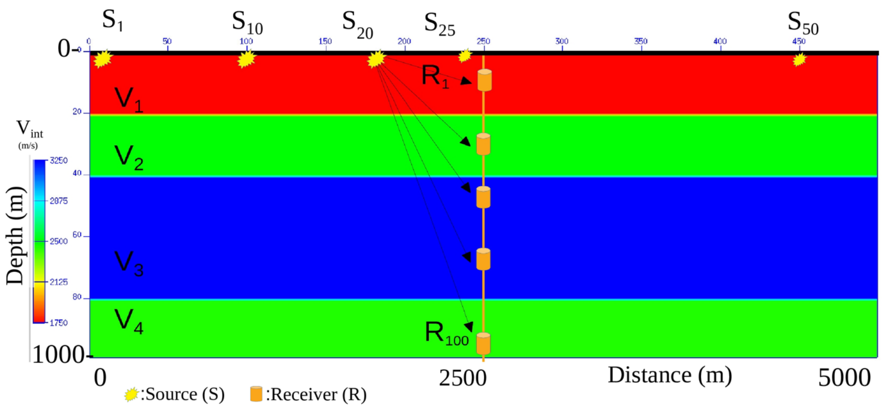

Figure 2. WSVP model. The first arrivals are illustrated schematically from one S location near the VSP borehole.

difference modeling data set equivalent ray tracing data set was created from the shown survey. The shots were created at 100-m intervals. The velocity analysis application was done at 500-m S intervals, where the S interval used was large because the model was not complicated. Down-going rays from the Ss to Rs are schematically shown in Figure 3 using straight ray drawings for simplicity. The ray-tracing algorithm, however, followed Snell's law and used bended rays. The shaded zones in Figure 3 indicate areas scanned by the down-going transmitted waves, where the scanned zones look larger at the top and narrower toward the bottom of the borehole. FBs were picked on the selected shot gathers. The FB times analyzed for the ZVSP data are shown in Figure 4, where the travel time picks are shown in (a) and the interval transit times are shown in (b) in microseconds (µs). The layer boundaries are indicated by circles.

The interval velocities were calculated using the ZVSP FB travel times, from which a horizontally layered model was created. The interval travel times, and the initial model are plotted in Figures 5a and 5b, respectively.

Two models were created to find the velocity interfaces; one was with V_1 for the down-going propagation from the S and the other was with V_2 for the up-going propagation from R. Both models are shown in Figure 6. For the ZVSP case, the forward travel times from the S and reverse travel times from the R and the ellipses from the S to R are shown in Figures 7a and 7b as circles, and in 7c as ellipses.

All possible ellipses were created for all the selected shot-R pairs for the analysis. For L_1, the ellipses extracted after matching the FB travel times are shown in Figure 8, where for the one shot-one R (S-R) pair, the ellipses are shown in (a), and for the same shot with many Rs the collected ellipses are shown in (b). As more Rs were added,

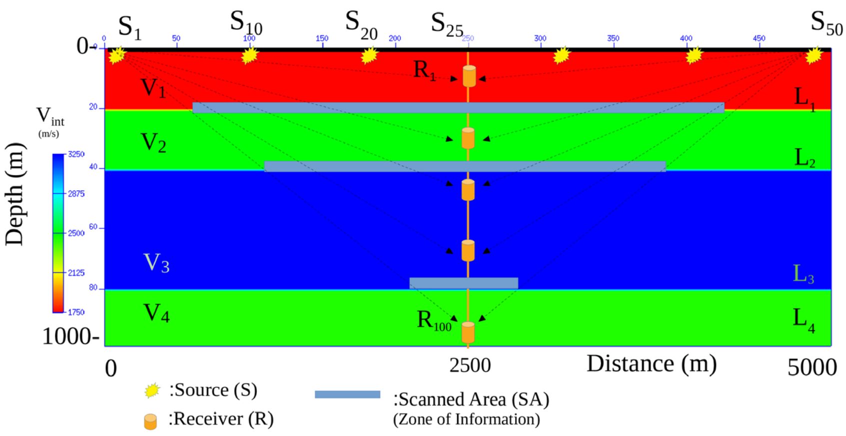

Figure 3. WSVP model. Zones of the reflectors scanned by the first arrivals are schematically illustrated in the model as horizontal rectangular blue shaded zones. For this geometry, first arrivals seem to form a cone or an upside triangle shape. As the R deepens, the zone of coverage shortens horizontally due to the nature of the acquisition geometry. The shaded zones are expected to be resolved by the algorithm. The borehole is at 2500 m in x corresponding to S_{25}.

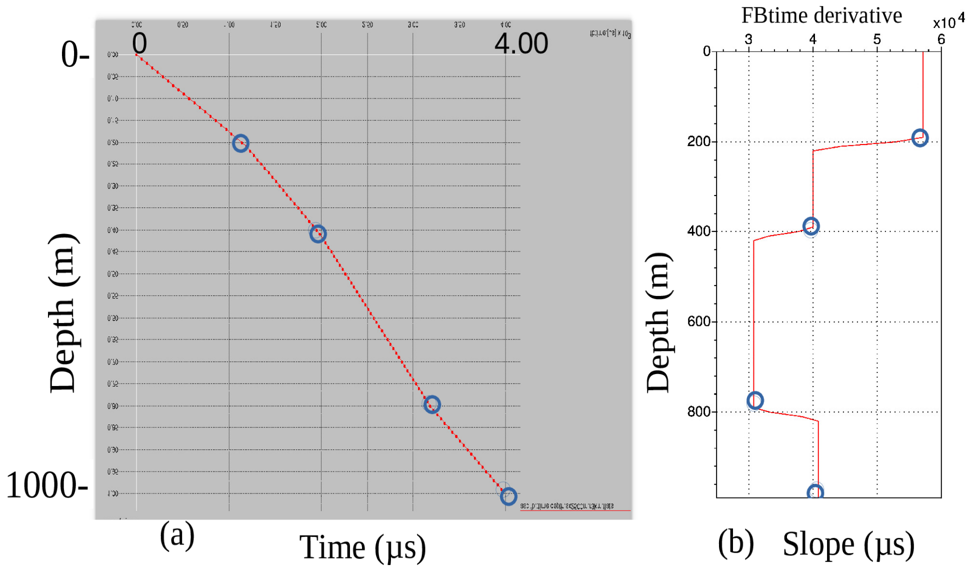

Figure 4. FB travel times from the ZVSP shot gather are shown in (a), interbed transit times [in microseconds (µm)] from the FB time picks in (b). Both curves were plotted as a function of depth in the vertical scale. Layer boundaries are shown in circles on both curves.

the ellipses accumulated and constructively reinforced each other in a region creating a maxima location there. The region is indicated by an arrow and a point (P) in Figure 8. The ellipses obtained from the other Ss were collected and plotted together in (c). The maxima locations are indicated by the green dots at the interface locations where the down-going transmitted waves pass through L_1 to reach the Rs in L_2 (R_{L2}). The maxima points line up at the bottom boundary of L_1 in (c).

There are interesting points in Figure 8, where it can be seen that the L_1 boundary was determined about 1750 m away from the borehole, while the layer depth was 200 m. As one would expect, the first energy arriving at the Rs in L_2 would be mostly refracted waves from those distances. Obtaining solutions from such large distances (about 1750 m) for a shallow layer suggests that the method and the algorithm seemed to also make use of the refracted first arrivals, in addition to the transmitted direct waves.

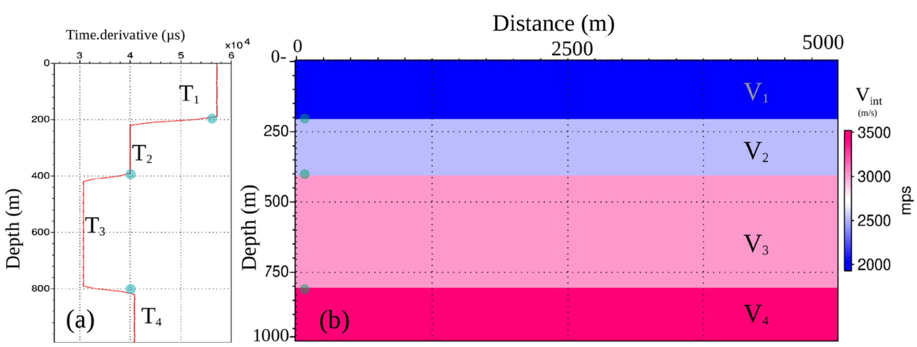

Figure 5. (a) Interval transit times calculated from the FB picks of the ZVSP gather, and (b) flat layer model constructed from the layer boundaries shown by the dots in (a).

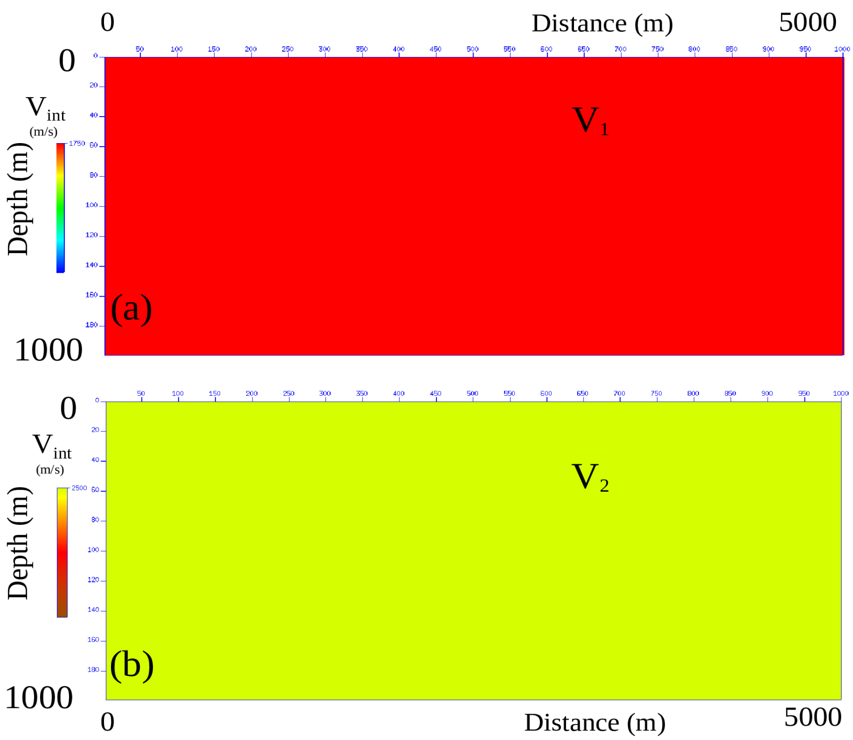

Figure 6. Two velocity models were created for the travel time calculations, where (a) is the S side model with V_1 (1750 m/s) and (b) is the R side model with V_2 (2500 m/s). The plots are given in number of grids where the grid spacing is 10 m in both horizontal and vertical (x, z) directions.

Since L_1 was now known, using the Rs in L_3, the maxima points for the bottom boundary of L_2 were determined next. Figure 9 shows the extracted ellipses from the selected Ss plotted together, where for the L_2 interface in (a) and similarly for the L_3 interface in (b), the combined ellipses from all three layers are plotted in (c), which can be used as a final image (or solution). It is seen in the plot that the maxima points aligned accurately at the layer boundaries of the respected layers.

As the R got deeper in the borehole, the zones scanned by the transmitted waves got narrower, as mentioned before. The final image was compared to the schematic of the WVSP acquisition geometry in Figure 10, where the image is shown in 10a and the geometry is shown in 10b. Notice the similarity between the two triangles drawn by the thick light green lines in (a) and (b).

3.2 Dipping layer model

The algorithm was next applied on a dipping layer model. The model and the WVSP survey are shown in Figure 11. The purpose here was to show that the dipping layer (V_3-V_4

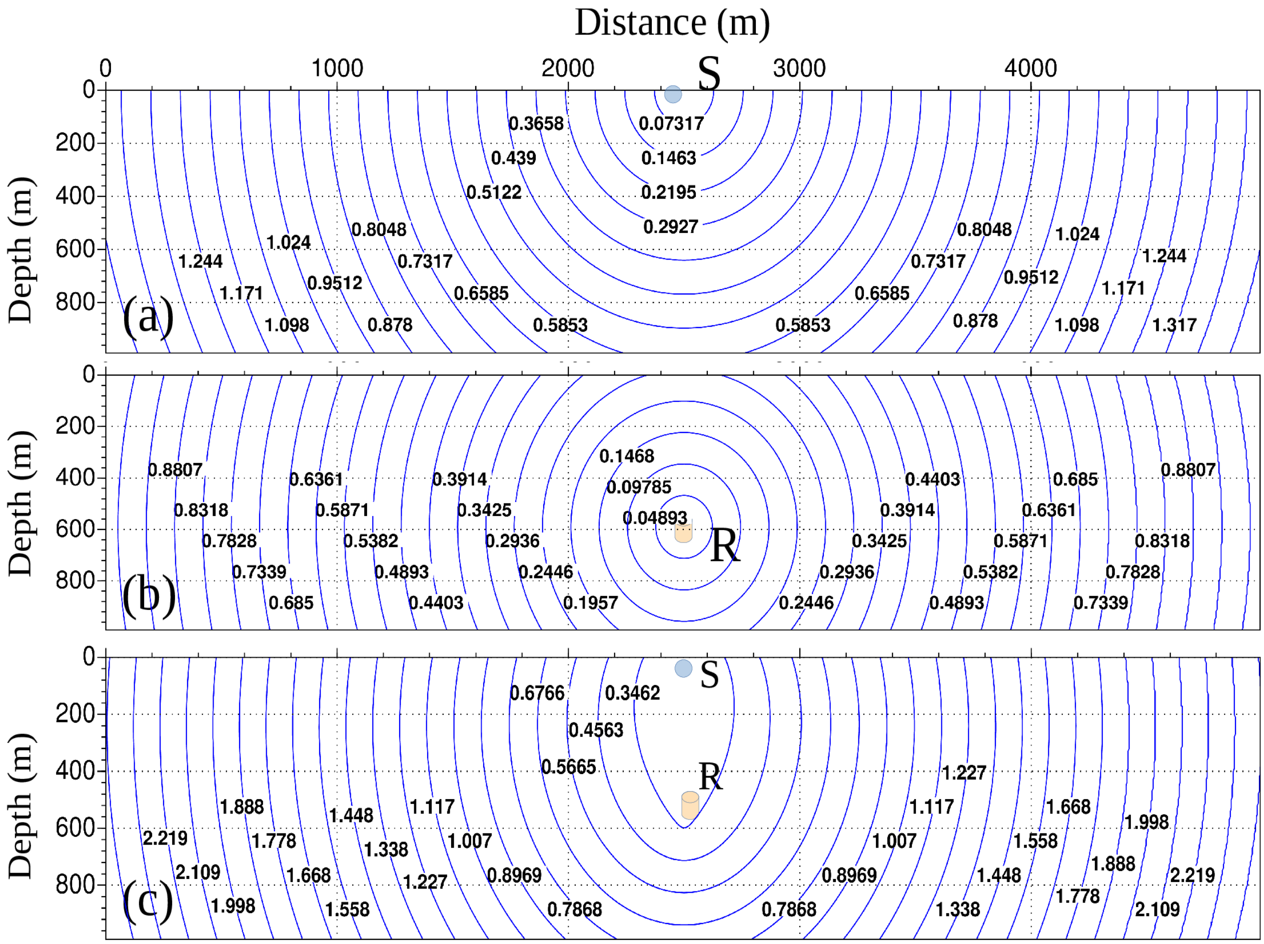

Figure 7. One-way travel times were calculated to every point in the medium using the models shown in Figure 6; (a) travel times from S shown as a green dot, (b) travel times from a R shown as a yellow cylinder, (c) travel times from the S to the R. The travel times form circles in (a) and (b) and ellipses in (c).

interface) as well as the layer below it could be resolved by the algorithm. The dipping layer was not a planer surface, it only flattened at both ends.

A WVSP survey was run on the model as before, and the FB travel times were picked from the data. The ZVSP FB picks, interval transit times, and interval velocities are shown in Figures 12a, 12b, and 12c, respectively. The interval velocity profile and the flat layer model created from it are shown in Figure 13.

The flat layers (the L_1-L_2 and L_2-L_3 interfaces) above the dipping layer were determined first. Their combined pseudo images from nine Ss are shown in Figure 14, where the L_1-L_2 interface is shown in (a) and the L_2 -L_3 interface is shown in (b). Moreover, a comparison of the L_2 -L_3 interface with the model boundary is shown in (c). The interfaces obtained from the maxima points of the ellipses seemed to match the model well, as shown in (a) and (c).

L_3, which is the dipping layer, was determined as follows. After L_2, the model was flooded with V_3 and using that, a three-layer velocity model was built. It was used for the S side propagation simulation. For the R side, a V_4 constant velocity model was built. The Rs below L_3 were used in the calculations. The S to R travel time files were calculated from the propagation models. The combined ellipses from the dipping layer analysis are shown in Figure 15, where the image from the ZVSP data is shown in (a), ellipses from the other Ss are shown in (b), and the pseudo images from the maxima points are compared to the exact model layer in (c). Notice that the ellipses and maxima points follow the dipping interface nicely on both sides of the VSP well. The L_3 interface was then assigned to the model.

L_3 is interesting because it has dipping parts as well as flat parts. Not only the dipping parts alone but also the flat parts of it seem to have been determined and resolved by the maxima points, as seen in Figure 15. What was seen in this test was very encouraging for the method. The test indicated that the algorithm accurately kept track of the

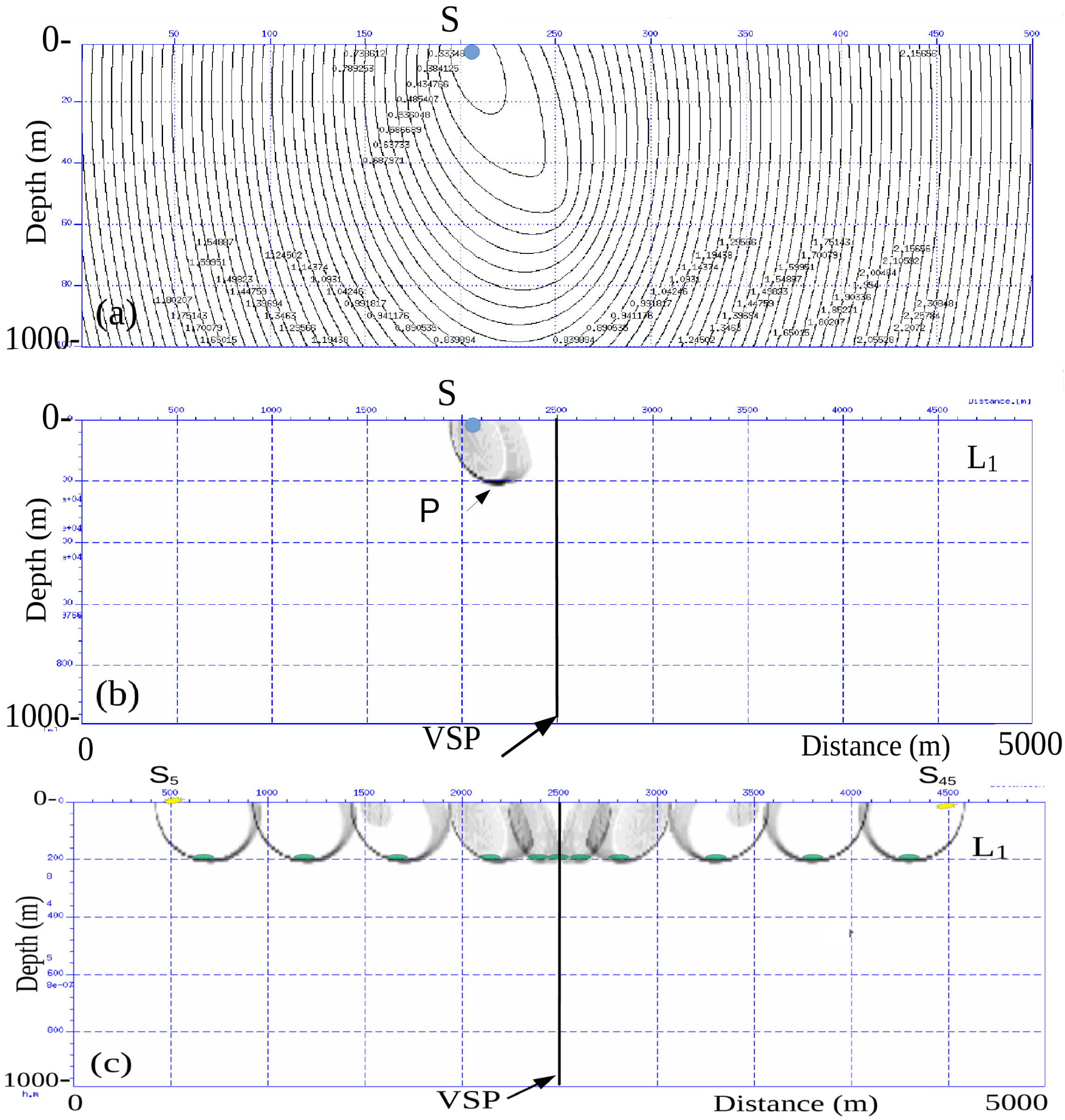

Figure 8. The calculated S to one R first arrival-travel time ellipses are displayed in (a), the ellipses corresponding to the FB times from the same S to the Rs in the L_2 were selected and plotted in (b), where a maxima time point is shown by P and an arrow. Ellipses for all the selected shots are shown in (c). Notice how the ellipses concentrate at the L_1 interface. The depth of the layer is 200 m, the borehole is at 2500 m in –x, and the ellipses seem to indicate the L_1 boundary as far as 1750 m away from the borehole on both sides (see the green dots).

upper-flat, up-dipping, down-dipping, as well as the down-flat parts of the horizon and on both sides of the VSP borehole.

In order to follow how the pseudo-images from individual Ss contributed to the whole, a progressive display of the ellipses from each shot was made for the L_3 boundary, which is shown in Figure 16.

The maxima points (or collection locations) for the L_4 interface, which was below the dipping layer, were similarly identified by the travel time ellipses and are shown in Figure 17, where the ZVSP case is shown in (a), the combined ellipses are plotted in (b), and the dots are connected and compared to the exact model in (c). The maxima points of the ellipses seemed to land correctly on the L_4-L_5 boundary, as shown in (c).

In the final step of the analysis, all the pseudo images from the WVSP survey were combined and plotted together in the same plot, where the dots were interpolated to yield the interfaces, as shown in Figure 18.

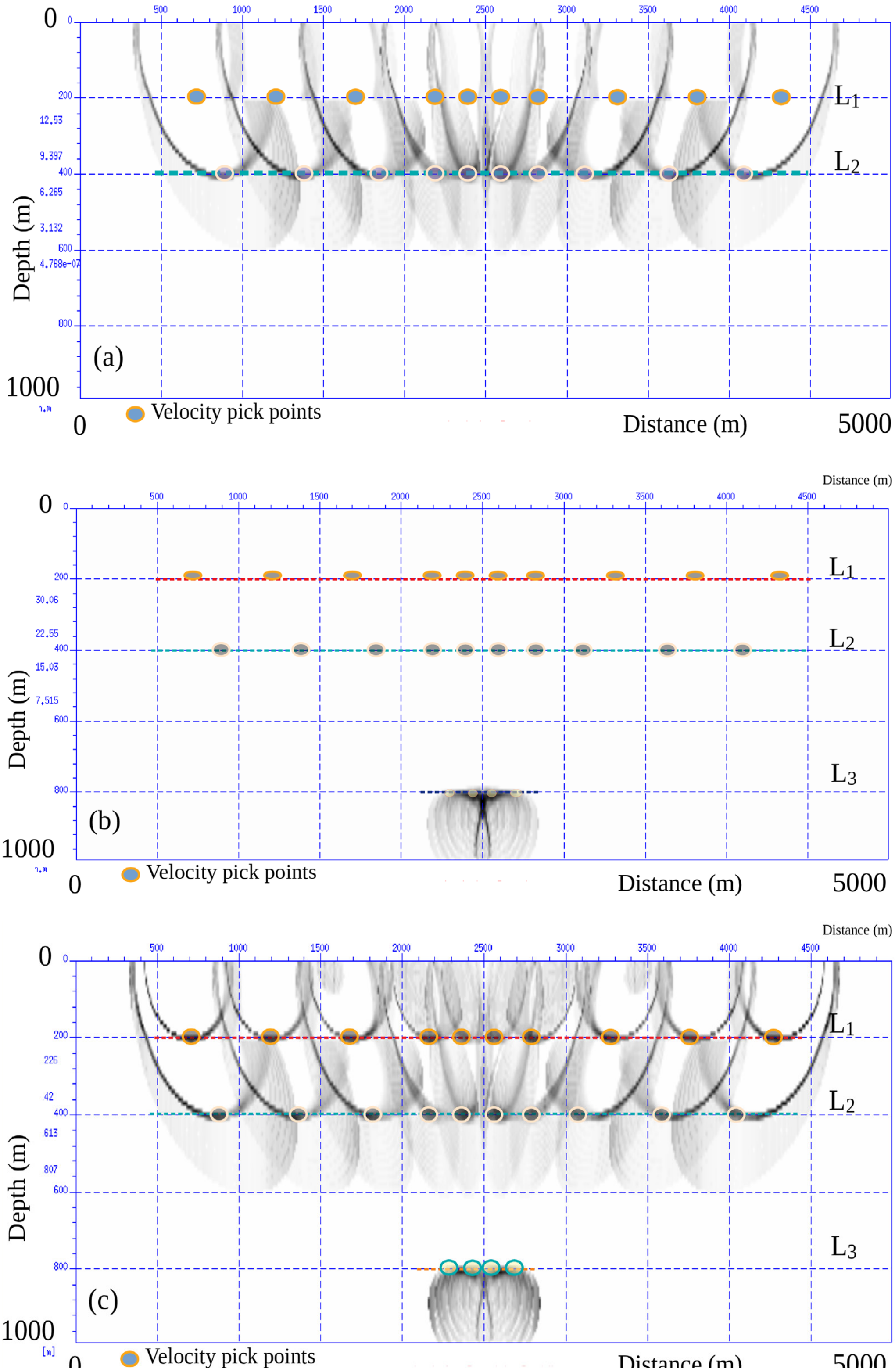

Figure 9. As the follow-up of Figure 8, the travel time ellipses were extracted and plotted together for the selected shots in (a) for L_2 and in (b) for L_3. The ellipses and the maxima points from the three layers were combined and plotted in (c). The maxima points or circles were connected by lines to create layer interfaces, as shown in (c). The dots are the picked points for the maxima zones.

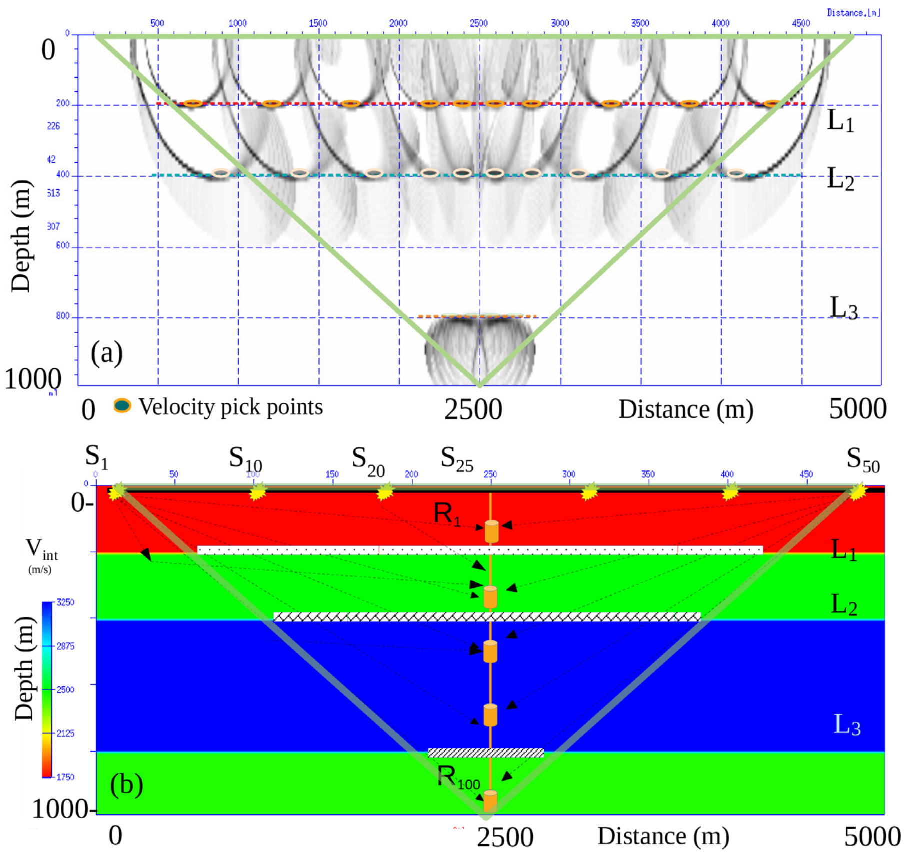

Figure 10. Scanned zones by the transmitted first arrivals were connected, resulting in an inverse triangle shape (shown in light green lines). The solution obtained from the algorithm is shown in (a) and the expected solution is illustrated in (b).

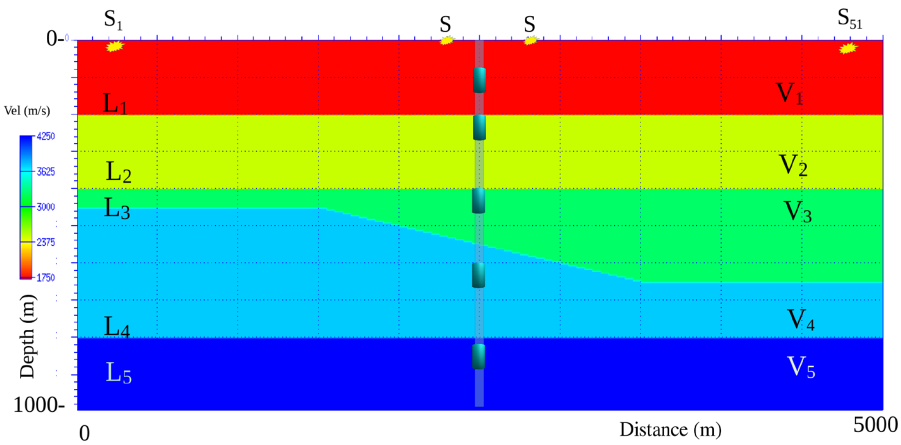

Figure 11. Dipping layer model with five different velocities. A dipping layer was introduced in the middle of the model with V_4.

4. Final words and recommendations for future work

It has been shown in the examples that the method and the algorithm herein produced promising results from the two modeling studies. When compared to the original models, the layer interfaces were imaged accurately. The flat layers were purposely examined first to see if the algorithm had any problems in determining flat layers and how far it could trace the interface from the borehole. The results indicated that no problems were seen in working with them. The method was

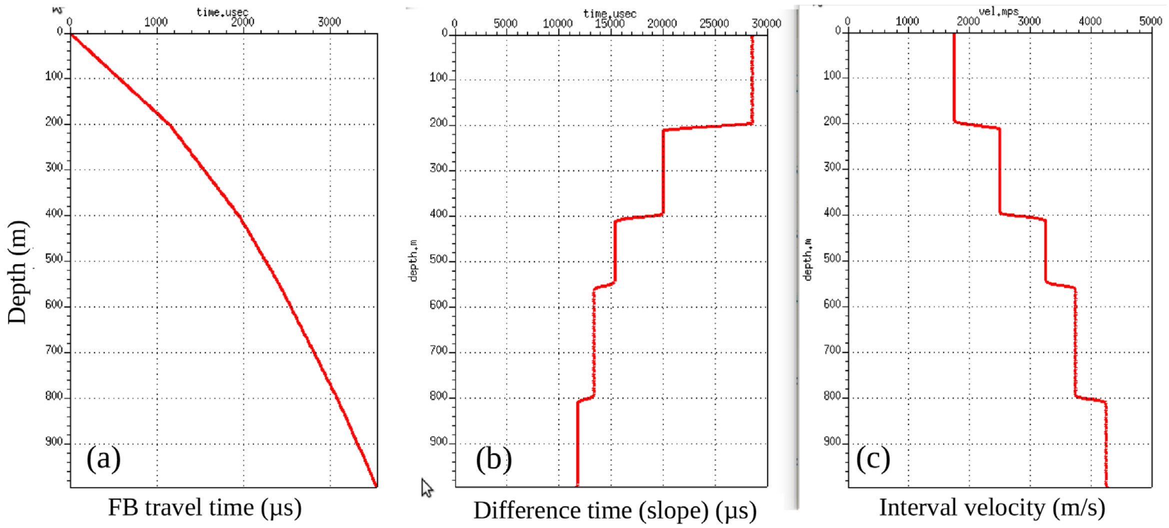

Figure 12. For the velocity analysis of the dipping layer model, the FBs were picked from the ZVSP shot gather. Shown here are (a) the FB picks, (b) interval travel times, and (c) interval velocity profile, where (b) and (c) were calculated from (a).

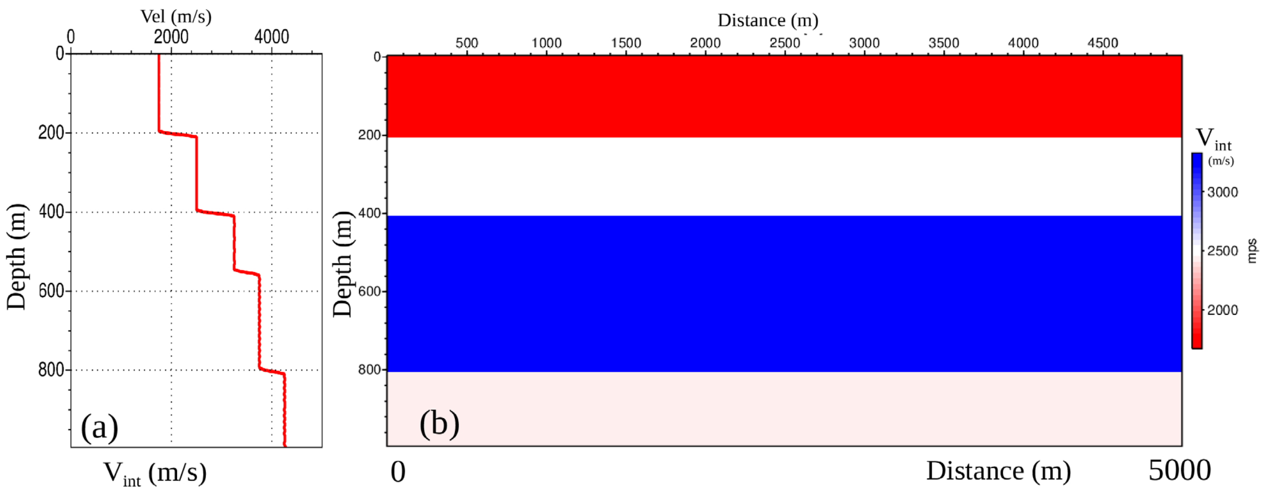

Figure 13. (a) Interval velocity profile and (b) a flat layer velocity model created from (a). This is the initial velocity model used in the algorithm for velocity structure analysis.

challenged with a dipping layer model, which had both a dipping layer and horizontal layers. It was seen in the solutions that the method successfully determined the interfaces on the dipping layer as well as the layer below it, accurately.

It was pleasant to see that the method used not only the direct arrivals but also the refracted arriving travel times in the solution. As a result, the layer boundary of L_1 with a 200-m depth was tracked as far as 1750 m away from the VSP borehole. The method could also be tested on farther distances to determine its resolution limit.

The results shown so far were obtained from model data sets and the data were noise free. Certainly, it should also be tested on field data sets to further challenge the algorithm. Some noise could be added to the travel time picks for further testing analysis.

The technique seemed to be holding fine when the velocities changed along the depth of the VSP borehole, as long as the layers cut thorough the borehole. However, when there are discontinuities within the layer or the velocity changes horizontally within the layer (for example, gradually changing from V_1 to V_2) on the same side of the borehole, the resolution power of the method is expected to degrade because the first arrival time would not be unique anymore; it would travel through more than one velocity unit yielding a FB travel time that

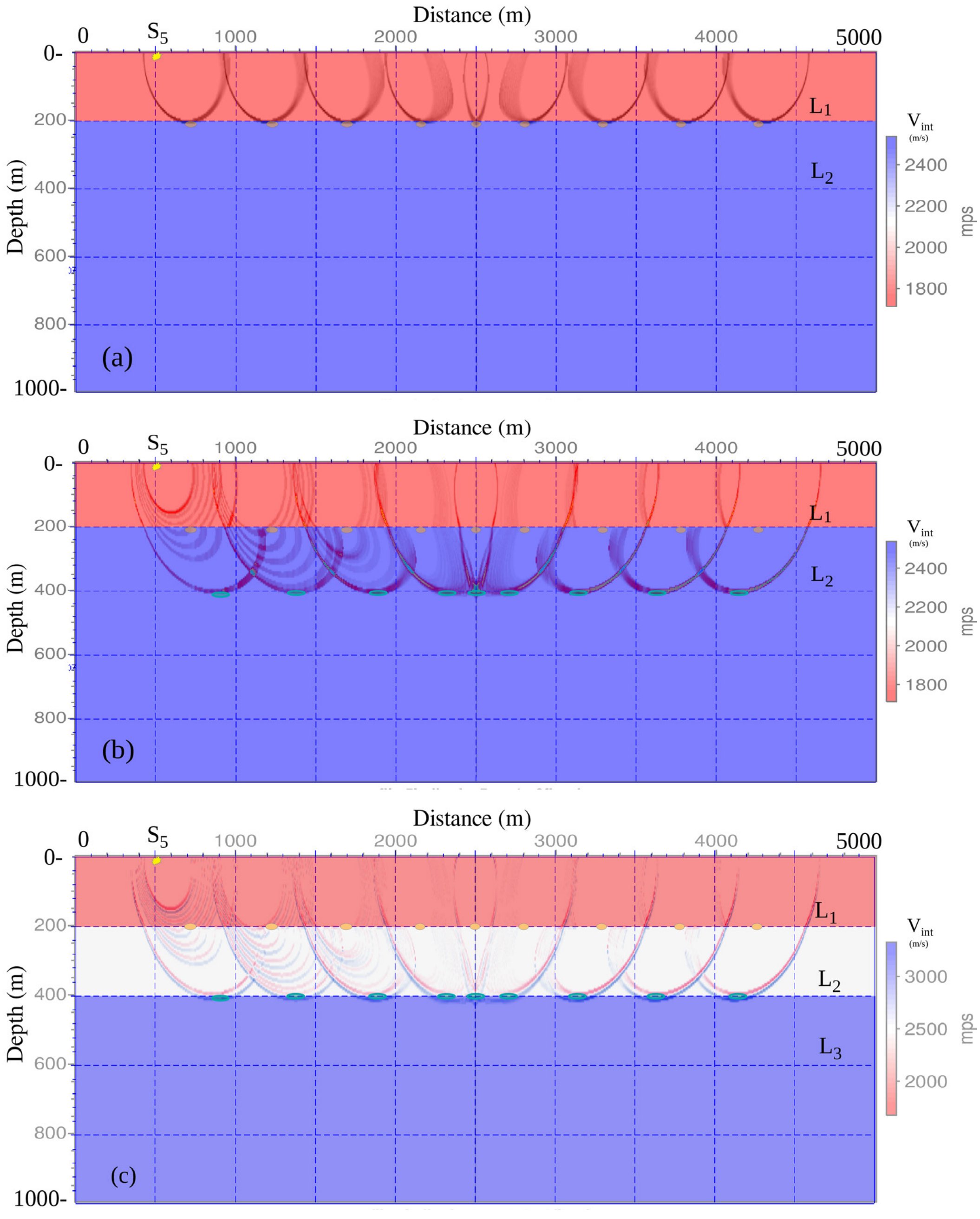

Figure 14. The ellipses from nine Ss were plotted together to form a surface. The maxima points picked on the ellipses were connected to form a boundary line. The interface between the L1 and L2 surfaces is shown in (a) and between the L2 and L3 surfaces in (b). Comparison of the L2-L3 surface with the exact model is shown in (c).

averaged both units. Some of these tests still need to be performed in near future studies for further elaboration of the method.

5. Conclusions

The algorithm developed herein seems to be a powerful tool to determine velocity layer boundaries of the subsurface in a WVSP survey using the FB travel times of the transmitted waves. The method was tested on two models; one was a flat layer model and the other was a dipping layer model. In both model studies, the interfaces were determined successfully at their correct locations. The layer boundaries calculated from the algorithm seemed to match the expected scanned zones of the transmitted waves.

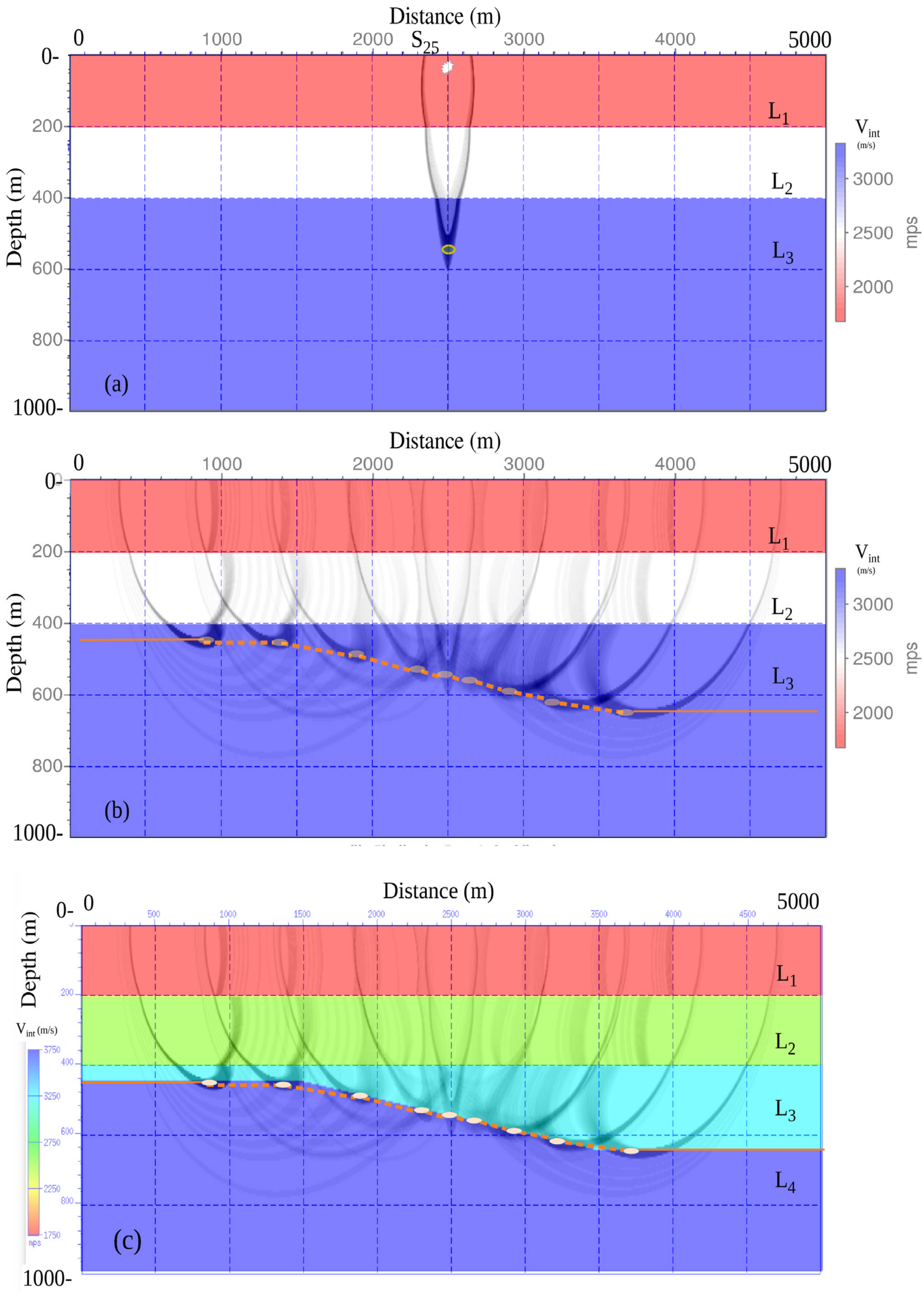

Figure 15. Building pseudo-images for the dipping horizon (L_3-L_4 interface). The ZVSP FB times were used first in the analysis. The extracted ellipses converged on the L_3-L_4 boundary, as seen in (a), where the dot indicates the boundary location for the shot. The other ellipses from all nine Ss were combined and plotted in (b), where the markings (or dots) are connected to form an interface. In (c), the interface was assigned as the border line between L_3 and L_4. The left most and right most points in (c) indicate that L_3 flattens at 1500 m on the left and 3500 m on the right sides of the borehole.

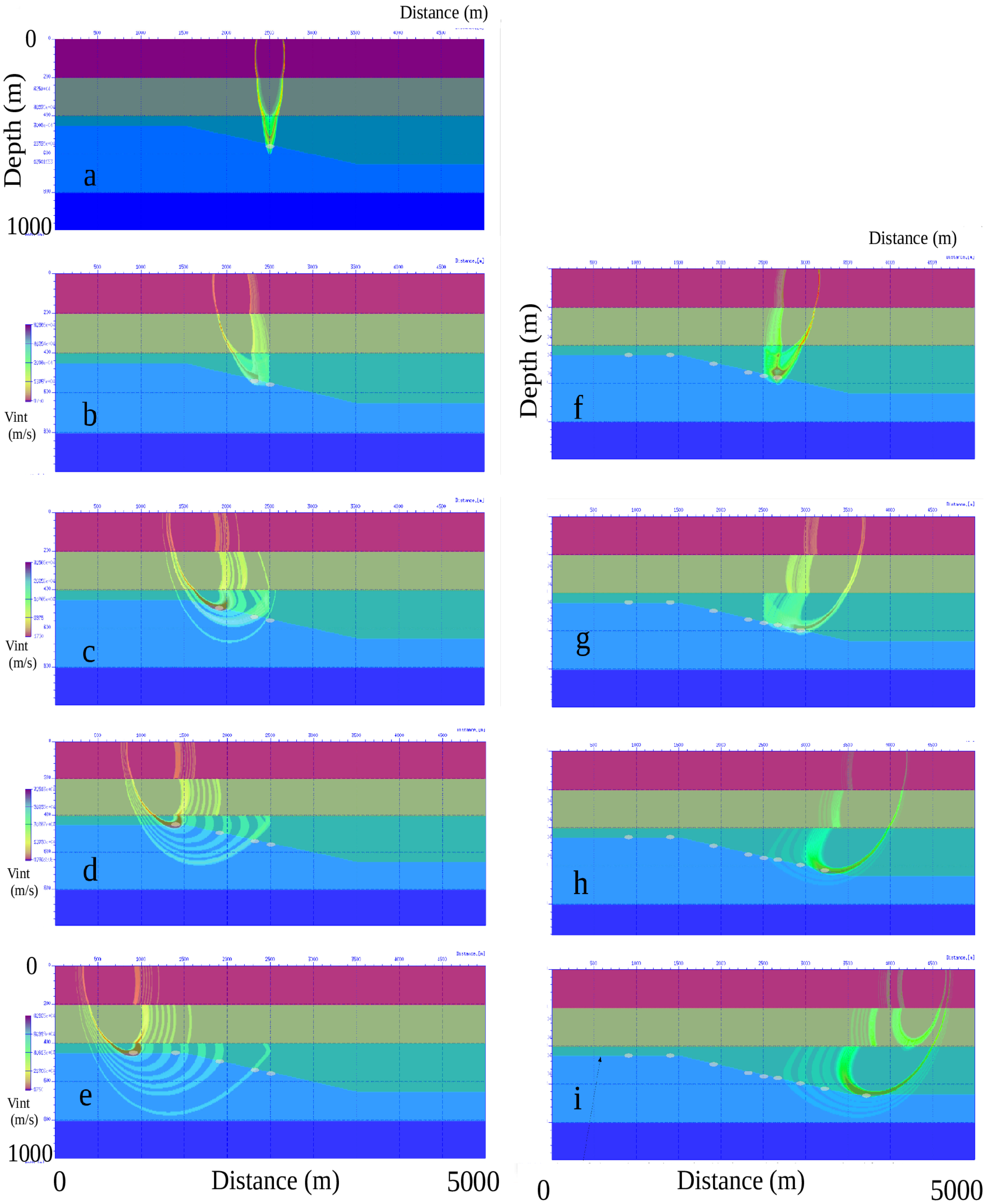

Figure 16. Progressive plotting showing how the dipping layer (L_3) was constructed. The ellipses extracted for each S were plotted in a panel. The panels in (b) through (e) are for the left side Ss and those in (f) through (i) are for the right side Ss. The S interval was 500 m. The exact model is presented in the background to check the accuracy. The ZVSP case is shown in (a). The dots indicate the maxima point locations, which were picked on the ellipses as interface locations.

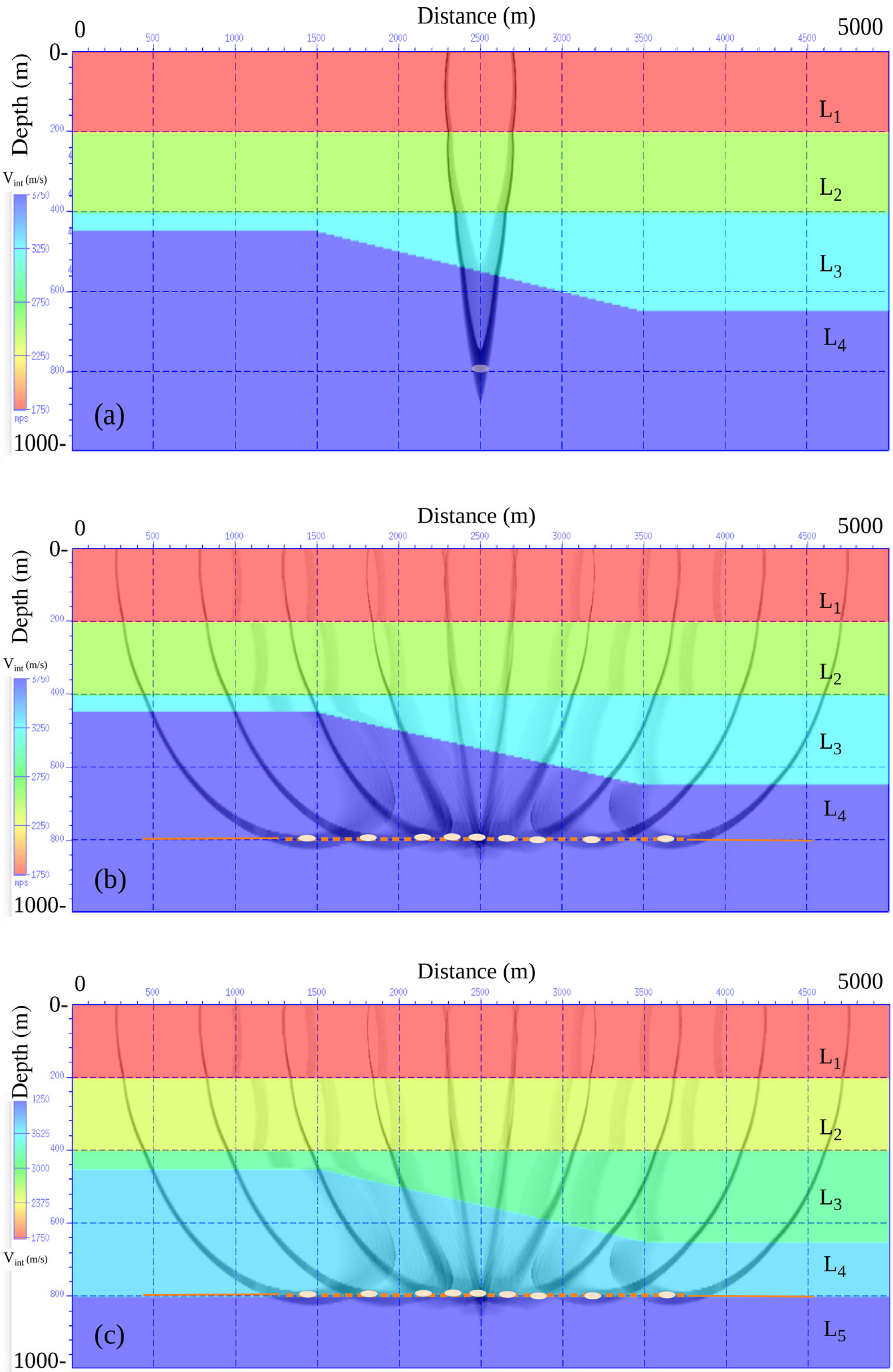

Figure 17. Velocity-related layer boundary analysis was also done for the L_4-L_5 interface. The result from the ZVSP shot is shown in (a). The results from nine shots are shown in (b), where the dotted marks are combined to form the L_4-L_5 boundary. The interface was compared with the model in (c). The maxima points picked on the ellipses are shown by the dots.

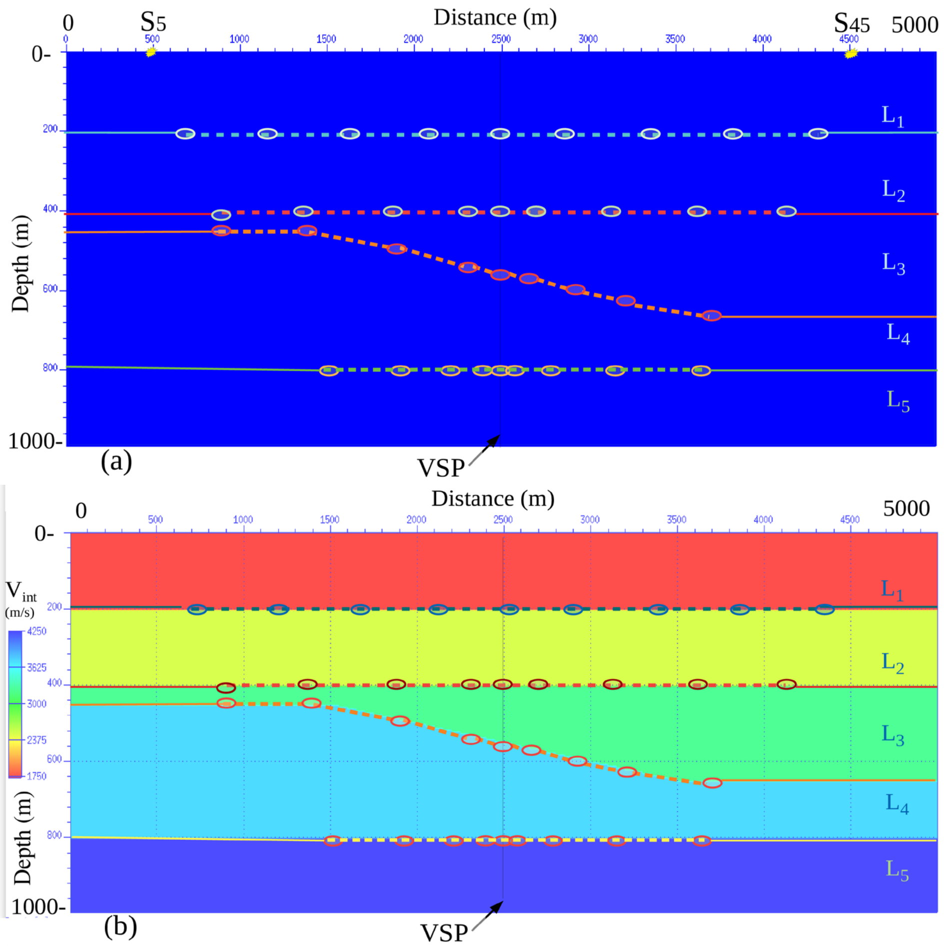

Figure 18. All the maxima points from the ellipses from the dipping model were combined and plotted in the same plot in (a), where the maxima points were connected and assigned borders. The regions within the borders were assigned velocity values to create a velocity field or model in (b). The constructed model from the algorithm is overlaid by the exact model in the background. A good match was seen between the two.

It seems that the method used both direct arriving travel times as well as refracted wave travel times. Due to the uses of the refracted wave travel times, information from layer boundaries of long distances away from the VSP borehole could be obtained, as it was in the case of the L_1 boundary in the current model studies.

The method was first applied on a horizontally layered velocity model, where the velocities changed only vertically. Then, it was tested on a model with dipping and also flat layer interfaces. The velocity changed horizontally in the dipping layer section. In both models, the results showed that the calculated layer boundaries matched the model true boundaries successfully. The results from the dipping layer were interesting; the up-dipping, down-dipping, as well as flat portions of the same layer were determined around the borehole successfully. L_4 below the dipping layer was also identified and resolved nicely at its correct location.

Based on the accurate results from the models, it was concluded that the method and algorithm will help fulfill a great need to build the interval velocity field at and around the VSP borehole using the FB arrival times from a WVSP survey.

In all the models and calculations, it was assumed that the layers were continuous and they passed through the VSP borehole.

No VSP data amplitude information was included in the analysis, only the travel time ellipses and first-break arrival times were used for simplicity. However, the method was quite computer time-intensive.

The calculations showed that it is necessary to use the Rs below the layer in order to determine the bottom boundary of the layer. If any R in the current layer is included in the search, then noise ellipses (or artifacts) are also produced, contaminating the solution.

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