PRACTICAL CONSIDERATIONS FOR GRM REFRACTION SURVEYS IN GLACIAL TERRAINS

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ABSTRACT

Generalized Reciprocal Method (GRM) refraction surveys in glacial terrains frequently encounter complex geologic and hydrogeologic conditions. The complexity frequently centres around the shallow water table and low velocity of the unsaturated zone. Inaccurate determination of the velocity and thickness of this low velocity layer can have a significant effect on the depth estimate of lower layers. This paper discusses methods to optimize field data collection and processing to ensure proper analysis in these situations.

A general rule of GRM surveys is that the geophone spacing should be less than one third of the XY distance of the shallowest layer. Since the XY of a shallow water table layer is often less than 2 metres, geophone spacings of less than 1 metre may be necessary. These spacings are frequently not cost effective, and alternative approaches may be required. Alternatives include; 1. using the GRM average velocity method and an estimate of the XY based on modelling, 2. combining the upper two layers, and 3. using time intercept methods to interpret short spreads collected at various points along the line.

The sensitivity of the GRM is evaluated using a simple model. Random pick errors are introduced into the model, and the merit of arrival averaging is studied. Similarly, layer velocity errors, XY analysis errors and hidden layer problems are reviewed.

Practical suggestions for GRM surveys in glacial terrains are offered. An approach for performing cost effective GRM surveys is presented. The approach is based on high redundancy data collection (multiple mid shots) for water table velocity analysis and duplicate arrival averaging. Finally, the importance of XY analysis for detecting hidden layers and bedrock surface features is discussed.

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INTRODUCTION

The Generalized Reciprocal Method (GRM) is a seismic refraction technique for mapping subsurface refractors from forward and reverse travel times (Palmer, 1980). The most common application of refraction techniques is the identification of stratigraphic layers; generally the depth to bedrock (Haeni, 1986). Refraction techniques are most commonly used when bedrock is less than 30 m deep.

The GRM is commonly recognized as the most sophisticated refraction method available (Scott and Markiewicz, 1990). Unlike ray-tracing and reciprocal methods, the GRM does not over-smooth or average the subsurface refracting layers. In addition, the technique provides an approach for recognizing and compensating for hidden layer conditions. In general, the GRM is one of the more accurate shallow geophysical investigation techniques.

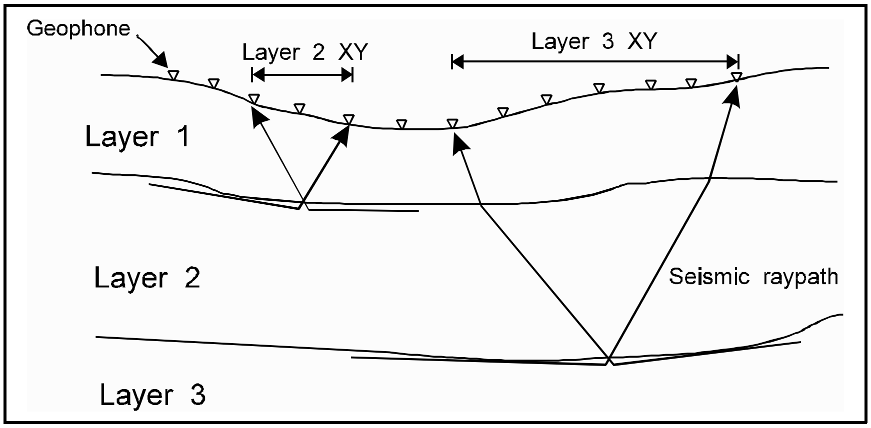

Figure 1: Cross section showing the XY distance for critically refracted seismic rays.

Central to the GRM is the determination of the XY distance. Forward and reverse seismic rays emerging from a point on the refracting surface appear at ground surface separated by the XY distance (Figure 1). For the XY distance to be determined from field data, forward and reverse refracted travel times must be collected at each geophone position. Furthermore, the geophone spacing must be sufficiently small to permit XY analysis. For these reasons the GRM requires a relatively more comprehensive field data collection program than other refraction techniques.

The GRM is used for the interpretation of both P- and S-wave seismic data. While this paper focuses on examples of P-wave seismic interpretation, the discussions and findings can be directly extended to encompass S-wave techniques.

GRM surveys in glacial terrains are characterized by a number of practical problems. Perhaps the most difficult problem is the identification of the thickness and velocity of the unsaturated zone, which can be highly variable in glacial terrains. Inaccuracies in this layer can add significant error to the depth estimates of lower layers. Economic considerations often prevent the use of the small geophone spacings necessary for the precise determination of the XY of shallower layers, and hybrid techniques may be used. Other problems are caused by poor signal quality, which directly affects first break pick accuracy. Finally, thin layers in the blind zone beneath a thicker layer (also known as a hidden layer) and velocity inversions can lead to depth estimate errors.

The purpose of this paper is to highlight some of the problems encountered when performing GRM surveys in glacial terrains. A synthetic data set, with layer parameters typical of glacial terrains, is presented to illustrate the common problems and potential solutions. A synthetic data set is used because potential errors can be easily isolated and analyzed for illustrative purposes.

INTERPRETATION OF AN ILLUSTRATIVE MODEL

Table I: Layer parameters used in model.

Layer Thickness	**Velocity** (m)	**XY** (m/s)	(m)
Unsaturated zone	8	600	-
Saturated zone	20	2000	5
Bedrock	-	3550	30

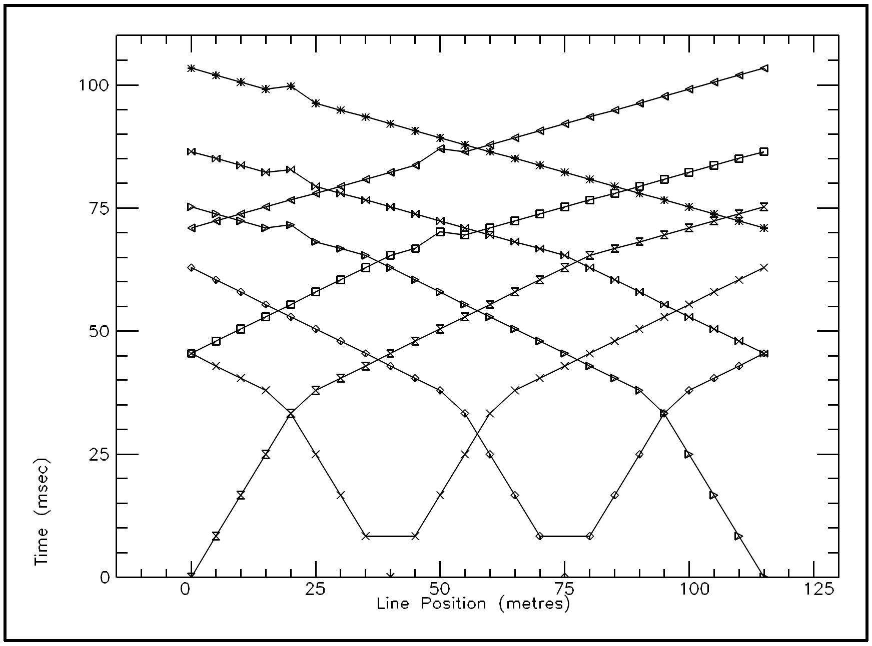

Figure 2: Synthetic arrival time data.

A synthetic seismic model can be used to clearly indicate the problems encountered in glacial terrains. Typical conditions consist of three layers, including (from ground surface) unsaturated overburden, saturated overburden and bedrock. While additional layers are occasionally encountered above bedrock, the velocity contrast is often insufficient to map using P-wave refraction techniques.

A synthetic model consisting of one 24 channel seismic spread was created. Typical velocities and layer thicknesses encountered in glacial terrains were used (Table 1). In addition, the theoretical XY distance is presented for each layer. Flat lying refractors were used, however a small bedrock depression was created in the data by adding a 2 millisecond (ms) anomaly to the bedrock travel time data. The time anomaly is separated by 30 m (the theoretical XY distance for the bedrock refractor) in the forward and reverse travel time data (Figure 2).

Sufficient synthetic shots were created to provide complete forward and reverse travel times for both refracting surfaces. This required a total of 8 shots, including 2 mid-spread shots. The model illustrates the difficulty in selecting a geophone spacing which is suitable for both refracting layers. As a general rule, the geophone spacing should be one third of the XY distance of the refracting layer. This allows the optimum XY to be determined from inspection of the velocity analysis and time-depth curves (discussed in the following sections). While the selected spacing of 5 m is suitably smaller than the XY of the bedrock refractor (XY=30 m), the geophone spacing is roughly equal to the theoretical XY of the water table refractor. This problem is commonly encountered when working in glacial terrains with a shallow water table. Ideally, a geophone spacing of 1.66 metres would be required to perform true XY analysis on the water table refractor. Economic considerations often prevent the use of such small spacings.

Phantoming the Arrival Times

The GRM interpretation begins with the phantoming (time shifting) of the forward and reverse arrival times. This creates a complete set of forward and reverse arrivals at each geophone position. The phantomed arrivals for the two refractors are shown in Figure 3. The 8 shots provide a degree of redundancy in the bedrock arrivals, with three duplicate arrivals available at the ends of the line. The effects of averaging the duplicates are outlined in a subsequent section of the paper.

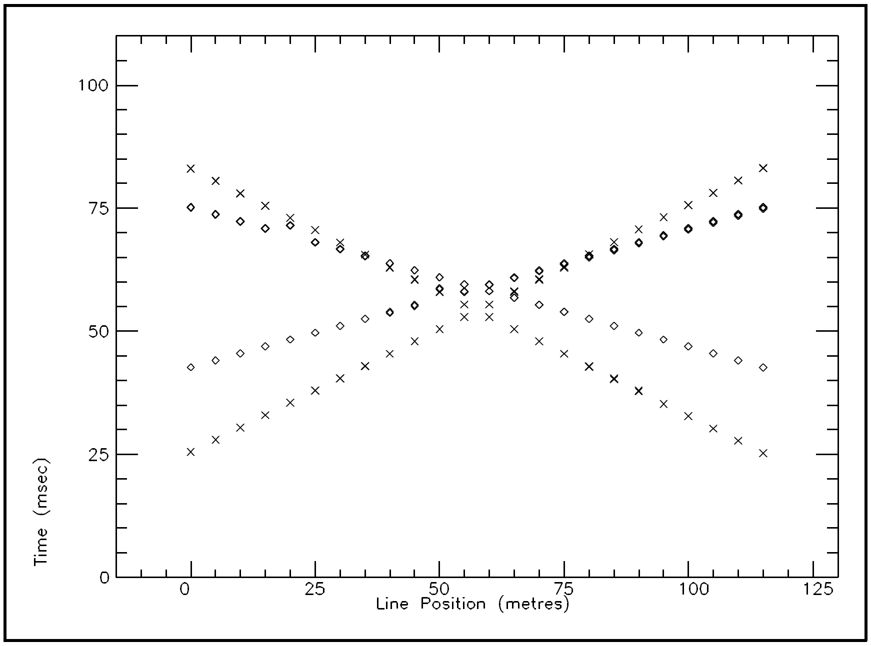

Figure 3: Phantomed arrivals (Layer 2=X Layer 3=Diamond)

Selection of the Optimum XY

After phantoming, the next interpretation step is to determine the optimum XY for each of the refractors. Palmer (1980, p. 32) suggests four methods for the determination of the optimum XY. These include:

CALCULATION OF THE THEORETICAL XY

Given estimates of the layer velocities and thicknesses, an estimate of the optimum XY can be calculated. The layer thicknesses and velocities of this model are known, so the XY for each layer can be calculated directly (Table 1).

INSPECTION OF DISTINCTIVE FEATURES IN THE ARRIVAL TIME DATA

Patterns in the forward and reverse arrival time data appear separated by the XY distance. One such features has been added to the synthetic model: the 2 ms anomaly which is separated by 30 m in the forward and reverse travel time data (Figure 2).

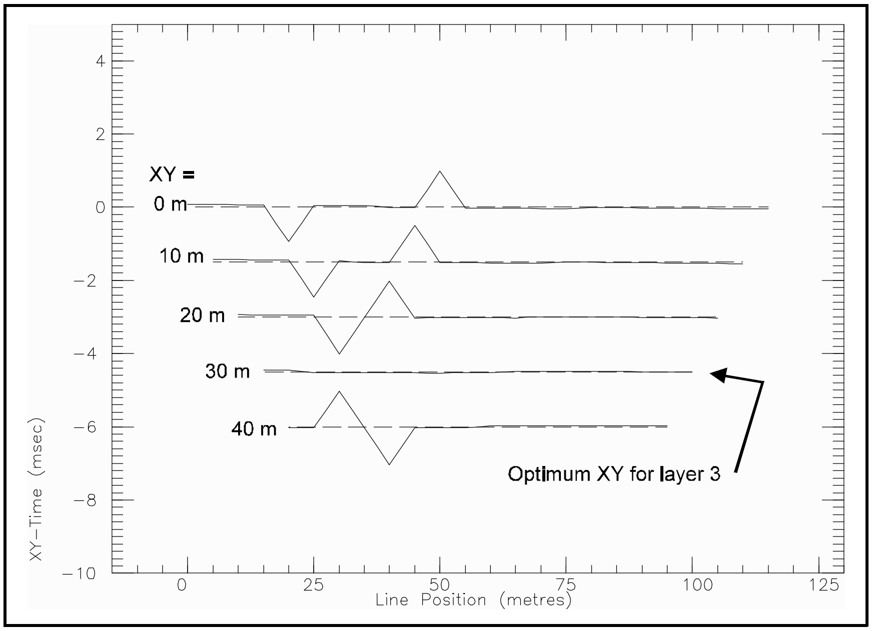

Figure 4: Velocity analysis curves for layer 3 (bedrock refractor).

INSPECTION OF THE VELOCITY ANALYSIS CURVES

GRM velocity analysis curves are calculated for a range of XY values, and converging patterns in these curves can indicate the optimum XY of each layer. In general, the velocity analysis curve exhibiting the smallest variation corresponds to the optimum XY.

The velocity analysis curves (with a constant velocity of 3550 m/s removed) for Layer 3 of the model are shown in Figure 4. Notice how the velocity analysis curve calculated with an XY of 30 m clearly shows the least variation (essentially flat). This confirms that the optimum XY of Layer 3 is 30 m.

The lack of variation in the water table refractor prevents the use of this method with the synthetic data, since each of the velocity analysis curves are straight.

INSPECTION OF THE TIME-DEPTH CURVES

In a similar manner to the velocity analysis curves, converging patterns in the time-depth curves, plotted over a range of XY values, can indicate the optimum XY. In general, the time-depth curve exhibiting the greatest magnitude of variation corresponds to the optimum XY.

The time depth curves for the bedrock refractor are shown in Figure 5. Note that a single bedrock anomaly is formed in the time depth curve calculated with the optimum XY value.

Since there is no variation in the water table refractor time-depth analysis cannot be performed with the synthetic data set.

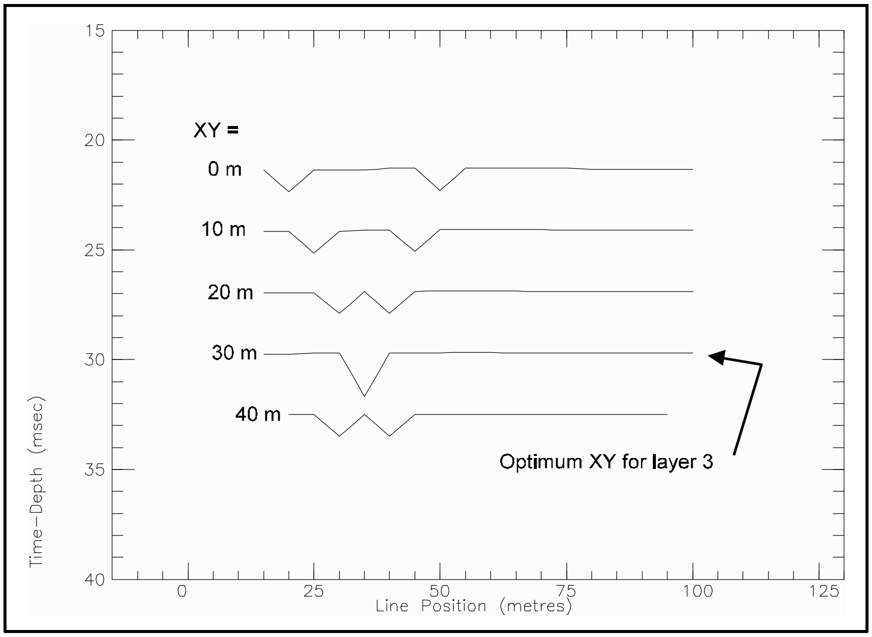

Figure 5: Time-depth curves for layer 3.

Velocity Analysis

The slope of the velocity analysis curves provide an estimate of the refractor velocity. Changes in the slope indicate lateral changes in the velocity of the refractor.

Depth Migration

With the velocity and XY known, the GRM provides two approaches for converting the time-depth curves to true depth. These include:

APPROXIMATE VELOCITY METHOD

The approximate velocity method of depth migration involves successively processing each layer from surface, and using the results of the previous layer during processing of lower layers.

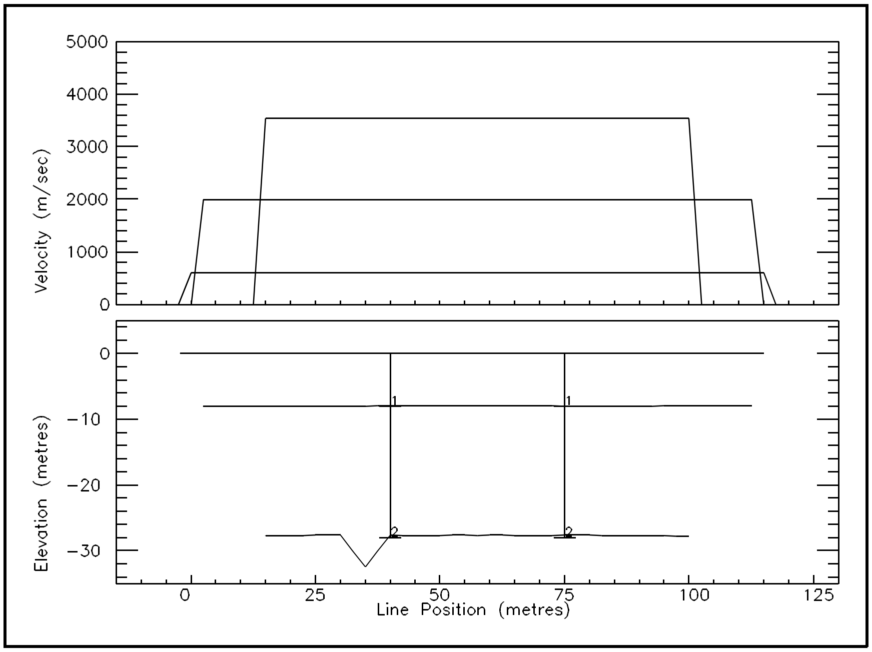

Figure 6: Depth migration results using the approximate velocity method and correct XY values for each layer.

The approximate velocity results for the synthetic data set are shown in Figure 6. Results were calculated using the approximate velocity method for both refractors, with the velocity of layer 1 determined from the direct wave arrivals. The 2 ms anomaly introduced into the planar model produces a small bedrock depression centred at line position 35 m.

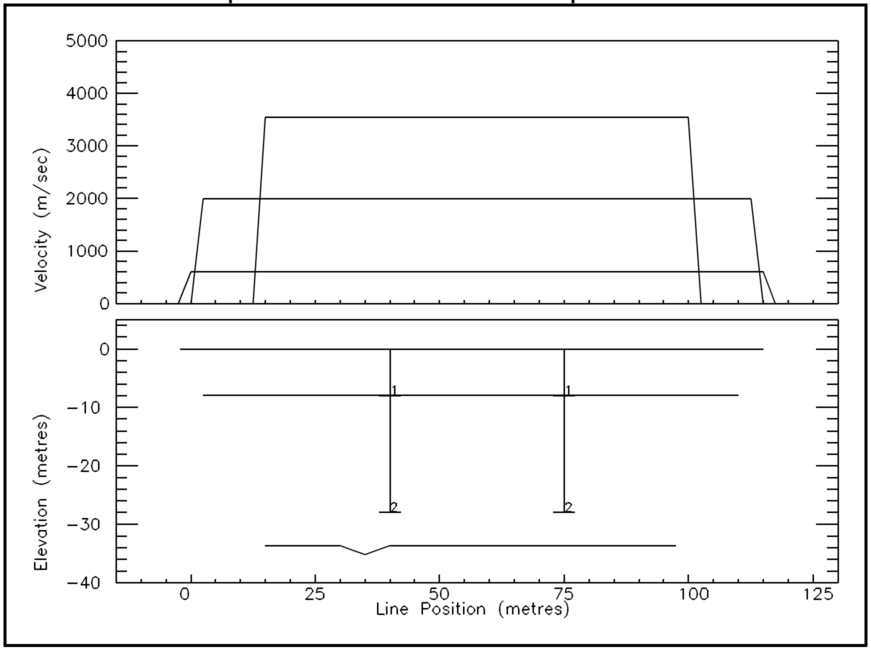

Figure 7: Depth migration using the average velocity method for both refractors.

AVERAGE VELOCITY METHOD

An alternative method for depth migration is the average velocity method. This method is very sensitive to the selection of the XY, however it can be useful when undetected layers are present or when borehole control is available along the seismic line.

The average velocity depth migration results are shown in Figure 7. Palmer (1980, Figure 28) outlines the error involved with using the average velocity method for three layer cases. Figure 7 shows that the there is no error in the use of the average velocity method to predict the position of the water table, however the predicted depth to bedrock is significantly deeper than true depth. This error is inherent to the average velocity method. Further discussion of the use of the average velocity method is presented in the following sections of this paper.

SENSITIVITY OF THE MODEL TO INTERPRETATION ERRORS

Effects of Pick Accuracy

Redpath (1973) summarized the problem of pick accuracy in shallow refraction surveys by stating "a millisecond is a large unit of time". First break pick accuracy has obvious effects on the end results of a refraction survey. Common sources of error include timing problems in the trigger and seismograph; cultural noise such as road traffic; electrical noise from power lines; wind noise and errors introduced during first break picking. Stacking to improve the signal to noise ratio may also cause the first breaks to be less distinct due to compression of the earth (and subsequent increase in near-source earth velocity) at the shot point.

Accurate first break picking can be especially difficult when low frequency data are encountered. Since high frequency data are more strongly attenuated, long offset shots are often of lower frequency, with a waveform period often around 15 ms. Accurately defining the start of a 15 ms waveform can be difficult.

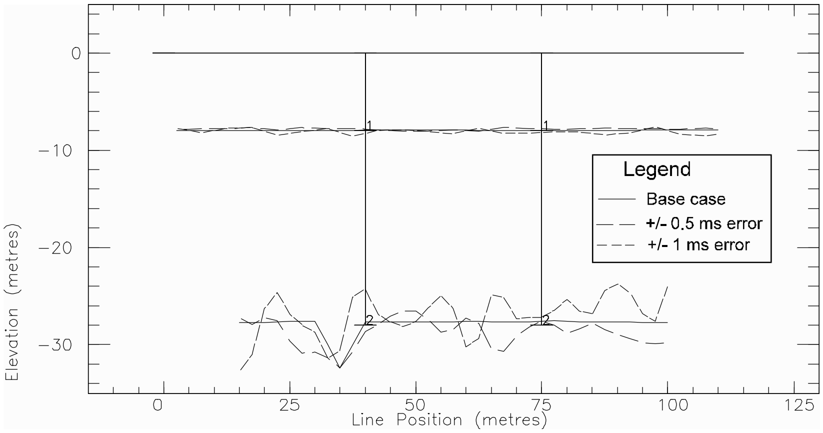

Figure 8: Depth section showing effects of random pick error.

To illustrate the effects of these errors, a random amount of time was added to each arrival time in the synthetic data set. Two ranges of error were chosen: a random time ranging between +/- 0.5 ms and secondly between +/- 1 ms. The GRM interpretation was repeated in each case. Only the long-offset shot data were used in the processing of the bedrock refractor. The results are shown in Figure 8.

Figure 8 indicates that the random error in the arrival times has little effect on the water table refractor. The opposite is true for the bedrock refractor, which shows significant topographic variation from the synthetic base case. The 0.5 ms error range produces bedrock variation of approximately +/- 2 metres from the true elevation.

Pick error can be reduced by common data collection procedures such as stacking and use of a high frequency source. Similarly, picking first breaks on a computer screen with control over trace scaling can improve arrival time selection. On particularly noisy records it may be wise to save repeat shots with just one stack in addition to the multiply stacked record. This repeat shot can often be used to help resolve discrepancies in first break times that may arise during interpretation.

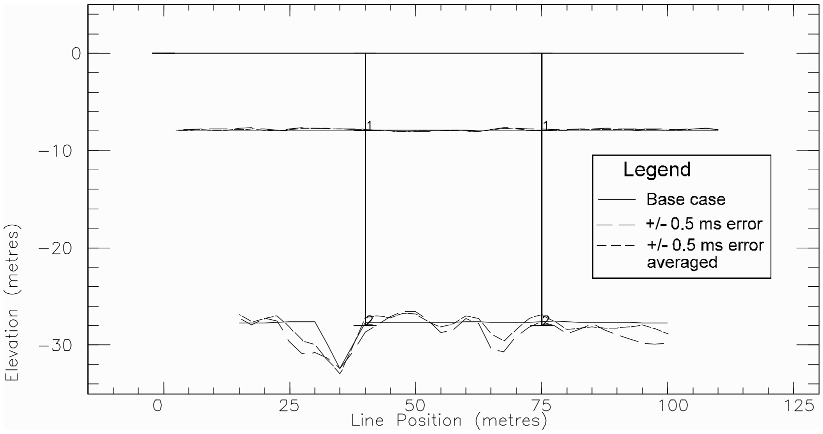

Figure 9: Comparison of averaged arrival time results to non-averaged results.

Another approach which can be used to reduce error is the averaging of multiple arrival times (Figure 9). Frequently more than one arrival time from a refractor is available at each geophone location. For example, there are three forward direction bedrock arrivals per geophone position between line positions 80 m and 115 m (Figure 2). These arrivals can be phantomed and then averaged to statistically reduce the random error in the picks. Figure 9 shows the depth section using averaged arrival times. The effects of averaging are most noticeable at the ends of the line, where three bedrock arrivals were averaged, noticeably improving the depth migration results.

In summary, the effect of averaging is broadly similar to the seismic reflection Common Depth Point (CDP) fold number. Arrival times refracted from different shot positions are together used to improved the first break position.

Layer Assignment and Phantoming Errors

Assigning layers and phantoming arrivals from flat or planar dipping refractors is usually a straight forward task. The addition of even simple layer topography and velocity variation can significantly complicate the task.

To illustrate, a simple model with a change in bedrock topography was created. Arrival times from three forward shots are shown unphantomed in Figure 10. A change in apparent velocity is observed at line position 42 m. The three shots cannot be used independently to determine if the velocity change is due to a change in bedrock dip or the existence of an additional refractor. A comparison of the two far offset shots, however yield an interpretation of a change in bedrock dip because the anomaly is observed at the same line position for both shots. If it was an additional refractor, we would expect to see the change in dip occur closer to the shot location for the far offset shot.

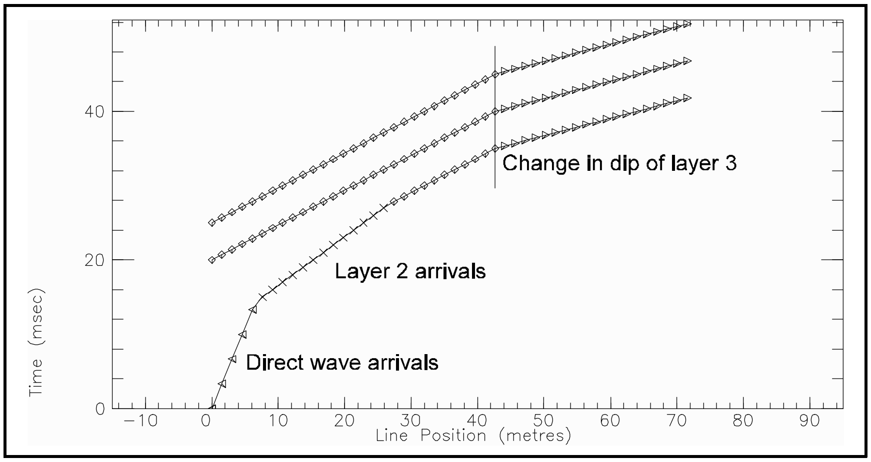

Figure 10: Arrival time data from three shots showing the effect of a change in bedrock topography.

Phantoming, or time shifting, the long-offset arrival times down to the zero offset forward shot can be used to select the point at which the curves diverge. The divergence indicates a change in layer assignment. This technique is particularly useful in uneven topography, where linear segments of arrival times are uncommon. An error in layer assignment would have locally increased the interpreted velocity of Layer 2 and resulted in inaccurate depth estimates as discussed. The effects of inaccurate layer velocities are significant, and are outlined in the following sections. Phantoming the long-offset shots allows layer changes to be clearly observed.

In summary, layer assignment errors can be minimized by both adding additional shots and phantoming the long-offset arrival times during layer assignment.

Errors in the XY Analysis

Palmer (1980) suggests that the depth predicted by the GRM approximate velocity method is relatively insensitive to errors in the selection of the XY. The selection of the XY does, however, affect the shape of the refractor surface.

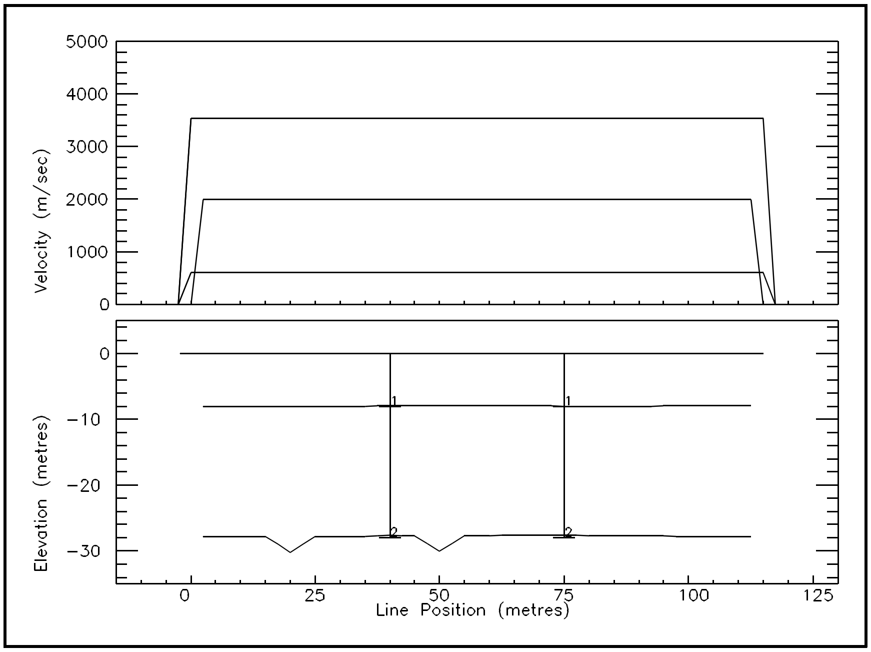

Figure 11: Approximate velocity results with XY=0 for the bedrock refractor.

The delay time method is one of the more commonly used methods for refraction analysis. This method is functionally equivalent to the GRM approximate velocity method when an XY of 0 m is used. The synthetic model results processed with a bedrock refractor XY of 0 m are shown in Figure 11. Note that the bedrock depth is only slightly shallower than the correct depth. The depression in the bedrock which should appear at line position 35 m now appears as two smaller depressions separated by 30 m. This is consistent with the smoothing effect of the delay time method (Redpath, 1973).

The GRM average velocity method, however, is very sensitive to the selection of XY. It is important to note that even if the proper XY is selected, the predicted depth in a multi-layer system may be in error if the average velocity is used (see Figure 7). In single layer situations, the approximate and average method will, however, provide the same results. The sensitivity of the average velocity method and possibility of error suggests that the method only be used in conjunction with borehole data. For example, an XY of 20 m places the bedrock refractor into the proper location (Figure 12). It can be concluded that the approximate velocity method is preferred for GRM surveys in shallow glacial terrains. Careful use of all four methods of XY determination (outlined earlier in the paper) is important because together they can be used to test for hidden layer conditions.

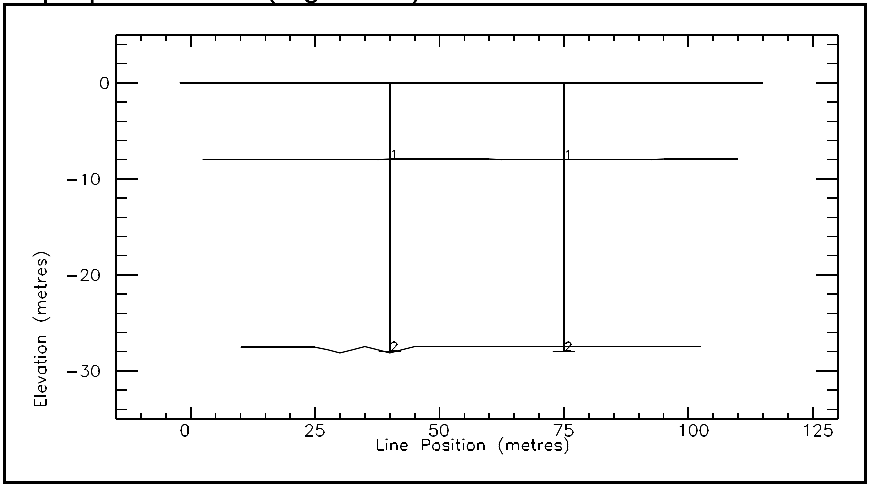

Figure 12: Average velocity results with an XY of 20 m.

Errors in the Layer Velocities

The variable nature of the overburden can cause significant problems when performing GRM surveys in glacial terrains. Changes in saturation and consolidation (the presence of fill zones) lead to significant variation in the thickness and velocity. The optimum XY of the unsaturated zone is often small, yet a corresponding small geophone spacing is often not economic. Other factors, such as interference of the air wave in first break picking, can complicate the interpretation.

To illustrate the sensitivity of the synthetic model to errors in the unsaturated zone, a range of velocities were used during

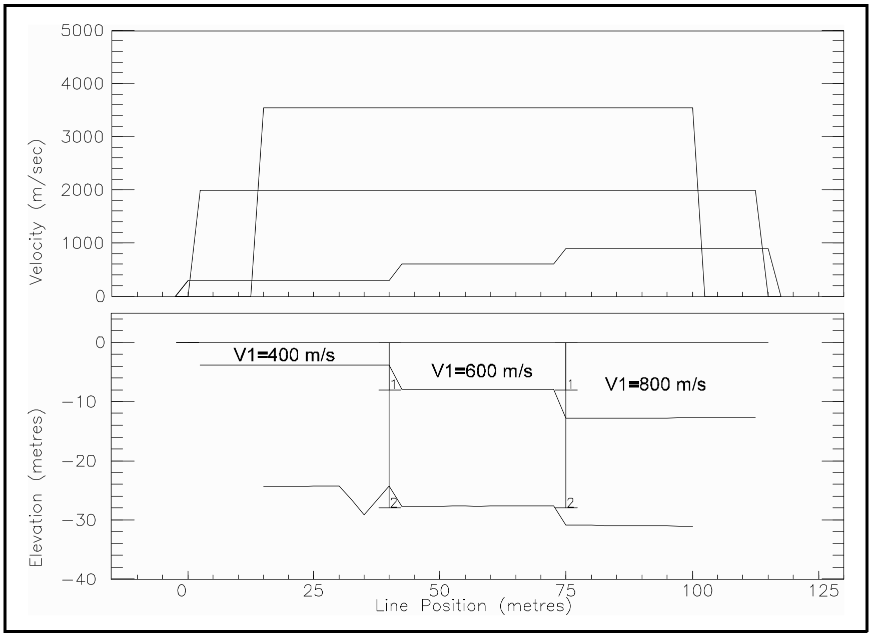

Figure 13: Effects of error in the velocity of the unsaturated zone.

processing. Figure 13 shows the depth section with two incorrect velocity zones. Velocities of 400 m/s, 600 m/s (the correct velocity), and 800 m/s are shown. When a V1 estimate of 400 m/s is used, the depth to bedrock is 3.7 m above the correct elevation. Over-estimating the velocity by a similar amount causes the depth estimate to be 2.9 m below the true elevation. Note that an over-estimate of the velocity causes less depth error than an equivalent under-estimate of the velocity.

One of the advantages of the GRM is that changes in the refractor velocity can be determined from the velocity analysis curves. The effect of errors in the velocity of the water table refractor are shown in Figure 14. Velocities of 1,600 m/s, 2,000 m/s (the correct velocity), and 2,400 m/s are shown. Note that the errors in the velocity cause negligible changes in the position of the water table refractor (Figure 14). In fact, both over- and under-estimating the velocity of the water table refractor cause its depth to be over-estimated.

Of greater importance is the effect of water table (Layer 2) velocity errors on the depth to bedrock. Using 1,600 m/s, the depth to bedrock is 5.4 m above the true depth. Over-estimating the velocity by a similar amount causes the depth to bedrock to be 6.7 m below the true depth. Unlike the velocity of the unsaturated zone, over-estimating this velocity causes a relatively greater error in the calculated depth to bedrock. Also note that a 33 percent error in the velocity of the unsaturated zone (Figure 13) causes less overall error compared to a 20 percent error in the velocity of the water table refractor (Figure 14).

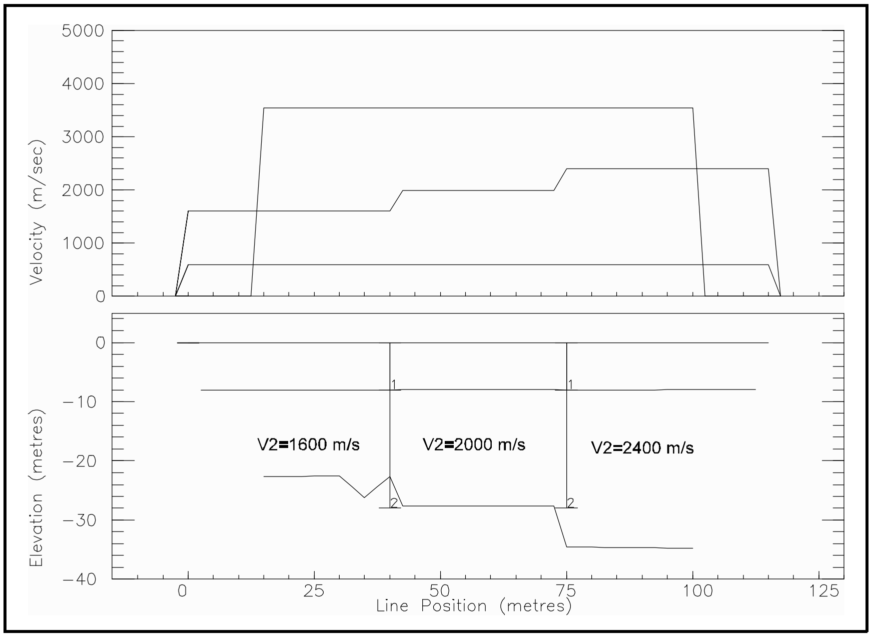

Figure 14: Effects of error in the velocity of the saturated zone.

Based on these scenarios, the following conclusions can be made about errors in the layer velocities:

1. The bedrock depth error associated with over-estimating the velocity of the unsaturated zone is smaller than an under-estimate of the velocity. The opposite is true for the saturated overburden layer.

2. Errors in the velocity of the refracting layer have little impact on the depth of the layer (when using the approximate velocity method), however they have a significant effect on the depth of lower layers.

3. Errors in the velocity of the unsaturated zone are less significant than errors in the velocity of the saturated zone above the bedrock.

4. Errors in the velocity of the bedrock have relatively little impact on the depth to bedrock.

The above analysis suggests that the depth to bedrock is most sensitive to errors in the velocity of the water table refractor. Approaches to the interpretation of the upper layers include:

1) INTERCEPT TIME ANALYSIS WITH SHORT SPREADS

One common field acquisition technique that is used to define the upper layer velocity is short spaced geophone spreads. Short spreads are simply geophone spreads with a very short (1 m) geophone spacing. Near surface velocity data can be acquired using short spreads at representative locations along the seismic line. This upper layer velocity model can then be extrapolated between short spreads along the line. Careful consideration must be given to changes in observed surface soil types.

2) COMBINING THE UPPER LAYERS

The GRM average velocity method can be used to predict the depth to bedrock if insufficient information is available from the upper layers. The average velocity method, as the name suggests, is used to determine the average velocity of all upper layers, including hidden layers. This method is subject to errors and should only be used in conjunction with borehole information (Palmer, 1980). The appropriate use of this method is further described in a following section on hidden layer analysis.

3) GRM ANALYSIS ON THE UPPER LAYERS

Identifying variation in the velocity of the water table refractor is difficult without complete forward and reverse coverage of the layer. With complete coverage, GRM velocity analysis can be used to determine water table velocity variation. In practice, even if it is uneconomic to use a geophone spacing small enough to perform full GRM analysis on the water table, a complete set of forward and reverse water table arrivals can be used to determine velocity variation.

One approach to collecting additional water table arrivals is the use of multiple mid-shots. For example, two mid-shots were added to the synthetic data set to provide compete Layer 2 coverage. A correctly placed and recorded mid-shot can also provide Layer 1 velocities.

One problem encountered when using mid-shot data occurs when the record is stacked multiple times (perhaps to improve refractions from deeper layers). The result in an increase in the near-surface velocity at the shot point and a corresponding smear of first breaks. A solution is to save the first stack as a record for V1 estimation and then continue to stack, if necessary, a separate record to enhance bedrock refractions on distant geophones.

In summary, while it is often uneconomic in glacial terrains to use a geophone spacing small enough for XY analysis on the water table, the addition of multiple mid-shots can improve the upper layer velocity estimates.

Hidden Layer Conditions

The GRM is recognized as one of the few refraction techniques which can indicate if hidden layer conditions exist (Lankston, 1989). A hidden layer need not consist of a velocity inversion, it can simply be a thin layer of higher velocity within the blind zone of an overlying layer. To illustrate this problem, a simple hidden layer model was created and interpreted using the GRM.

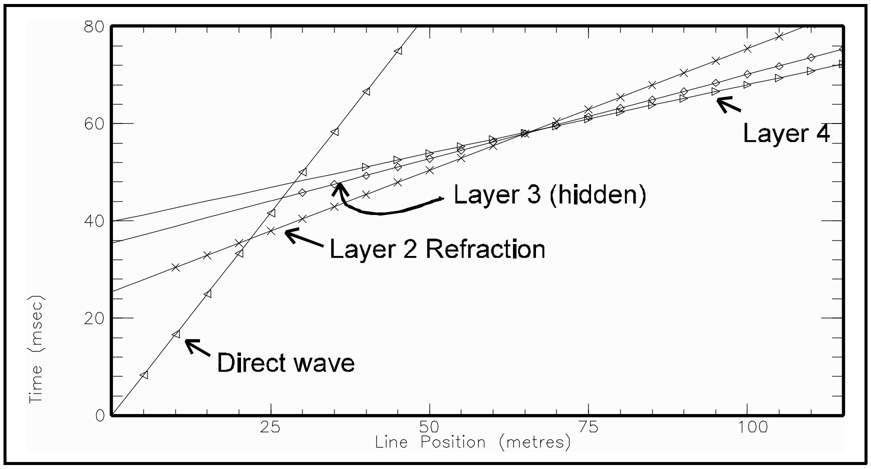

Figure 15: Forward shot data showing arrival times for hidden layer 3.

It is not uncommon in glacial terrains to encounter changes in the density, and therefore velocity, of a layer. For example, changes in the density of a till layer are not uncommon. A typical condition, in which a dense zone overlies the bedrock, was created using the parameters in Table 2. In this case the third layer, with a velocity of 2885 m/s, is too thin to produce the first arrival time at any point along the spread (Figure 15). Note that the Layer 3 arrivals always occur after the Layer 2 and Layer 4 arrival times.

Arrival time data, velocity and time depth analysis curves for the hidden layer case are shown in Figure 16. The data were interpreted assuming no knowledge of the hidden layer. Based on the velocity analysis and time depth curves, an optimum XY of 40 m was selected for deepest layer. Note that the true XY of Layer 4 is 40 m (Table 2).

The results of the depth migration of the hidden layer case are shown in Figure 17. Marker lines indicate the true position of the layer interfaces. By failing to detect the hidden layer, the depth to the lowest refractor interface is 4 m shallower than the actual interface.

Palmer (1980) suggests that comparison of the calculated and observed XY can indicate whether hidden layer conditions exist. The calculated XY for the hidden layer case, based on the observed layer thicknesses and velocities, is shown in Table 3. The calculated XY for the bedrock layer is 24.7 m, whereas the observed optimum XY for the layer is 40 m. The large discrepancy between the calculated and observed XY is a clear indication that a hidden layer may exist.

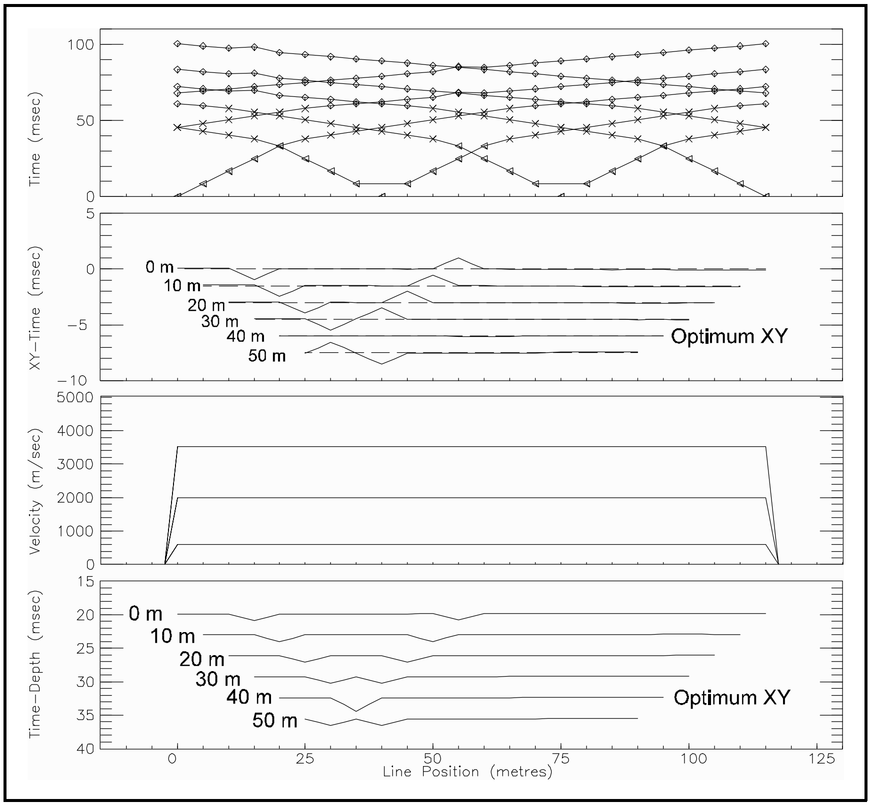

Figure 16: Arrival times, velocity and time depth analysis for the hidden layer case.

Table II: Layer parameters used in hidden layer model.

Layer	**Thickness** (m)	**Velocity** (m/s)	**XY** (m)
Unsaturated zone	8	600	-
Saturated zone	13	2000	5
Dense till zone	7	2885	28.4
Bedrock	-	3550	40

The average velocity method of depth migration can be used in conjunction with borehole data if hidden layer conditions are detected. By adjusting the XY of the layer until the depth matches the borehole data, the refractor surface will shift into the proper position. For example, a depth match was achieved using an XY of 22.5 m (Figure 18).

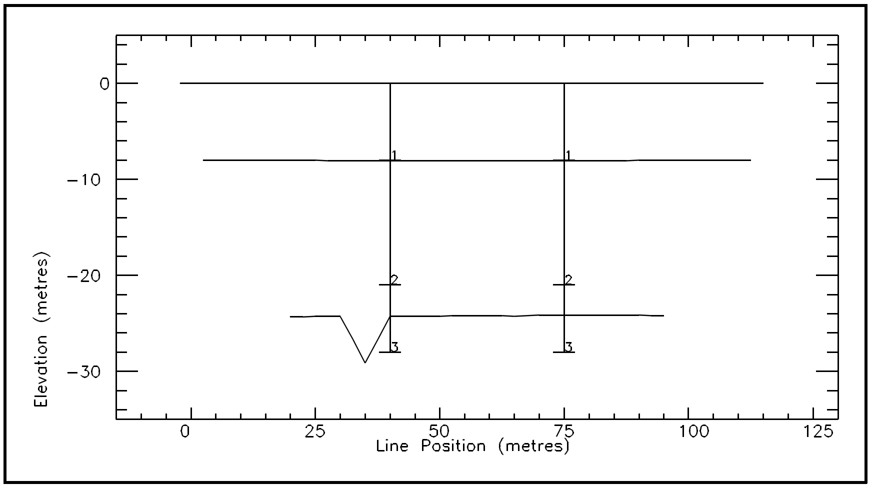

Figure 17: Approximate velocity depth migration results for the hidden layer case.

CONCLUSIONS

The GRM is often criticised for the amount of data required for proper analysis. Certainly, economic limitations often prevent the use of the small geophone spacings necessary for full XY analysis on the upper layers. Where economic limitations exist, certain aspects of the GRM can be utilized with little additional cost. Two features of the GRM are particularly useful.

Table III: Layer parameters observed if hidden layer conditions exist.

Layer	**Thickness** (m)	**Velocity** (m/s)	**XY** (m)
Unsaturated zone	8	600	-
Saturated zone	16.13	2000	5
Bedrock	-	3550	24.73

1) Adding additional shot points along the line can provide a complete set of forward and reverse refracted arrivals from the water table. Phantoming these arrivals allows velocity analysis to be completed on the water table refractor. In the example presented in this paper, the depth to bedrock was most sensitive to the water table velocity. Additional shot points can often be added with only a small increase in the cost of the survey and they offer other significant advantages. For example, pick errors can be reduced by averaging the multiple first break picks and additional far-offset shots can be used to improve layer assignment.

2) Even if a full GRM analysis has not been performed on the upper layers, XY analysis

on the bedrock layer can substantially improve the results. The main advantage of XY analysis is the detection of hidden layers. A second advantage is that smaller features in the surface of the refractor will not be smoothed if the proper XY is selected. Fortunately, the depth of the bedrock is very insensitive to the selection of the XY distance when using the approximate velocity migration technique.

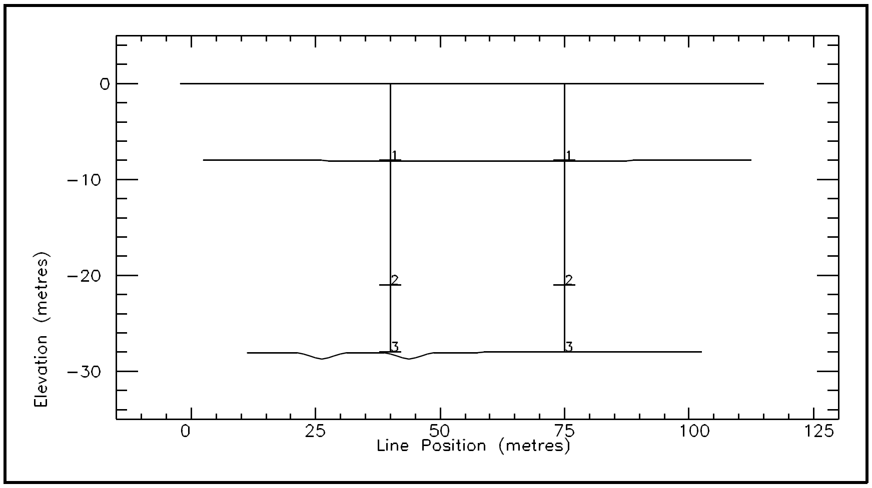

Figure 18: Depth migration results using the average velocity method with a layer 3 XY of 22.5 m.

The velocity of the unsaturated zone can also have a significant impact on the predicted depth of the bedrock. The error associated with using the average velocity method (lumping Layers 1 and 2 together) is often too large to be acceptable, unless hidden layer conditions are suspected. A field approach based on estimating the velocity of the unsaturated zone from a combination of mid-shots and short-spreads is appropriate.

The analysis in this paper is limited to a data set considered representative of conditions in glacial terrains. While limited to one set of conditions, the analysis illustrates the sensitivity of the interpretation process.

With knowledge of the sensitivity, the GRM can, however, provide some of the best depth estimates available from a surface geophysical technique.

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