THE POTENTIAL OF RAY TRACING FOR THE INTERPRETATION OF ENGINEERING SCALE SEISMIC REFRACTION SURVEYS

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A B S T R A C T

Seismic refraction experiments are widely employed in the investigation of geotechnical problems in Greece. Such problems may include the determination of recent sediment thickness and basement depth in prospective dam sites like the one in the Vatochorion basin. Commonly used interpretation procedures, based on the Plus-Minus method, provided satisfactory results. In order to better resolve problems associated with lateral inhomogeneities, attempts have been made to implement ray tracing techniques for the interpretation. Thus, for the Amindeo case the original 2D models obtained as a result of the interpretation based on the Plus - Minus method were used as starting models for a ray tracing based reinterpretation. This second interpretation stage introduced significant improvements on the original model. The results of this study indicate that ray tracing methods can provide a very useful interpretation tool for refraction surveys and can improve or verify results originally obtained by other methods, provided that a good ray coverage is available.

Η ΔΥΝΑΤΟΤΗΤΑ ΕΦΑΡΜΟΓΗΣ ΤΗΣ ΜΕΘΟΔΟΥ "RAY TRACING" ΣΤΗΝ ΕΡΜΗΝΕΙΑ ΜΙΚΡΗΣ ΚΛΙΜΑΚΑΣ ΔΙΑΣΚΟΠΗΣΕΩΝ ΣΕΙΣΜΙΚΗΣ ΔΙΑΘΛΑΣΗΣ

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Π Ε Ρ Ι Λ Η Ψ Η

Ερευνες σεισμικής διάθλασης χρησιμοποιούνται ευρέως για τη διερεύνηση γεωτεχνικών προβλημάτων στην Ελλάδα. Τέτοια προβλήματα μπορεί να αφορούν τον προσδιοριομό του βάθους του υποβάθρου ιζηματογενών λεκανών, όπως στην περίπτωση της λεκάνης στην περιοχή Βατοχωρίου. Συνήθης μέθοδος ερμηνείας είναι η μέθοδος "plus-minus" που δίνει ικανοποιητικά αποτελέσματα. Για την καλύτερη διερεύνηση των προβλημάτων αυτών έχουν γίνει προσπάθειες ερμηνείας τους με τη μέθοδο "ray tracing". Στην περίπτωση που παρουσιάζεται εδώ, τα αρχικά διδιάστατα προσομοιώματα επανερμηνεύθηκαν με χρήση της μεθόδου "ray tracing". Το δεύτερο αυτό στάδιο μελέτης οδήγησε σε σημαντικές βελτιώσεις των αρχικών αποτελεσμάτων. Τα συμπεράσματα της εργασίας αυτής συνηγορούν στο ότι η μέθοδος "ray tracing" μπορεί να αποτελέσει ένα αποτελεσματικότατο εργαλείο για την ερμηνεία δεδομένων σεισμικής διάθλασης και μπορεί να οδηγήσει σε εμφανή βελτίωση των αποτελεσμάτων που έχουν αρχικά προέλθει από άλλες μεθόδους, αν

υπάρχει ικανοποιητική κάλυψη σεισμικών ακτίνων.

INTRODUCTION

The potential of seismic refraction methods in modelling the earth's velocity structure is well known to geophysicists for many years. The modern period of shallow target refraction surveying started in the late 1960's when several seismograph manufacturers introduced compact, multichannel recording instruments. Since then, many studies describing the application of the seismic refraction method in engineering projects, have been presented. Depending upon the scope of the geotechnical study and the geology complexity at the investigated site, several computer based interpretation techniques and corresponding algorithms have been developed in order to assist in the analysis of obtained seismic data (Ackermann et al. 1983, Haeni, 1986). All these commonly used advanced interpretation procedures were proven to be capable to provide satisfactory results, but are subject to theoretical limitations of the method.

Recently, efficient algorithms based on ray tracing theory have been developed in order to better resolve problems associated with lateral inhomogeneities and exploit additional recorded seismic phases which may better constrain the resulting model (Cerveny et al. 1974, 1977, Whittal and Clowes, 1979, Spence et al. 1984). Such interpretation requires the calculation of theoretical travel times and seismograms for a specific two-dimensional model, which are compared with the observed ones and by a trial and error process through successively modified models, comparisons and improvements are made until an acceptable fit is achieved.

In 1982 seismic refraction investigations, interpreted using conventional methods (Louis and Papadopoulos, 1982), were carried out at the Vatochorion basin in Florina area (Northern Greece), aiming to delineate the bedrock surface, determine the condition of the bedrock and detect the presence of any fault zones. However, problems related to the strong lateral variations of the bedrock velocity and high interface gradients observed in the results of the conventional investigations, incited us to attempt the confirmation of the structure obtained using ray tracing techniques which allow lateral variations of layer velocity as well as abrupt variations of interface geometry to be taken into account.

GEOLOGICAL SETTING

The study area (fig.1) of the Vatochorion valley is located 32 km Southwest of the town of Florina, Northern Greece. The older rocks present along the basin margins are gneisses of Palaeozoic age, while Mesozoic limestone overlay unconformably this formation. The basin is filled with a series of Plio-quaternary sediments composed of marls, sands, clays, silts and gravel. In some areas these fluvial and lacustrine deposits extend over the basin margins. The expected thickness of sediments is between 1 and 100m as it was confirmed by four exploration wells drilled in the area (fig. 1). Wells Γ2, Γ3 and Γ4 ended in the sediment cover with final depths ranging from 60 to 90 m, while Γ1 intersected the limestone basement at a depth of 101 m. Finally, the geological framework of the area is complicated by the granite intrusion outcropping at the eastern margin of the basin.

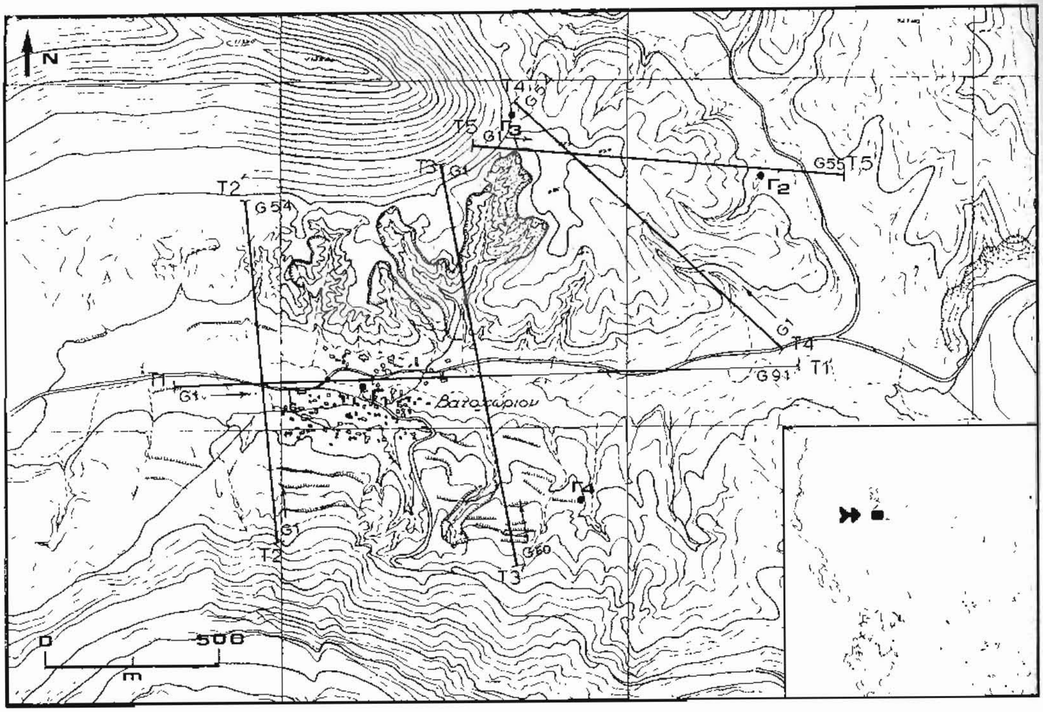

Fig.1. Location map of the study area.

DATA ACQUISITION

Five seismic refraction lines with a total length of 6200 meters were recorded along the riverbed and the banks of the valley. The number of geophone spreads in each line varied from 3 to 5 and the geophone spacing was 20 m. Five to seven shots were fired for each spread. On-spread shots were located at 130m intervals within each spread, while outshots were at a distance of 160 to 200 meters from the end geophones. Shots within the spread were fired to obtain information from the near-surface layers, while the outshots were fired in order to obtain forward and reverse arrivals from the main refractor along the full length of the spread. The recording equipment used was a 24 channel ES 2415F EG&G seismograph. A separate weathering spread with smaller geophone spacing was shot at the central part of the basin aiming to a more reliable determination of the surface layer velocity.

The data obtained from the field campaign were in the form of printed record outputs with a record length ranging from 250 to 500 msec. The picking of first arrivals was carried out manually. Total travel times were then corrected for topography variations using the velocity of the surface layer and were input to a PC system for further interpretation.

THEORETICAL ASPECTS - METHODOLOGY

During the last two decades seismologists have used ray tracing techniques in the interpretation of seismological and seismic refraction data in order to model, as precisely as possible, the velocity versus depth structure of the earth. The application of the same methodology for the interpretation of refraction data in geotechnical, engineering and environmental problems requires a scale adaptation from the kilometres and seconds used in seismology to meters and milliseconds. It is obvious that such an adaptation requires high accuracy standards to be imposed in both the measurements and calculations in order to secure the successful application of the method.

Within the framework of such an interpretation procedure, based on the comparison of the results obtained from the theoretical calculations and the observed data, two main stages can be distinguished. First, in the kinematic stage ray tracing is performed, using a specific model and the theoretical travel times at different shot-receiver positions are calculated and compared with the observed ones. Next, the required modifications to the initial model are made and the first stage calculations are repeated until the comparison results are deemed satisfactory.

In the dynamic stage theoretical seismograms are calculated and compared with the recorded seismic signals in order to provide additional constrains for the fine tuning of the model. However, due to the uncertainties involved in defining seismic wave attenuation and scattering such comparisons are limited to the examination of relative amplitudes of different phases within the same trace or the amplitude of the same phase in different signals (Weber, 1988). The above procedure of incorporating both travel-time and amplitude information to the interpretation of seismic data has enabled more realistic models of the earth's structure to be derived.

A number of ray tracing algorithms for two dimensional laterally varying media, based on various methods as the Gaussian beam, the Kirchoff integral methods and the generalisation of WKBJ seismograms, have been developed by various authors (Cerveny et al. 1982, Chapman and Drumond, 1982, Haddon and Buchen, 1981, Whittal and Clowes, 1979). The method used in the present study is based on the direct application of the Asymptotic Ray Theory (ART). This method, first described by Cerveny et al.(1974, 1977), is characterised by its relative simplicity, since a single ray path is used in order to determine both the onset time and the amplitude of a particular arrival and was first applied to refraction data by McMechan and Mooney (1980). Part of the success of the application of the method lies on the fact that any available geological or geophysical data can be introduced to the initial model and retained unaltered during the iterative procedure constraining thus the acceptable solutions.

The calculations required by the method are performed by solving a set of differential equations involving amplitude parameters simultaneously with a set of differential equations for the ray tracing of the rays (Cerveny et al. 1977). However, since a solution must be obtained for each of the many points along the ray the numerical solutions are excessively time consuming. In order to minimise the required computational time, a simpler, flexible and more efficient ray tracing algorithm was

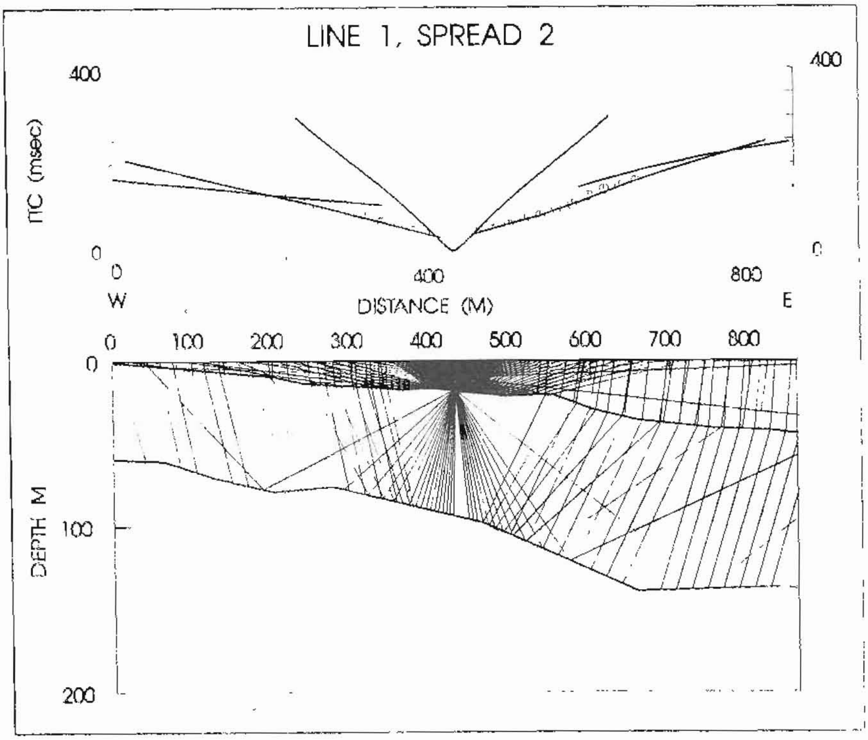

Fig.2. Example of ray tracing interpretation model with corresponding travel time curves.

initially developed by Whittal and Clowes (1979) and extended to include amplitude calculations by Spence et al. (1984). This algorithm transformed into computer code by the program RAYAMP was used in this study.

The key to an effective fast algorithm, which is capable of accepting realistic structures and at the same time generating synthetic seismograms, lies in the way the two dimensional velocity model is defined. The use of large blocks with arbitrary boundaries within which the velocity gradient is constant and of arbitrary orientation, permits the simple specification and modification of the model, while at the same time the required calculations are faster. This flexible procedure was initially suggested by Whittall and Clowes (1979) and has been used successfully in a number of refraction interpretations (Clowes et al. 1981, Delandro and Moon, 1982, Ellis et al. 1983, Green et al. 1983). The modifications of Spence et al. (1984), incorporated in program RAYAMP, allow the use of both model and divider boundaries for the definition of the velocity structure. The term model boundary refers to a straight line of arbitrary dip with a constant velocity along its length and a non-zero velocity gradient normal to its length, while a divider boundary, with a velocity of zero, separates two areas of different velocities and velocity gradients. In that way the flexibility in defining the velocity model is increased further and the defined blocks are characterised by arbitrary magnitude and gradient velocity values. From the above it follows that the ray path within a given block is circular arc and the corresponding distance and traveltimes can be easily calculated using simple analytical expressions. The result obtained when a ray intersects a given boundary can be defined using well known physical laws. Refractions, reflections or head waves can be generated using incidence and critical angles, which can be calculated on the basis of the model geometry and velocity distribution. An example of a model obtained using the above described methodology along with the observed and calculated total travel times for the first arrivals is presented in figure 2.

DISCUSSION - RESULTS

Since the aim of this study was to examine the potential of ray tracing techniques in geotechnical and engineering seismic refraction surveys, as well as to verify and improve the original interpretation, three spreads from lines 1 and 3 were reinterpreted. The final models obtained along with the various ray paths and plots of the observed and calculated total travel times are presented in figures 3 and 4 for lines 1 and 3 respectively. By examining these figures it is clear that the ray coverage was very satisfactory allowing for reliable determination of interface geometry.

The final product of the interpretation is presented by means of two cross sections in figure 5, a and b for lines 1 and three respectively. Both cross sections are constructed with a vertical exaggeration of 200% for better presentation of the interface geometry. The dashed line that appears in both cases represents the free surface topography. Four different layers with distinct velocities are present in the area. The first covers the white area above and below the free surface and corresponds to P-wave seismic velocity of 660 m/sec. The second layer appears with a velocity ranging from 2100 to 2290 m/sec and it covers the area with the lighter shading. A third layer with velocity ranging from 3850 to 4200 m/sec covers the area with the intermediate shading, while the fourth layer with the darker shading corresponds to a seismic velocity of 5500 m/sec.

As far as line 1 is concerned the first layer appears to have depths ranging from 1 to 8 m. This layer with a very low seismic velocity probably corresponds to the loose soil cover of the area. In this point it must be noted that the determination of the velocity of this layer for both lines was mainly based on

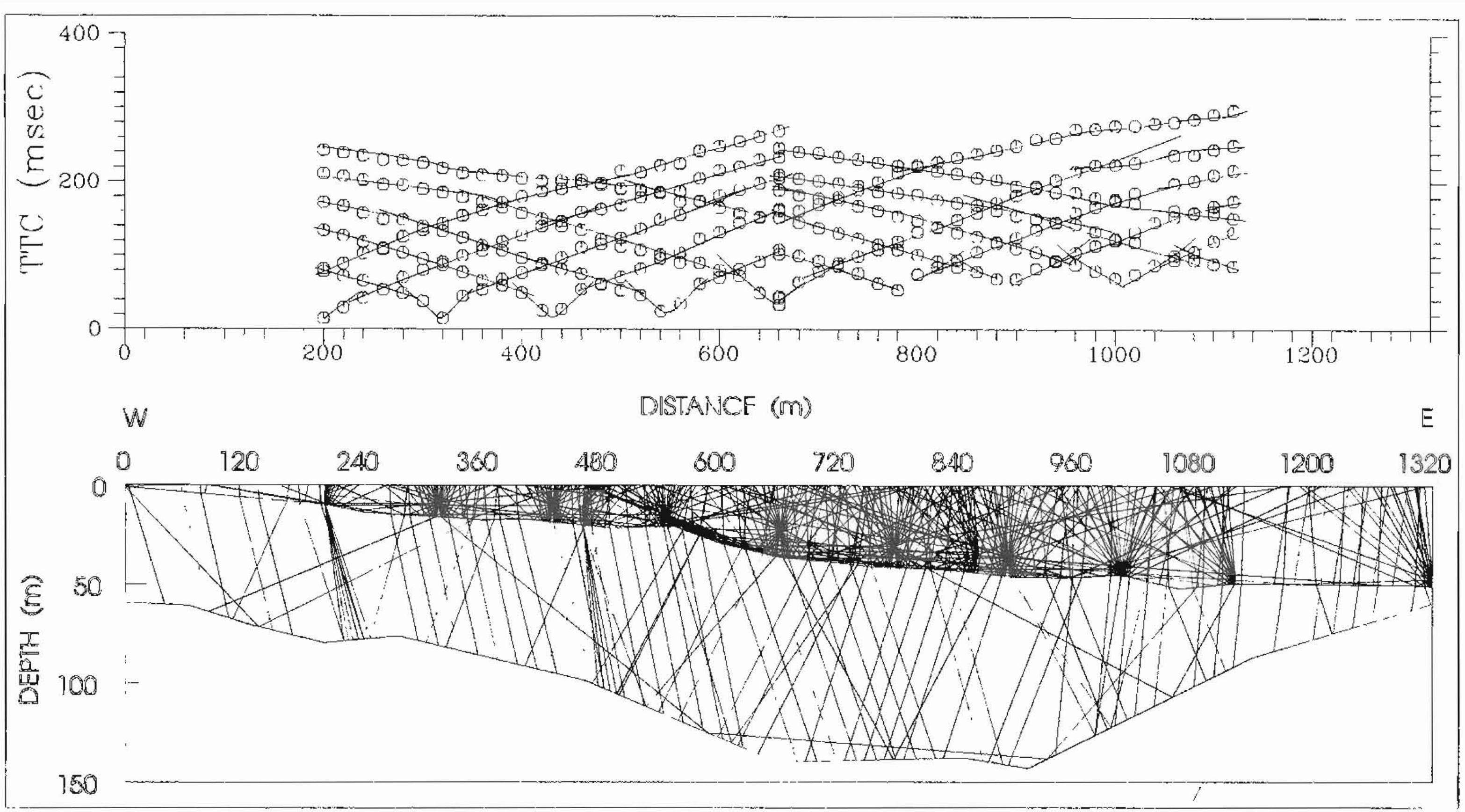

Fig.3. Model with ray paths and corresponding observed (symbols) and calculated (curves) travel times for line 1.

a weathering spread shot close to the starting point of line 1. The next formation with higher velocity can be related to the fluvial and lacustrine deposits underlying the surface layer. The base of this layer forms a synform with relatively steep slopes leading to a variation of the formation thickness from about 60 to 100 m. The grater thickness of this formation is encountered close to the centre of line 1. Underlying this second layer is the bedrock consisting of two different formations. The western formation appears with a velocity of about 4000 m/sec, probably representing the Mesozoic limestone sequence in the area, a fact that was verified by exploration well Γ1. The eastern formation showing seismic velocity of 5500 m/sec can more likely be related to the Palaeozoic gneisses outcropping in the eastern part of the margin.

In line 3 a very similar situation is present. In this case, however, one can note the relatively thick cover of soil accumulated at the northern end of the line, and note the absence of the gneisses formation. It must be noted that the two lines have a crossing point. The interpretation presented here is consistent at this crossing point both in terms of seismic velocities and depths to the base of various formations.

The final cross sections discussed in the previous paragraphs present a realistic model for the shallow substratum of the area. The numerous shots allowed for a reliable determination of the velocity distribution. The trial and error

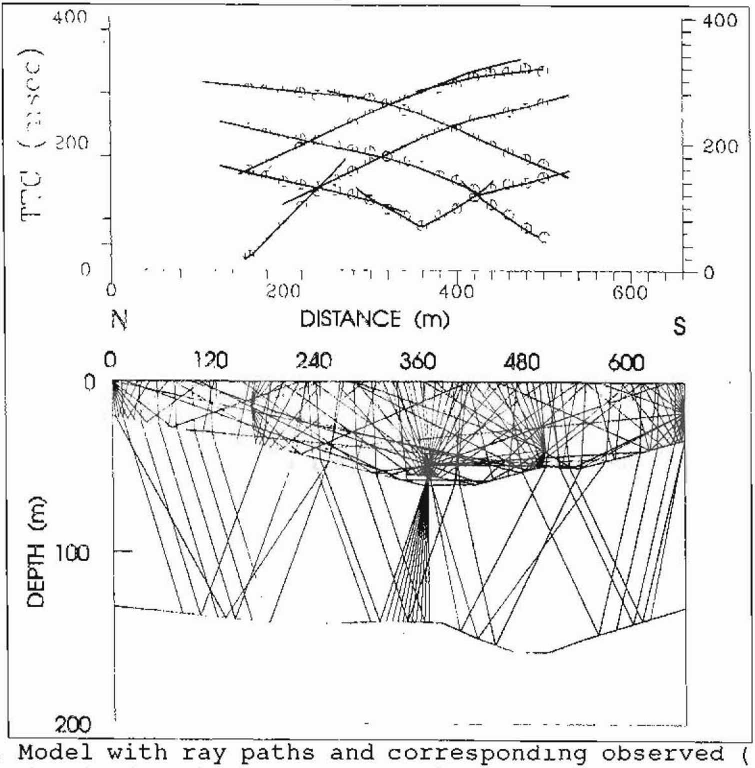

Fig.4. Model with ray paths and corresponding observed (symbols) and calculated (curves) travel times for line 3.

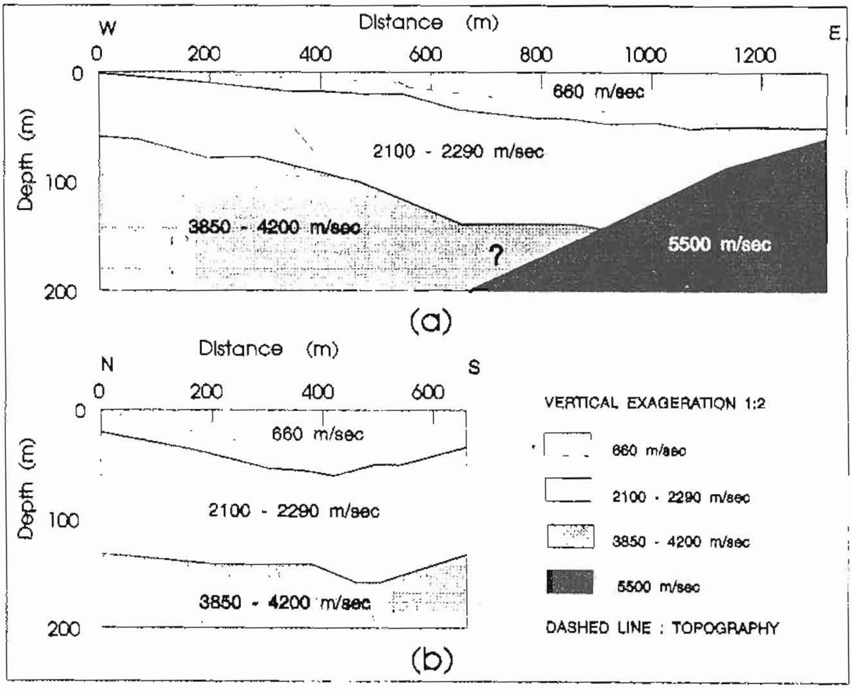

Fig.5. Final velocity models for lines 1 (a) and 3 (b).

procedure employed for the interpretation although time consuming proved to be very effective in achieving a very satisfactory fit between observed and calculated total travel times. Attention must be drawn to the fact that this fit was achieved with a model which is realistic from the geological point of view. In addition to this the method allowed the delineation of the interfaces even where they appeared to have relatively steep slopes. These structures were not distinguished by the use of conventional refraction interpretation techniques that fail to be accurate when the slope of interfaces is not gentle. In addition to this the original interpretation required the use of abrupt lateral variations of velocity within each layer in order to achieve the final solution, while ray tracing based interpretation using smooth lateral velocity variations of smaller range as well as the available geological information led to a more realistic and consistent final model. The above observations underline the potential of ray tracing techniques as an interpretation tool for seismic refraction surveys of engineering scale, provided that attention is given to the theoretical constrains imposed by the validity and stability conditions of the equations that describe the selected ray tracing methodology (e.g. A.R.T., Gaussian Beams). Finally, it should also be noted that adequate accuracy should be maintained throughout the processing sequence.

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