VELOCITY MODELLING: THE INTERPRETERS MAGNIFYING GLASS+

RON MacCALLUM* and JOHN CARD**

ABSTRACT

Velocity anomalies are defined as fluctuations in stacking velocity along a seismic horizon. They magnify variations in the overlying geology and through interactive seismic modelling can be interpreted to measure depths, thicknesses and lateral changes in either the near surface or subsurface geology.

The technique of interactive modelling constitutes a type of reverse approach to normal interpretation procedures. Instead of proceeding from the seismic results to some image of the earth section, the interpreter starts from a model of the subsurface and evaluates how well the synthetic seismic data generated from the model match the actual field observation.

With examples in the Mackenzie Delta and the Foothills of Alberta, we will illustrate how velocity anomalies are created and how velocity modelling can be used as a tool in interpretation of complicated areas of interest.

INTRODUCTION

Seismic data is being acquired in more and more challenging areas; areas where the earth is less amenable to the seismic system. These present complications are beyond the capabilities of conventional procedures and interpretation techniques. Today, development of an understanding of the geology requires more than the traditional seismic travel time displays.

This paper discusses how stacking velocity can add another dimension to geophysical interpretation. Geologic variations are magnified in stacking velocity anomalies. These anomalies have traditionally been ignored as false picks or noise. However Merland (1) showed how better interval velocity control could be obtained from analysis of the details in stacking velocity data and in this paper, even further exploitation of these data will be discussed. Following an explanation of how and why the anomalies are created, an example will be presented to illustrate how geophysical interpretation can benefit from detailed decoding of stacking velocity anomalies.

PROBLEM AREAS

The technique is applicable on data from the Mackenzie Delta area (figure 1), where permafrost distorts seismic arrivals. This line is 9 miles long, and shows 3 highs separated by noisy 200 ms. saddles. Highlighting horizons A and B helps to demonstrate the apparent structure and reference will be made to travel times picked along the top of the shaded zones. An interpretation of this profile will be developed which proves that most of this apparent structure is false and results from variations in the overlying permafrost layer.

+Presented at the 1978 C.S.E.G. National Convention, Calgary, May 10-12, 1978.

*Geodigit, Calgary
**Sun Oil Co. Ltd., Calgary

An analogous problem in seismic interpretation is illustrated using a depth model of an Alberta Foothills play (figure 2). The model is about 6 miles long and shows 20,000 feet of sediment for which thicknesses and velocities are realistic for the Foothills area. A sheet of Mississippian and Devonian carbonate is thrust over Cretaceous sediments. This faulted sedimentary sequence overlays the Cambrian basement which has a smooth west dip across the profile.

The seismic interpretation problem is again due to distorted travel times. A synthetic time section was generated (figure 3) using wave equation modelling to simulate actual seismic data, including all possible diffraction patterns. The events from within the thrusts are recognizable but notice particularly the reflection from the Cambrian. The smooth west dip is now distorted by a 100 ms down-to-the-East fault. The "real" geology is almost impossible to interpret from this time section. However, by also interpreting velocities, and particularly the stacking velocity anomalies, the geophysicist can understand the complex geology.

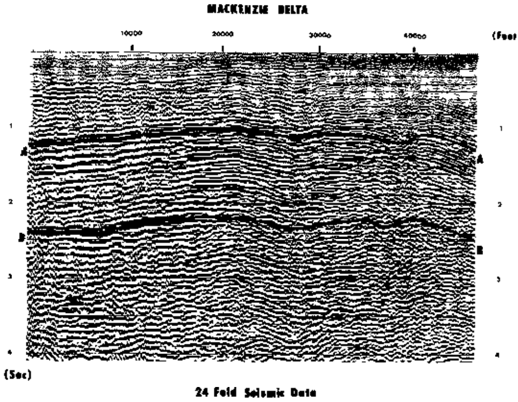


Fig. 1.

The intepretation technique will be shown but first it is necessary to review some principles of stacking velocities to demonstrate that velocity anomalies are created in seismic data by the effect on normal moveout of raypaths distorted by geology variations.

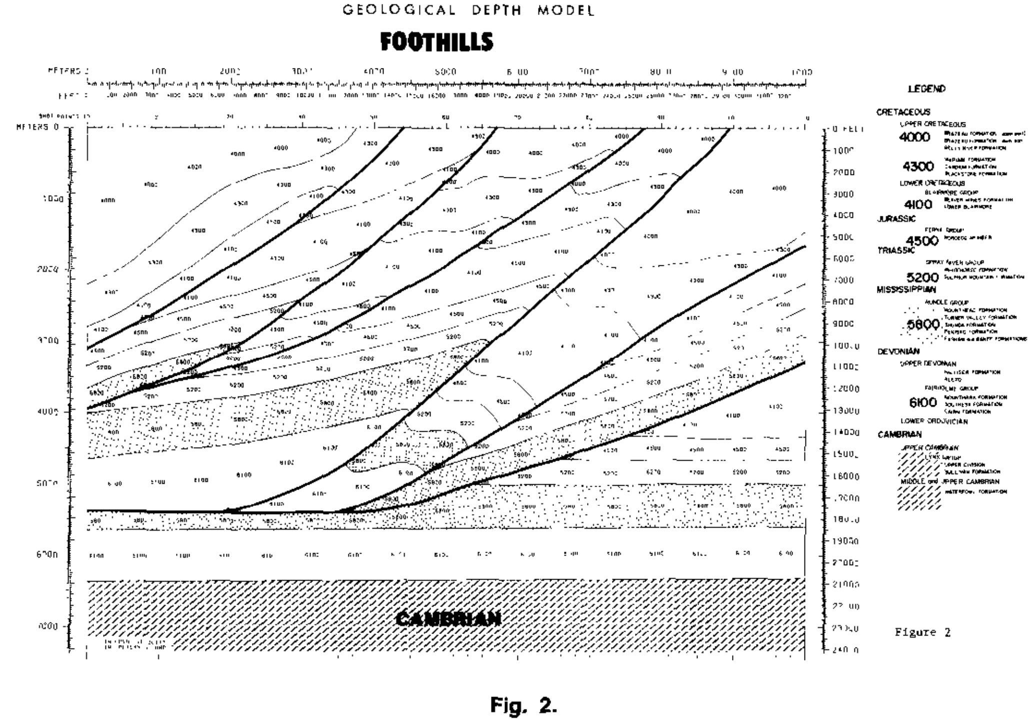


Fig. 2.

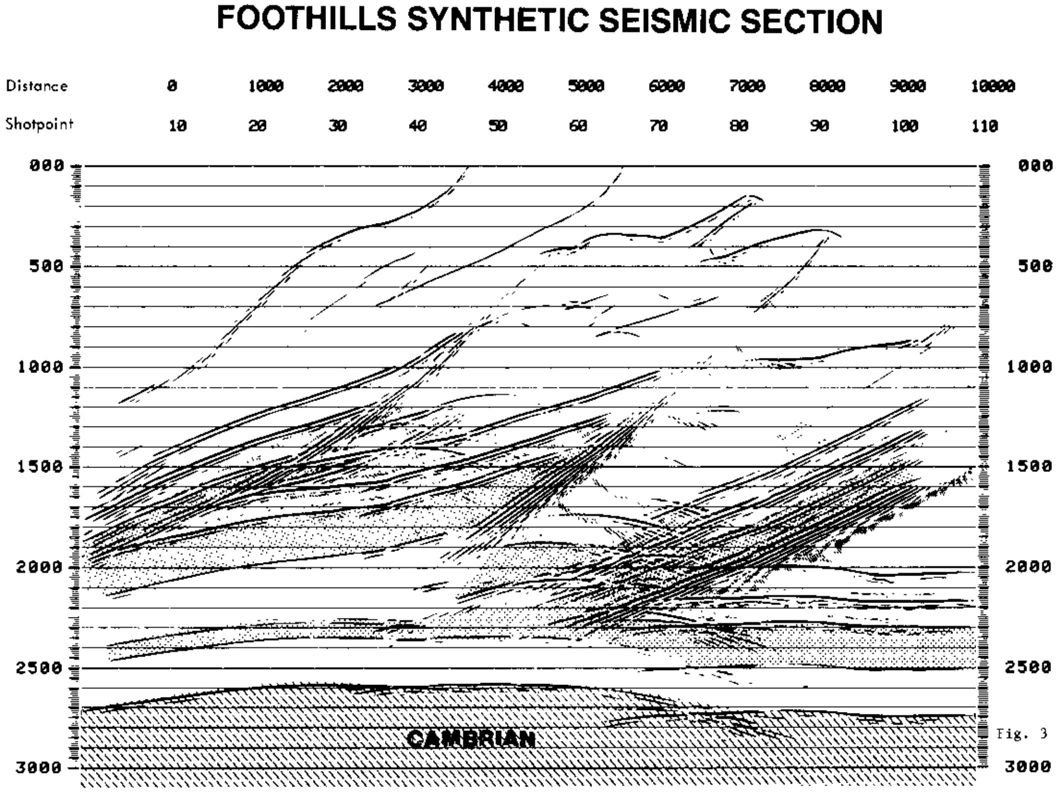


Fig. 3.

Stacking Velocities

There are four types of velocities significant to geophysicists: interval, average, RMS and stacking.

RMS and stacking velocities are usually considered synonymous. This is not a valid assumption. The difference can be demonstrated using a model (figure 4) of the Mackenzie Delta profile. The permafrost layer, with a velocity of 10,250 ft/sec, varies in thickness above a relatively smooth reflector buried between 4,000 and 5,000 feet. From the interval velocities shown, RMS velocity curves were computed for 3 shotpoints; A, B and C. These curves are plotted beneath each shot. At A and C the permafrost is thick and the RMS curves are faster than at B.

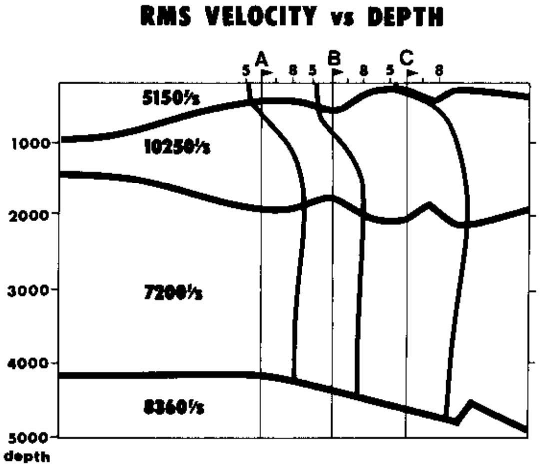


Fig. 4.

With this plotting format, the RMS differences are difficult to recognize. They are more obvious on Figure 5 where velocity down to the reflector is displayed as a continuous curve in what will be called the velocity horizon format. This format will be used on all subsequent displays.

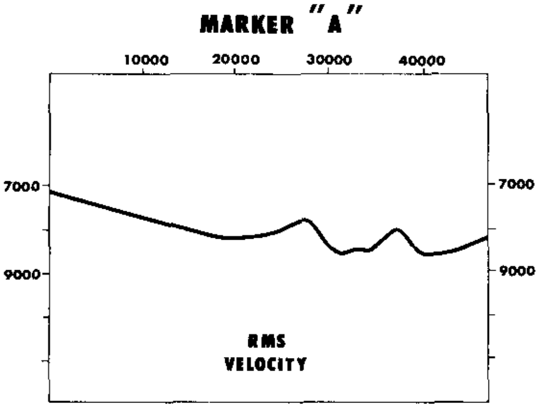


Fig. 5.

The RMS velocity for marker A (figure 5) has a regional variation of 1,500 ft/sec across the profile and some minor fluctuations on the right part of the horizon. RMS velocities are computed directly from interval velocities and react in a smooth, predictable fashion to any geology change. Only a slight variation is observed in response to the 800 feet change in permafrost at B.

Stacking velocities, on the other hand, must be obtained directly from the seismic data; they cannot be computed from interval velocities alone. The optimum stacking velocity horizon for marker "A" of the seismic line (figure 6) indicates that stacking velocities are in a galaxy of their own! The stacking velocity shows wild swings of almost 3,000 ft/sec compared to smooth RMS changes of only 500 ft/sec (figure 5). These stacking velocities are from real seismic data from the Mackenzie Delta profile. Stacking velocities *can* add a new dimension to interpretation of the subsurface.

THE INTERACTIVE TERMINAL

To show that these stacking velocities are real and how they are produced by geology changes, an interactive terminal was used to create synthetic seismic data. Interactive modelling (figure 7) simulates field conditions such as spread, trace spacing and fold and applies this field system to a geologic model. For the following examples, a 24 trace spread with 220 feet trace spacing was used to create 2400% subsurface coverage. Through ray tracing, seismic travel paths are simulated and the synthetic field records created are subsequently processed in the same manner as seismic data. On the interactive terminal, displays of depth and synthetic responses of both time and stacking velocity for any model input can be produced.

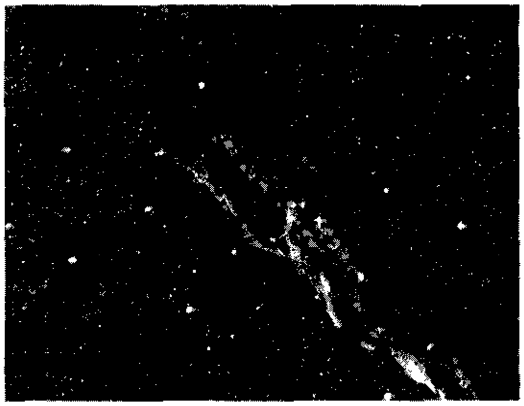


Fig. 6.

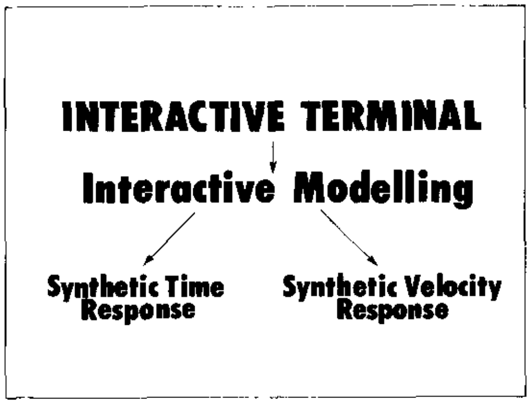


Fig. 7.

STACKING VELOCITY ANOMALIES

The following figures demonstrate that geologic changes do produce velocity anomalies on seismic reflectors and indicate the parameters which affect the magnitude and shape of the stacking velocity curves.

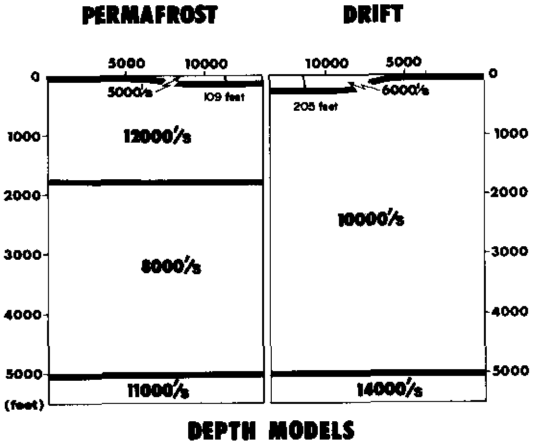


Fig. 8.

On the left half of Figure 8 is a depth model indicating the thinning of a permafrost layer. The permafrost is 1,800 feet thick and it has a velocity of 12,000 feet per second (Permafrost this thick does exist in the Mackenzie Delta). It is enclosed by a 5,000 ft/sec mud layer on the surface and an 8,000 ft/sec sedimentary sequence below. The permafrost thins by 109 feet across the profile and we will examine the effects of this thinning on two reflectors, the one shown at 5,000 ft and another at 12,000 ft which is not shown. This model should interest the Arctic explorationists.

On the right half is a model typical to the plains of Alberta. Glacial drift is shown thickening by 205 feet. The effects of this change on the 5,000 foot and 12,000 foot reflectors will also be examined.

These two models represent near surface problems. Buried geologic changes, such as overthrusts in the Foothills, create similar anomalies on deeper reflections. Our examples will apply to all conditions.

On Figure 9, the time and stacking velocity responses from the 5,000 foot reflector are shown. In time, both models created a 30 ms delay which develops smoothly across the profile, conforming to the smooth change in near surface geology. In stacking velocity, the changes are not so smooth and intuitively obvious. An anomalously low stacking velocity is observed where the RMS velocity should be high (at surface position 5500 ft) and an anomalously high stacking velocity is created where it should be low (at surface position 8,000 ft). The super low/super high velocity pair created by a smooth change in overlying geology is the stacking velocity anomaly.

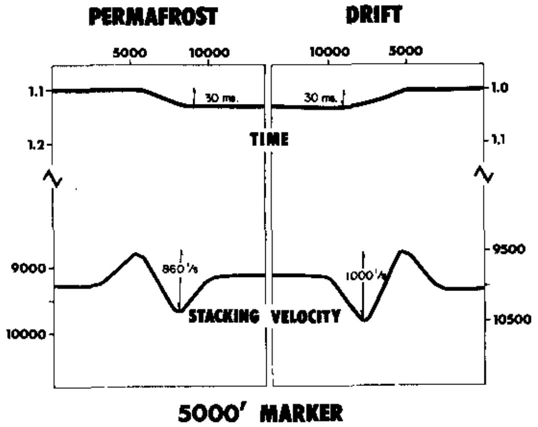


Fig. 9.

From the 12,000 foot marker (figure 10), the stacking velocity anomaly has the same shape with even greater amplitude. More magnification is put on the near surface geologic change even though the time shows the same 30 ms. delay.

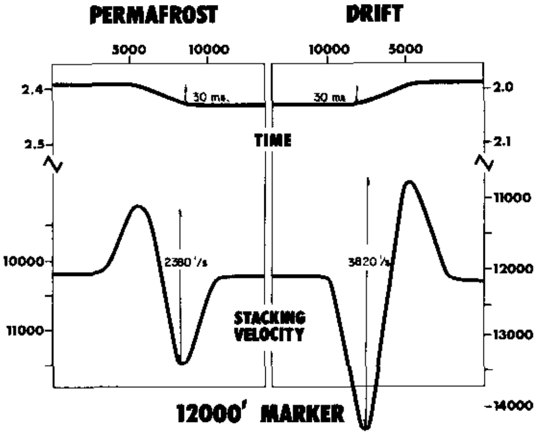


Fig. 10.

These wild swings in stacking velocity are created by distortion of normal moveout in the CDP gathers. Reflections recorded on long offset traces are delayed or accelerated relative to near trace arrivals because the rays travel through different geology. The distortion is particularly significant on deep reflectors where normal moveout is small and therefore very large velocity anomalies are created.

Stacking velocity anomalies *are* produced by geology changes and the magnitude of the anomaly depends, at least in part, on the depth to the event upon which the analysis is made. The magnitude also depends on the amount of geologic change. In Figure 11, permafrost is present across the profile but thins by 408 ft in the centre. (A more realistic permafrost model would have melting occurring on the bottom surface also. The effect of that extra thinning will be ignored at this time.)

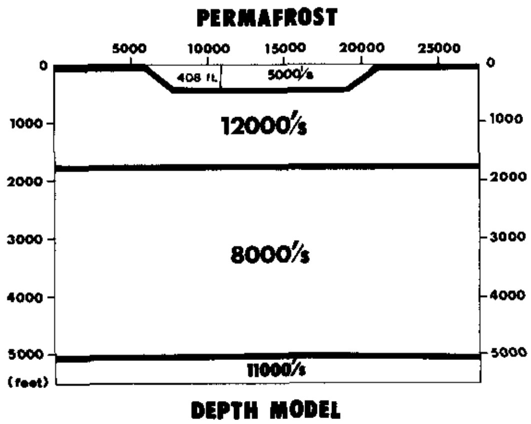


Fig. 11.

Figure 12 shows the effect of this permafrost change on both the 5,000 ft and 12,000 ft reflectors. In time, both events have a 100 ms static anomaly. At 5,000 ft (on the left), the velocity anomaly is now 3,500 ft/sec but at the 12,000 ft marker, the anomaly is in excess of 18,000 ft/sec. When the distortion approaches 100% of the normal moveout, the velocity effects are phenomenal.

So far it has been shown that the stacking velocity anomaly is affected by the amount of geologic change and by the depth of the marker being examined. Two other parameters which affect the magnitude and character of the anomaly are: "spread length" and "slope".

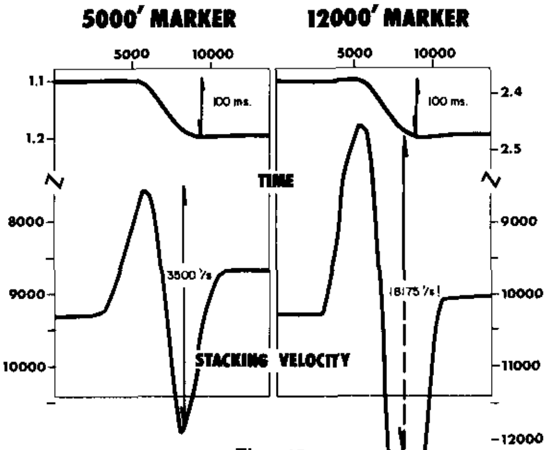


Fig. 12.

The interaction of these two parameters will be demonstrated using the models shown on Figure 13. The change in permafrost thickness is the same as the previous model (408 ft) but the slope on the top permafrost surface is reduced to 5.3° so that the geologic change occurs across 1 spread length on the left. On the right, the slope is reduced to 3.5° and the change occurs over 1½ spread lengths. On Figure 14, the resulting time and stacking velocity horizons for the reflector at 5,000 ft are shown. The time anomalies change only in slope but the stacking velocity anomalies

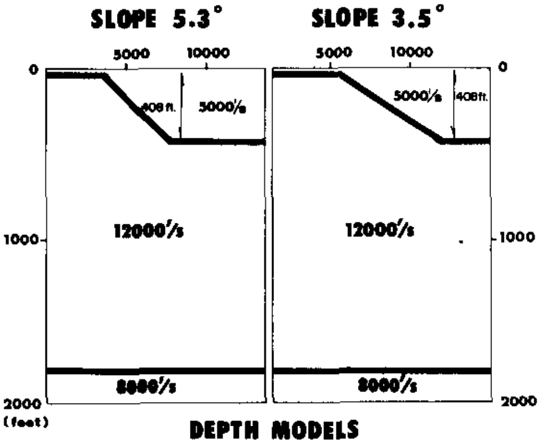
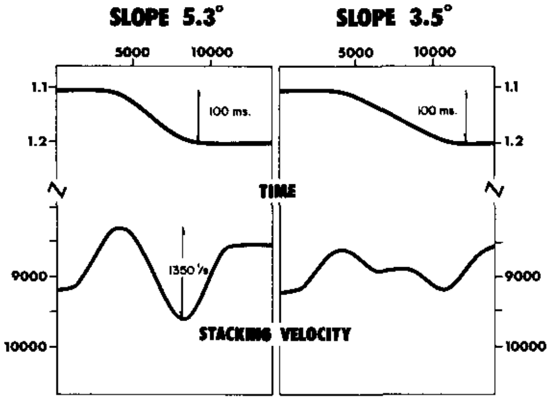


Fig. 13.

change in both magnitude and character. Similarly on the 12,000 ft marker (figure 15), the velocity anomaly which was 18,000 ft/sec on the previous model is reduced to less than 6,000 ft/sec with the slope of 5.3°. In the 3.5° slope model, the character of the anomaly changes and the amplitude reduces to ONLY 3,040 ft/sec.



5000′ MARKER

Fig. 14.

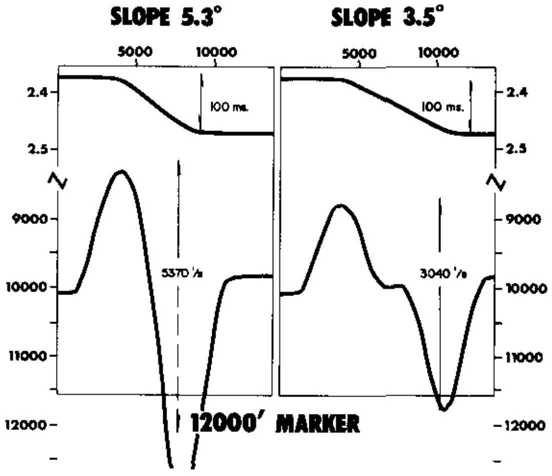


Fig. 15.

These figures begin to introduce the complications in stacking velocity anomalies in real seismic data. In the earth, changes do not necessarily occur with the right degree of slope to match the seismic spread and neither are the geologic changes isolated from one another to keep the velocity anomalies clearly defined. Interpretation of stacking velocity anomalies in real seismic data is extremely difficult except through modelling on the interactive terminal.

Interactive Modelling — The Method

The flowchart (figure 16) shows how the interactive terminal is used in an "interpretation mode". Reflection time and stacking velocity are computed from real seismic data and displayed on the terminal screen. Superimposed are the time and velocity horizons generated from a model. These four responses are compared and the model is adjusted iteratively until a satisfactory match is attained.

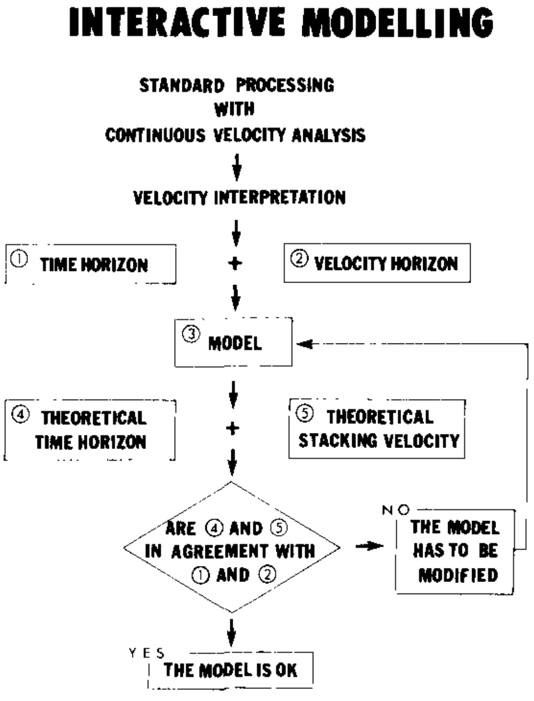


Fig. 16.

Interactive Modelling — A Case Study

The technique will be demonstrated using selected displays from a study of the Mackenzie Delta seismic line shown earlier (figure 1). To supplement this time display,

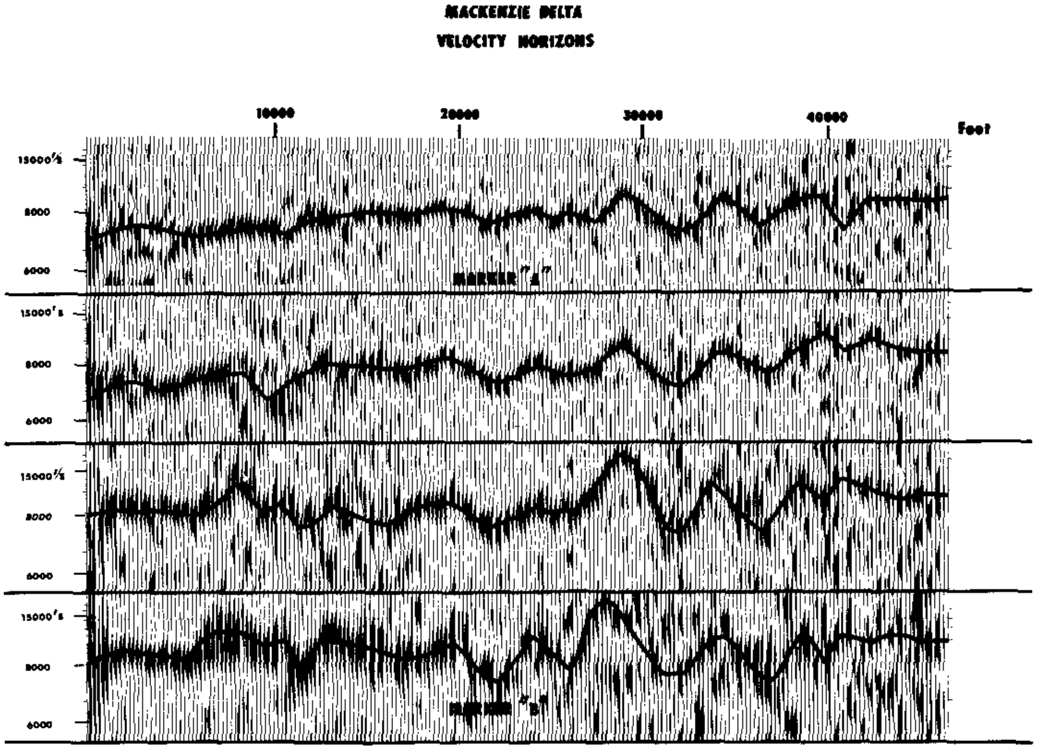


Fig. 17.

stacking velocity is added (figure 17). Results of continuous velocity analysis along four horizons are displayed, on logarithmic scale-plots. The top velocity horizon is from the event marked "A" on the time section and the deepest from event "B". Geologically, the area is expected to have only Tertiary sediments within which velocity increases linearly with depth. Stacking velocity horizons should then be reasonably constant, but they are not. Velocities exhibit wild fluctuations which apparently align vertically and increase in amplitude on the deeper markers. Distortion due to permafrost is the logical cause of these anomalies and since no reflections are obtained from permafrost boundaries (Card, 1977), variations in that shallow layer must be deduced from anomalies created on deeper reflectors.

Time and stacking velocity for horizon "A" are reproduced on the interactive terminal screen (figure 18). They appear in thin black lines, with the velocity scale now linear (making the fluctuations even more obvious). Superimposed with thicker lines are the responses of an initial synthetic model; time flat at approximately 1.05 seconds and

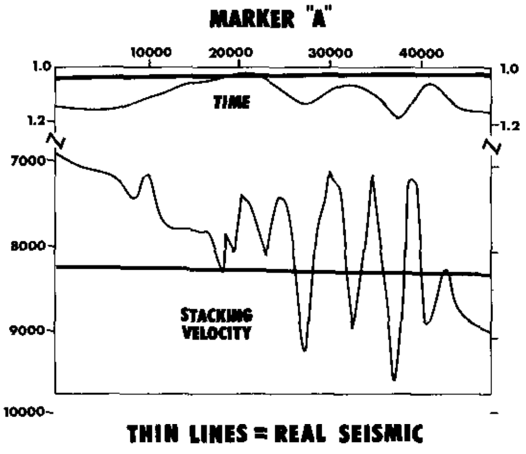


Fig. 18.

stacking velocity constant at approximately 8,300 ft/sec. These responses are from an initial model (figure 19) having flat layers of mud, permafrost and sedimentary sequence overlying the flat reflector at 4,300 ft. The obvious first adjustment is to thin permafrost to the left (figure 20). This change in the near surface layer affects time and stacking velocity for marker "A" (figure 21). The regional trends are approximated and now attention is focussed on the wild velocity anomalies. The interpretation technique is iterative. One of the high/low velocity pairs is selected and the permafrost layer thickness is adjusted until a match in responses is obtained.

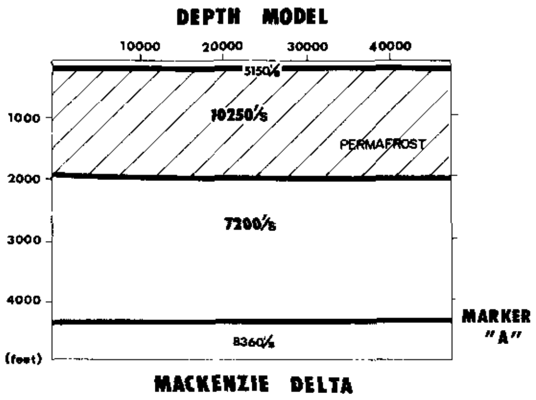


Fig. 19.

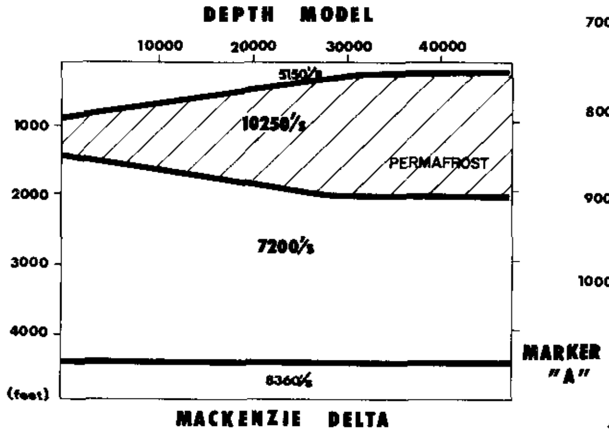


Fig. 20.

Figure 22 shows responses at an intermediate stage. Anomalies are beginning to show in the time response and the stacking velocity is starting to approach the real seismic data but further changes to the model are needed to make the match better. Notice at the left end of the profiles, along the regional trends, no adjustment has been made to the permafrost layer and the response is still linear.

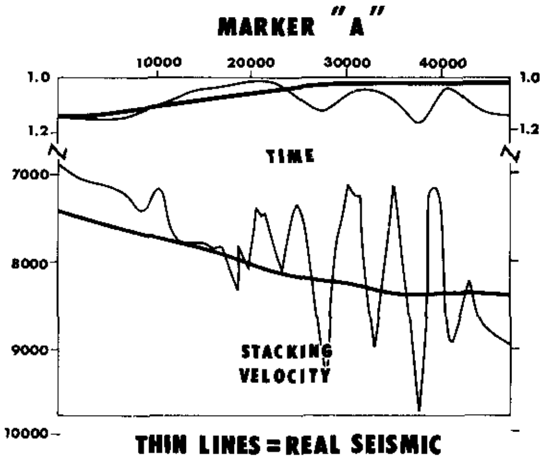


Fig. 21.

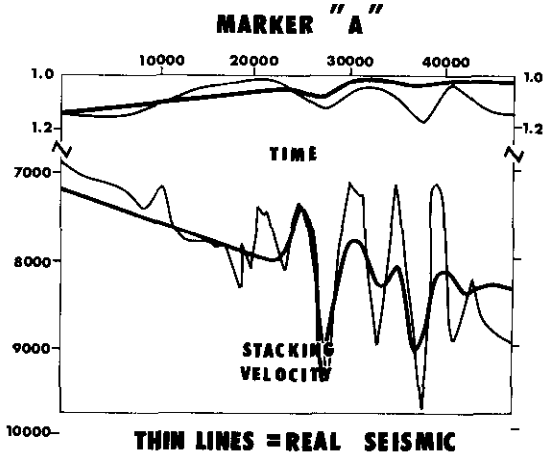


Fig. 22.

After many iterations, a "final" result is obtained (figure 23). The permafrost layer, which started out flat, now shows regional thinning to the left, interrupted by two major anomalies and several minor fluctuations, some of which do not show on the figure. Each of these fluctuations produce noticeable effects in the stacking velocity curves even though some of them indicate less than 50 feet of permafrost change. The final time and stacking velocity results are shown on Figure 24. The synthetic responses (thick lines) match very well to the real seismic data (thin lines). Remarkably, most of this match was obtained by adjusting only the permafrost layer. Some structure was detected at 4,000 ft in order to get travel times to match but this structure has essentially no effect on the stacking velocity anomalies. The permafrost interpretation thus developed can be checked by examining responses on the deeper marker (figure 25). Again, time and stacking velocity match remarkably well. Some minor adjustments could still be made but already the interpretation procedure used has shown that the two saddles in the original time section are entirely false and that the whole regional structure has been distorted by the permafrost layer.

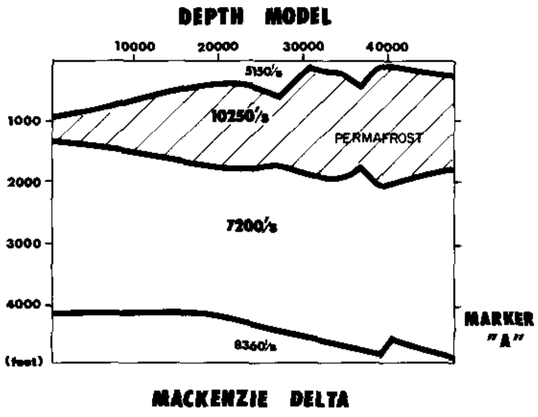


Fig. 23.

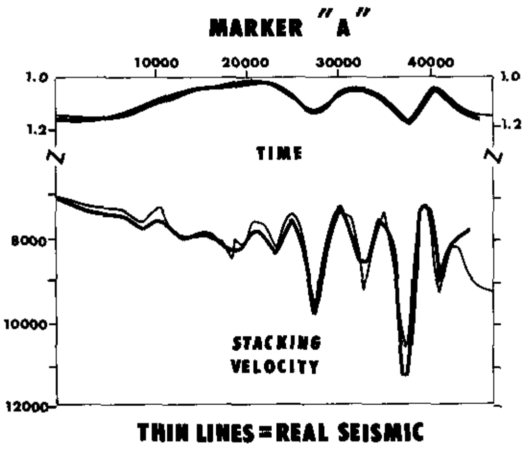


Fig. 24.

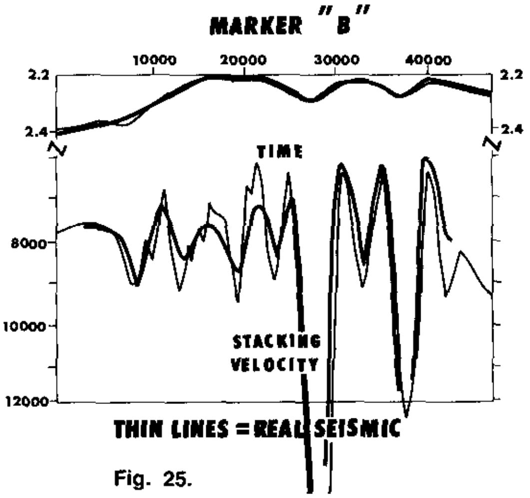


Fig. 25.

The structure on marker "A" shown in Figure 23 is not absolutely accurate. Further refinements could be made but were not necessary in this study because prime interest was in the variation of permafrost along the profile. This seems like a common statics problem. But notice the statics are of 200 ms magnitude in both local anomalies and regional trend. No conventional statics approach will handle these changes, and further, no conventional approach would provide any geologic control on the layer which caused the original disturbances.

CONCLUSION

Through interactive modelling an interpretation of the permafrost geology has been developed based only on time and stacking velocity anomalies on deeper events.

This technique is applicable on many statics type problems — permafrost, glacial drift, sand dunes — and on complicated subsurface interpretations including thrust fault and reef plays. In each, geological changes distort reflection events from deeper markers. By combining interpretation of the resulting time anomalies together with the stacking velocity anomalies, the distortions can be decoded and the interpreter's understanding of the whole geologic sequence is improved.

The interactive terminal provides the capability through its speed, but *stacking velocity anomalies* provide the new dimension in seismic interpretation which makes "Velocity Modelling the Interpreters Magnifying Glass".

ACKNOWLEDGEMENTS

We would like to express our appreciation to Sun Oil Company Ltd., Bow Valley Exploration, Arctic Coast Petroleums and Numac Oil and Gas for their permission to show the Mackenzie Delta seismic data. Also, we thank Geodigit for the use of their interactive terminal and software for the purposes of this paper.

REFERENCES

(1) Merland, Jacques, 1975, Application of Seismic Modelling to Velocity Studies: Journal of the Canadian Society of Exploration Geophysicists, Vol. 11, No. 1.

(2) Card, J. D., 1977, "Permafrost in the Mackenzie Delta ": N.R.C. (Canada) Technical Memoranda Series; Proceedings of a Symposium on Permafrost Geophysics (in print).