SEISMIC RECONNAISSANCE PROFILES ACROSS THE SVERDRUP BASIN, CANADIAN ARCTIC ISLANDS

Project 770018

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Abstract

Seismic data may be described as multifold reversed profile data, with multiplicities ranging from 300 to 700% in each direction of the reversed profile. The viewpoint that reversed refraction profiles are more determinate than unreversed profiles is stringently tested for these deep sedimentary basins, and results show that great quantities of data complicate rather than simplify interpretations. Attempts to use traditional reversed profile refraction analyses based on a layered model with dipping interfaces failed to reveal unique velocities, dips and structures for the layers which could be matched bidirectionally.

A different analytical approach, using a model with velocities gradually increasing with depth, so that seismic events may be treated as wide angle reflections near critical incidence, appears to be justified. This approach yielded delay time-velocity profiles which match perfectly for the two directions of the reversed profile and uses all the available seismic data without internal conflict. The delay time-velocity structures are also consistent with observed gravity anomalies.

Introduction

In 1972, industry and the Federal Government jointly sponsored detailed shallow and deep seismic refraction and gravity studies along a profile located 60 km south of, and parallel to, the axis of the Sverdrup Basin (Fig. 19.1) in the Canadian Arctic Islands. G.D. Hobson of the Geological Survey of Canada (GSC) initiated and organized the project and led the operations. The Earth Physics Branch (EPB) of Energy Mines and Resources, Canada, conducted the gravity profiling and the deep crustal seismic sounding. Six oil companies participated: Canada Southern Petroleum Limited, Canadian Reserve Oil and Gas Limited, Deminex (Canada) Limited, Dome Petroleum Limited, Mobil Oil Canada Limited, and Panarctic Oils Limited. Details of the joint responsibilities are described by Hobson (1972). In 1973, the GSC and EPB extended the profile eastward across Amund Ringnes Island, and in 1974 added the north-south profile off the east coast of Ellef Ringnes Island (Fig. 19.1). Analytical problems relating to the seismic data for the sedimentary section were reported by Overton and Hobson (1977). Interpretation of the deep seismic refraction data is reported by Forsyth et al. (1979). This report documents the logistic details and the interpretation problems encountered with the unique multifold seismic refraction coverage obtained for the sedimentary section.

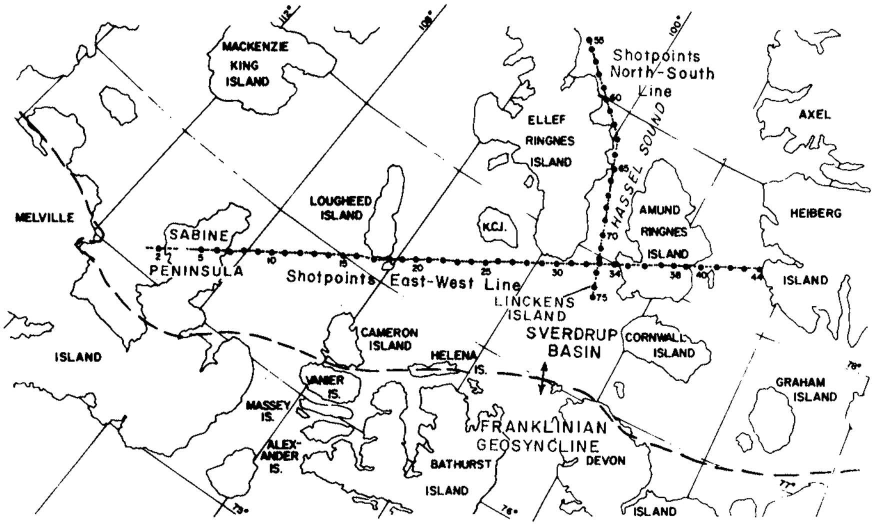


Figure 19.1. Location map and extent of reconnaissance profiles.

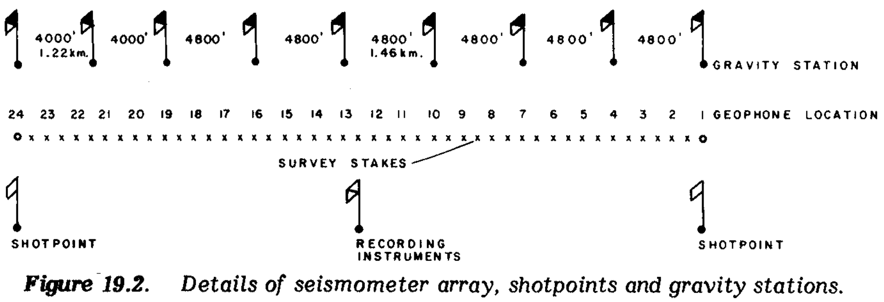


Figure 19.2. Details of seismometer array, shotpoints and gravity stations.

Logistics, Operations, and Instrumentation

Three campsites were established in 1972 as the work progressed east from Melville Island: at Drake Point on Sabine Peninsula, on Stupart Island at the southern tip of Lougheed Island, and at Sun Oil's King Christian Island airstrip. This last campsite was used in 1973 and 1974.

The operations involved up to 9 staff members of GSC and EPB, and Inuit Labour from Cambridge Bay and Resolute were employed each year.

The principal means of mobilizing and demobilizing the bulk of equipment, personnel, fuel and supplies during the winter season was by fixed-wing aircraft; field operations used helicopters. In the 1972 operation a cat train transported and housed the surveying crew as the line was surveyed and flagged from Sabine Peninsula to Axel Heiberg Island. Extensive use was made of snowmobiles for laying out and picking up the seismometers and cables; during 1973 and 1974 they were used to survey and flag the profiles.

For surveying, in 1972, elevations on land were determined by levelling and tying into base stations on Sabine Peninsula, Lougheed Island, King Christian Island, Linckens Island, Amund Ringnes Island, Ellef Ringnes Island and Axel Heiberg Island. Water depths were measured using an echo sounder coupled to the ice surface at every gravity station at intervals ranging from 980 to 1460 m. The accuracy of gravity station locations is within 30 m. Elevations are accurate within 0.3 m, and water depths are estimated to be accurate within 1 m. In 1973 and 1974, the surveying was done by triangulation from control points on King Christian Island and Ellef Ringnes Island using two snowmobiles. The lines were flagged by chaining and staking, using visual backsiting, every 243.8 m along bearings established from the triangulation control. These procedures proved to be very successful.

The seismic refraction profiling of the sedimentary section was conducted using 48-seismometer linear arrays, one seismometer per station, with 243.8 m station spacing for the east-west profile. Seismometers were Mark Products LIU, 4.5 Hz. An 11 460 m cable (Fig. 19.3) connected seismometers to the recording instruments at the centre of the array. The cable and seismometers were laid out using two snowmobiles except where extremely rough ice made helicopter airlifting necessary. The arrays were laid end to end along the profile with end seismometers common on adjacent arrays. Shotpoints were placed at increasing distances from both ends of the array, at equal intervals (array lengths, Fig. 19.3), until a first arrival velocity of 6 to 6.8 km/s was obtained. These velocities were taken to represent granitic or Ordovician limestone basement, respectively (Overton, 1970). For the north-south profile a 24 seismometer array was used with 487.6 m station spacing (Fig. 19.2) in order to minimize logistic problems. Apparently, no disadvantage resulted from this compromise.

Shots consisted of 60% geogel in 23 kg centre-tunneled cylinders. Charges made up in weights ranging from 23 kg to 68 kg were detonated on the ground surface on the islands and in the water on the seafloor, or at a depth of 60 m where water depth exceeded 60 m. Shots located on land or in shallow water on the shore were ineffective seismic sources and were not recorded beyond one cable length. Shotholes were drilled in the ice, generally about 2 m thick, using a gasoline powered auger. Charges were electrically detonated, producing a time reference pulse which was transmitted by radio to the recording seismograph. The 48 channel amplifier bank was made up of four 12-channel Texas Instruments VLF-2 systems modified to equalize signals to two SIE-PMR-20, 24 channel FM tape systems which were coupled mechanically and electrically. Adjustments to the PMR-20 proved to be extremely critical and sensitive to vibrations and temperature changes in the instrument shack. The drive mechanism was prone to freezing, and moisture condensation caused ice accumulations on the magnetic tapesand heads. Also the tape systems

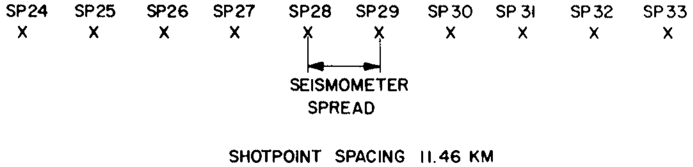


Figure 19.3. Seismometer array and shotpoint details used in generating the reversed profile multifold seismic data.

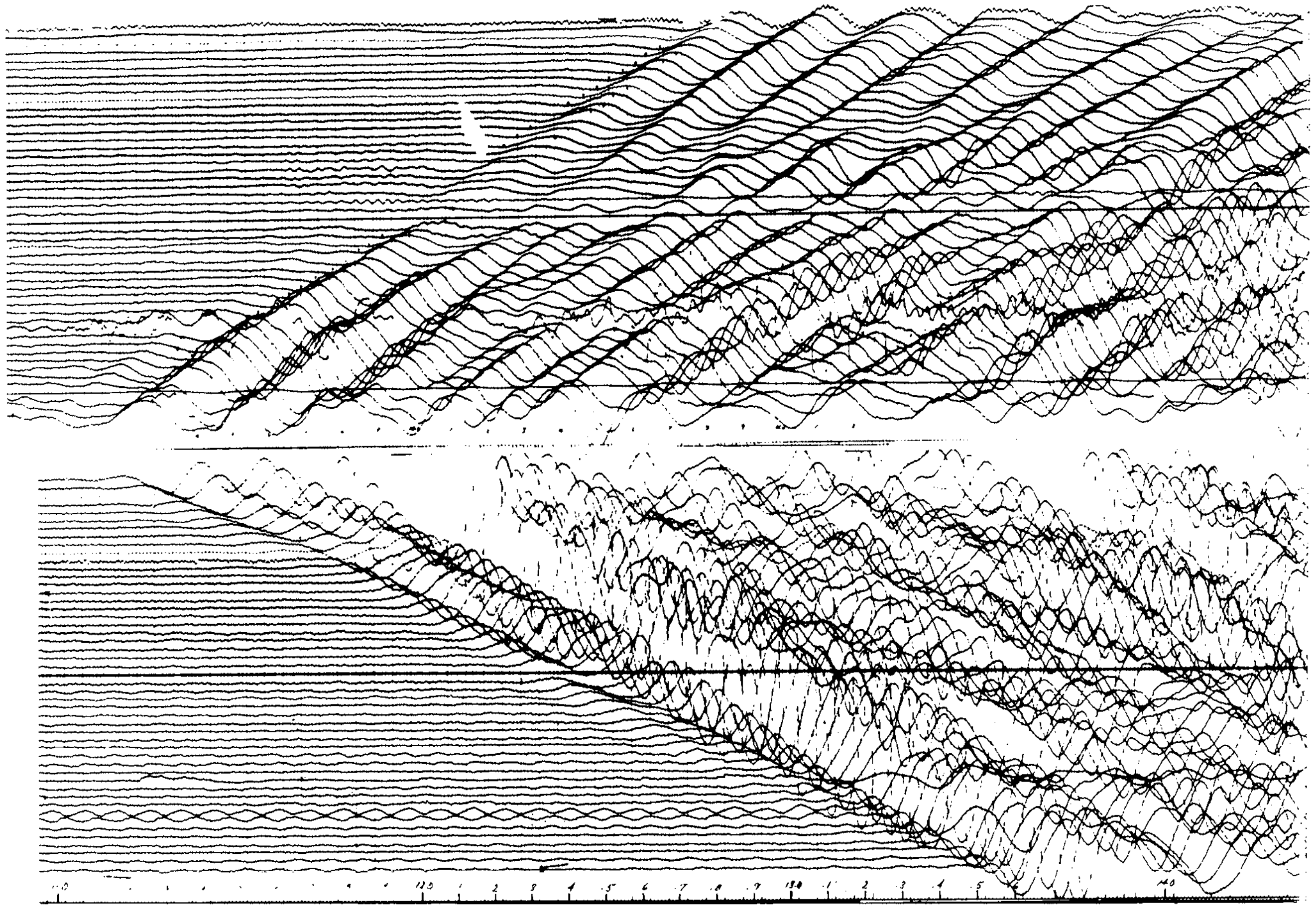


Figure 19.4. Two examples of the reversed profile seismograms.

caused a great deal of electrical interference on the seismograph amplifiers. These problems forced an early abandonment of attempts to record the data on magnetic tapes. A Texas Instruments RS-8U oscillograph using liquid developer and fixer was used with difficulty in the cold climate, only because an electrostatic oscillograph was not available. Oscillograph paper speed was 16.6 cm per sec. System bandpass response was 6 db down at 5 Hz and 48 Hz.

Results

Two sample records from the east-west line are shown in Figure 19.4. The first arrivals are characterized by weak onsets followed by stronger phases. The interpreter is compelled to pick progressively later events within the first arrival wavetrain, as the distance of the traces increases from the shotpoint. This results in an en-echelon pattern of segments on the time-distance plots, often causing timing conflicts in the interpretation. Early attempts to interpret these data were by conventional reversed profile methods which sought to establish layered velocity models on the basis of the reversed profile time-distance plots. All first arrivals and conspicuous secondary arrivals were plotted. Figure 19.5 is an example of the time-distance graphs. The method of recording shots from various distances into a stationary array is a sensitive indicator of velocity changes associated with depth of seismic penetration; variations of 0.25% can be significant depending upon the dispersion of the residual times about their regression line. Most velocity differences are larger than this and are highly significant. Figure 19.5 shows the difficulty in selecting a discretely layered model, and the difficulty of matching reversed profile segments for any given velocity. Velocity changes are subtle, with some obvious distortions due to local structures. Note the change to 5.33 km/s between shotpoints 29 and 30 decreasing to 5.12 km/s between shotpoints 28 and 29. This makes reversed profile matching of velocity segments virtually impossible. The subtlety of velocity variation is further illustrated in Figure 19.6 which shows frequency distributions of velocities for each direction of each of the reversed profiles. No discrete pattern of velocity layering is noticeable. No velocity shifts between the distributions for the reversed profiles are apparent. Regional dips (which would contribute to such shifts) of up to on half degree would produce bilateral velocity differences no greater than one class interval.

On the east-west line the prominent peak at 2.74 km/s represents ice arrivals at small distances. The north-south line shows several observations at 1.52 km/s which represent ice coupled water arrivals. Velocities greater than 6.75 km/s represent events modified by local structures and probably some diffractions.

Interpretation

The velocity distributions suggest complex multilayered models; however, the number of layers remains obscure. The velocity histograms do not indicate a lower limit. Even allowing one layer for each class interval, the problem of matching reversed profile segments to avoid conflicting structures persists. The interpreter is forced to accept each velocity segment of the time-distance plot at face value and to consider the concept of gradually increasing velocities with depth, a concept which has been used routinely to interpret reflection data in sedimentary basins for decades (Slotnick, 1936).

Another problem remains with head wave interpretations; that is, which part of the subsurface span between the shotpoint and the seismometers does an event represent? The simplest approach is to think of the seismic events as wide-angle, or near-critical, reflections. In this way the events may be viewed as representing the halfway point on the subsurface. This can be done for each direction of the reversed profile. A comparison of the bidirectional results may provide insight into interpretational refinement. Further to the concept of gradually increasing velocities with depth, near-critical reflection trajectories are commonly curved (circular for strictly linear velocity increases), with the apparent velocities representing the velocity at the maximum depth penetrated (Dobrin, 1952). This provides the most convenient approach for interpretation because it solves all the mechanical problems; that is, since the recorded events are considered to be wide angle reflections, they would represent the halfway subsurface span. Also in the sense that the events are critical reflections, their apparent velocities are representative of those at the maximum depths of penetration, and may also be interpreted as head waves. In this way, the time-distance-velocity values for each event may be reduced to a delay time. This fully describes the method: for each direction of the reversed profiles, velocities and associated delay times were computed for all segments of the time-distance graphs. The delay times were plotted on sections, and annotated with their velocities, halfway between the shotpoints and seismometers. Velocity contours were then drawn on these sections. The two directions for the reversed profiles were then compared and, with minor modifications to the contours, were found to match. The results from the two directions, now being compatible, were combined (Fig. 19.7, 19.8). This was considered a major accomplishment, especially since prior interpretations using reversed profile headwave analyses and layered models produced gross conflicts in structures. Thus, a fundamental prerequisite is satisfied: the interpretation utilizes all of the data systematically without internal conflicts. The practical meaning, as with any interpretation, requires substantiation.

Discussion

Certainly for the deep Sverdrup and Franklinian sedimentary basins (Thorsteinsson and Tozer, 1960) composed of an alternating sequence of marine and nonmarine sediments, faulted and folded, containing igneous, carbonate, gypsum and halite intrusions, the complexity of the seismic refraction results is not surprising. Previous seismic studies in this area (Hobson and Overton, 1967; Overton, 1970; Sander and Overton, 1965) used layered velocity models and headwave interpretations simply because the data were sparse and no conflicts were encountered. The highly detailed work of this experiment has demanded attention to these conflicts.

The most serious criticisms of the interpretation are:

1. the resulting velocity contours do not correspond with, or even resemble the results of seismic reflection work over the same area (reported in Forsyth et al, 1979), and
2. the velocity contours do not correspond with the stratigraphy as it is known from borehole control.

These criticisms are easily dismissed as the refraction method, with wide ranging soundings, traverses a highly diverse geological environment and in the process it does a lot of averaging of structures. The borehole and seismic reflection correlations show detailed, localized structures.

As for geological implications the 3 km/s contour approximates the water delay time and it shows the highly variable seafloor topography. Other geological correlations are obscure and are undoubtedly complicated by stratigraphic variations. However, some general regional effects may be seen. Judging from depth estimates the 5.25 km/s contour in Figures 19.7 and 19.8 appears to approximate the base of the Sverdrup Basin. It shows a general thickening from the west toward the east (Fig. 19.7) and from the north toward the south (Fig. 19.8) approaching the axial region of the basin.

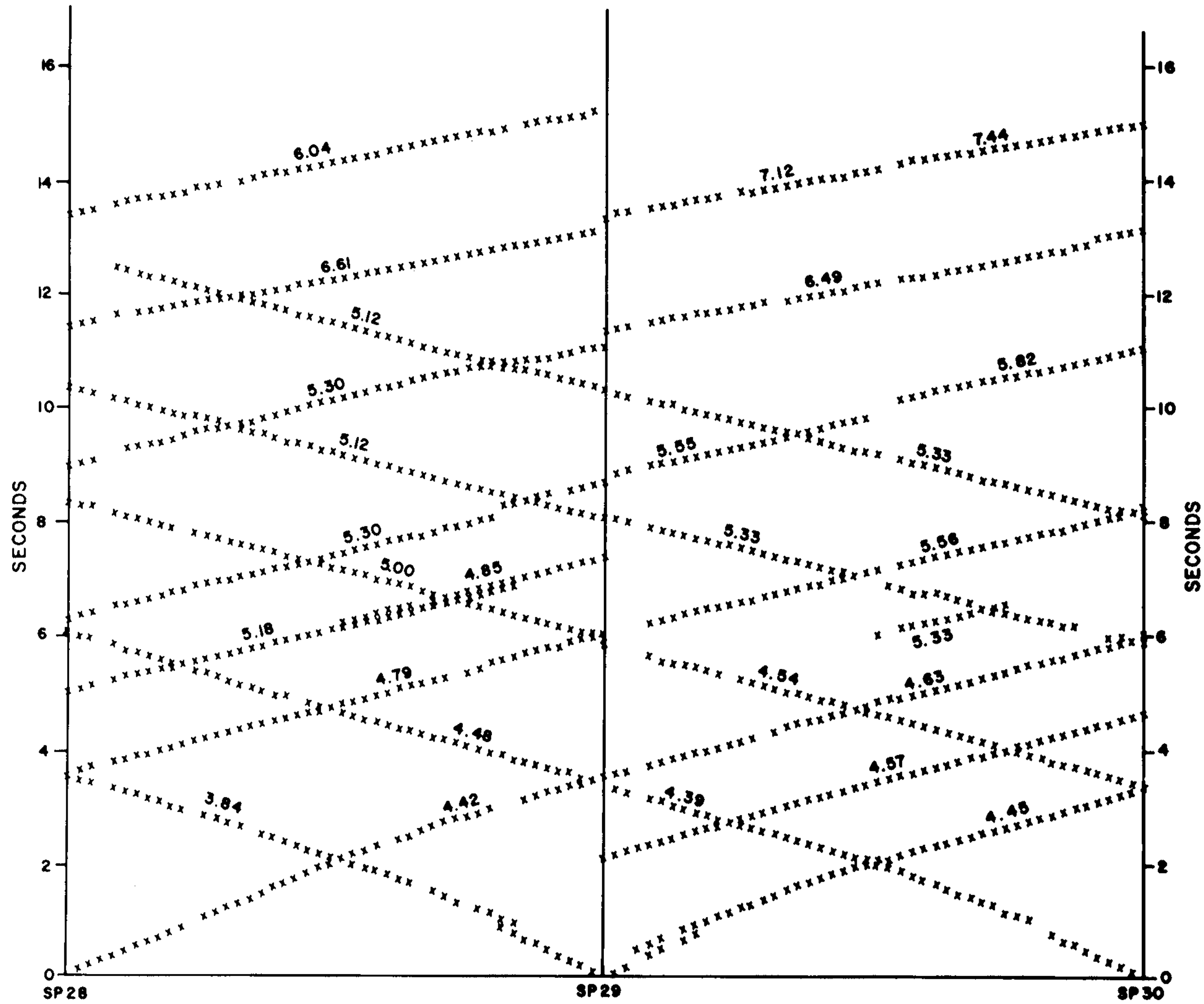


Figure 19.5. *Example of reversed profile time-distance plots. Velocities are in kilometes per second.*

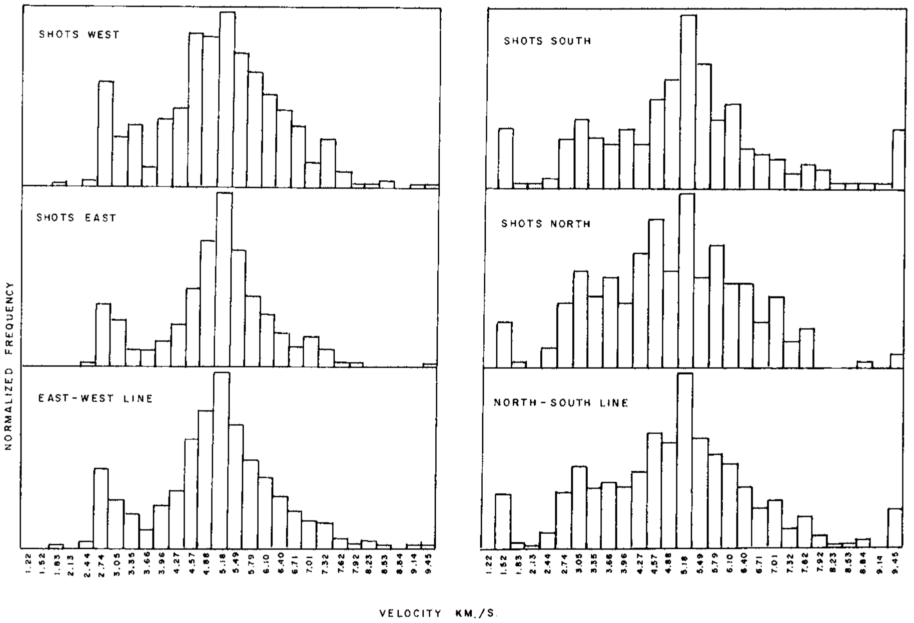


Figure 19.6. *Histograms of first arrival velocities for reversed profile multifold seismic refraction data.*

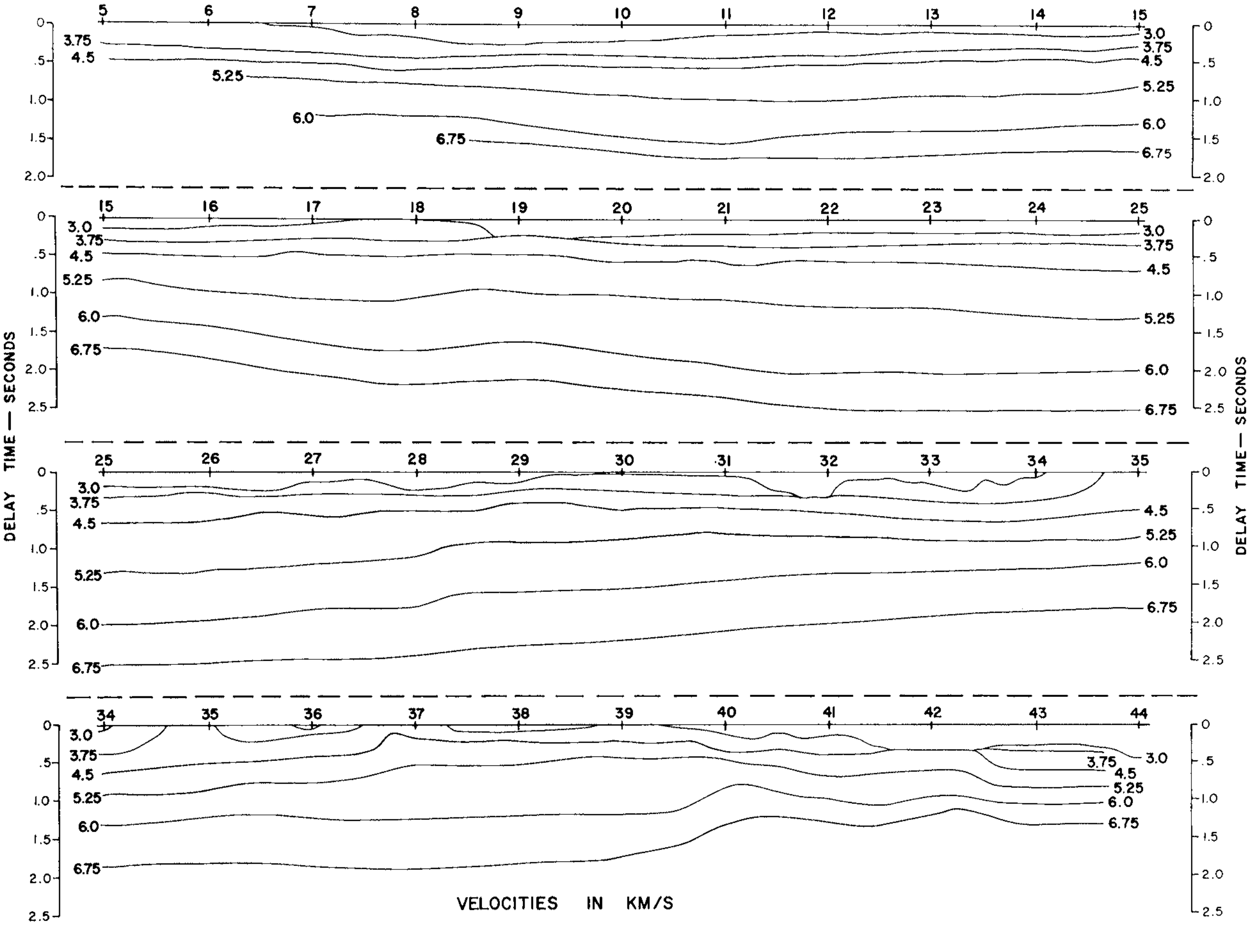


Figure 19.7. Contoured velocity-delay time profile for the east-west line.

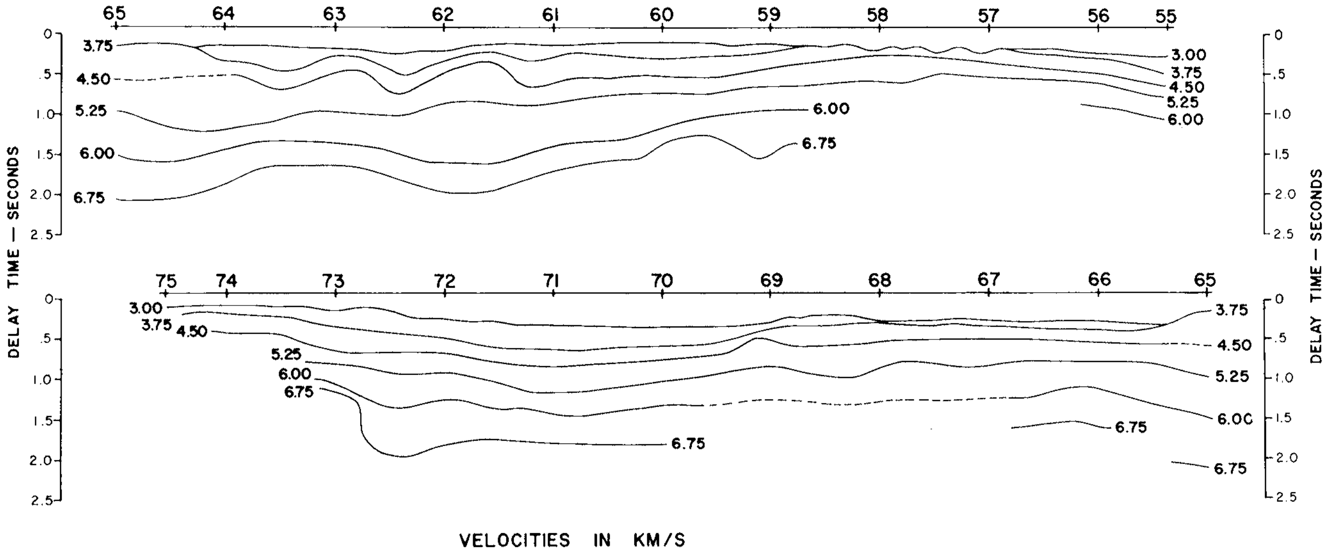


Figure 19.8. Contoured velocity-delay time profile for the north-south line.

The 6.75 km/s contour is ubiquitous on the east-west section (Fig. 19.7) and is considered to be seismic basement, and coincides with early Paleozoic carbonate belts which fringe the Sverdrup Basin. The seismic refraction method is very effective in mapping these carbonate belts.

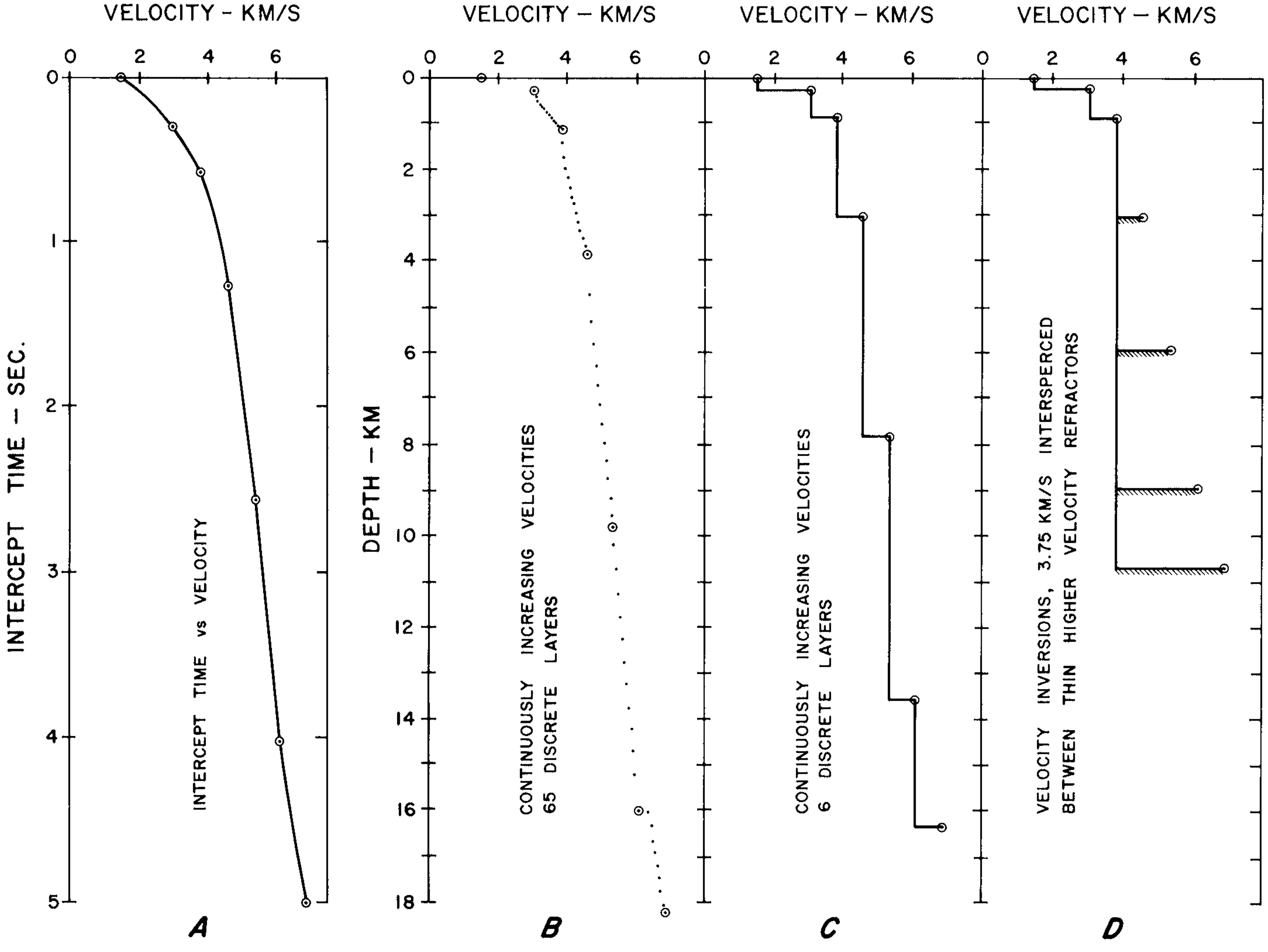
Another basin-like thickening is suggested for these deeper Paleozoic strata, and may represent the Franklinian geosyncline underlying the Sverdrup Basin. Increased complexity of folding east of Ellef Ringnes Island, across Amund Ringnes toward Axel Heiberg is in accordance with known geological models, as well as structural complexities on Amund Ringnes Island.

Figure 19.8, the contoured velocity-delay time section for the north-south profile shows a sharp rise in the 6.75 km/s contour at shotpoint 73 which appears to be significant. This coincides with a pronounced local gravity feature which may be related to the northern extension of the Boothia Arch and the Cornwallis Fold Belt (Thorsteinsson and Kerr, 1968; Kerr, 1977). Poorly controlled contours are dashed. The absence of the 6.75 km/s contour between shotpoints 67 and 70 may signify a change from carbonate to shale or clastic facies. This effect has been observed in previous work (Overton, 1970) near Emerald Isle, between Prince Patrick Island, Mackenzie King Island and Sabine Peninsula where a high velocity basement was absent. Truncation of sedimentary beds on the seafloor is suggested on an arch centred under shotpoints 57 and 58 (Fig. 19.8) This feature coincides with a 60 mgal positive gravity anomaly (Sobczak et al., 1963). The pronounced folding at shotpoints 62 and 63 on the shallow contours is the most conspicuous seismic feature. This coincides with a 30 mgal negative gravity anomaly representing a gypsum piercement structure.

Further support for this seismic interpretation is discussed in a manuscript by Sobczak and Overton (submitted to Earth Physics Branch).

Depth Conversions

Alterating sequences of marine · and nonmarine sediments in sedimentary basins invariably cause velocity inversions which complicate depth conversions, particularly for the seismic refraction method which only shows monotonically inceasing velocities. Delay times obtained from refraction profiling, however, are directly related to these inversions. Thus it is necessary to examine the effect of these inversions on depth estimates. In the absence of velocity information from deep boreholes or from deep seismic reflection data, it is necessary to examine reasonable



DEPTH COMPUTATIONS, SHOTPOINT 24

Figure 19.9. *Comparison of depth conversions for selected velocity models.*

possibilities for velocity models. Three methods were tested for the purpose of comparison. First, Figures 19.7 and 19.8 indicate the monotonically increasing velocities characteristic of refraction profiling. Accepting these as representing one possible model with a large number of increasing velocity layers gives one set of depth estimates. Second, Figures 19.7 and 19.8 may be taken to represent six discrete velocity layers overlying the 6.75 km/s basement, giving another set of depth estimates. Third, the velocity contours of Figures 19.7 and 19.8 may be considered as representing thin refractors interspersed within a low velocity matrix. Figure 19.9 shows the depths resulting from these three models for shotpoint location 24. The greatest difference in computed depths is given by Figure 19.9D for which an extreme degree of inversion has been assumed. The model in Figure 19.9C represents depth uncertainties of 10%, compared with the model in Figure 19.9B and models assuming a moderate degree of velocity inversion.

Conclusions

Reversed seismic refraction profiling in the Sverdrup and Franklinian basins has produced data which generate conflicting and confused structures by traditional headwave analyses and discretely layered velocity models. An interpretation which assumes that first arrivals represent wide angle critical reflections appears to eliminate these conflicts and allows the data to be mapped as contoured velocities on delay time sections. The resulting sections are consistent for reversed profiles and utilize all the available data.

Details of structures are not seen in these wide ranging seismic refraction measurements, while the broad, well known features of depth variations, folding and faulting complexities and diapiric structures are evident in the interpretations. The seismic refraction method is effective in mapping the high velocity Paleozoic carbonates of the Franklinian geosyncline. Depth estimates appear to be within expected limits, allowing for reasonable variation in the velocity model.

Acknowledgments

The considerable efforts of G.D. Hobson, initially the leader of the seismic team, the later the Director of the Polar Continental Shelf Project, in planning, contracting and organizing the project, and in manuscript revision, are gratefully acknowledged.

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The Earth Physics Branch conducted the gravity measurements during all three field seasons, and the long range seismic refraction surveys of 1972 and 1973. Several people were involved in various aspects of the field work, which was often conducted under harsh conditions. The bulk of this work was done by, or under the supervision of, H.A. MacAulay, R.A. Burns and R.M. Gagne.

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