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Energy, Mines and Resources Canada
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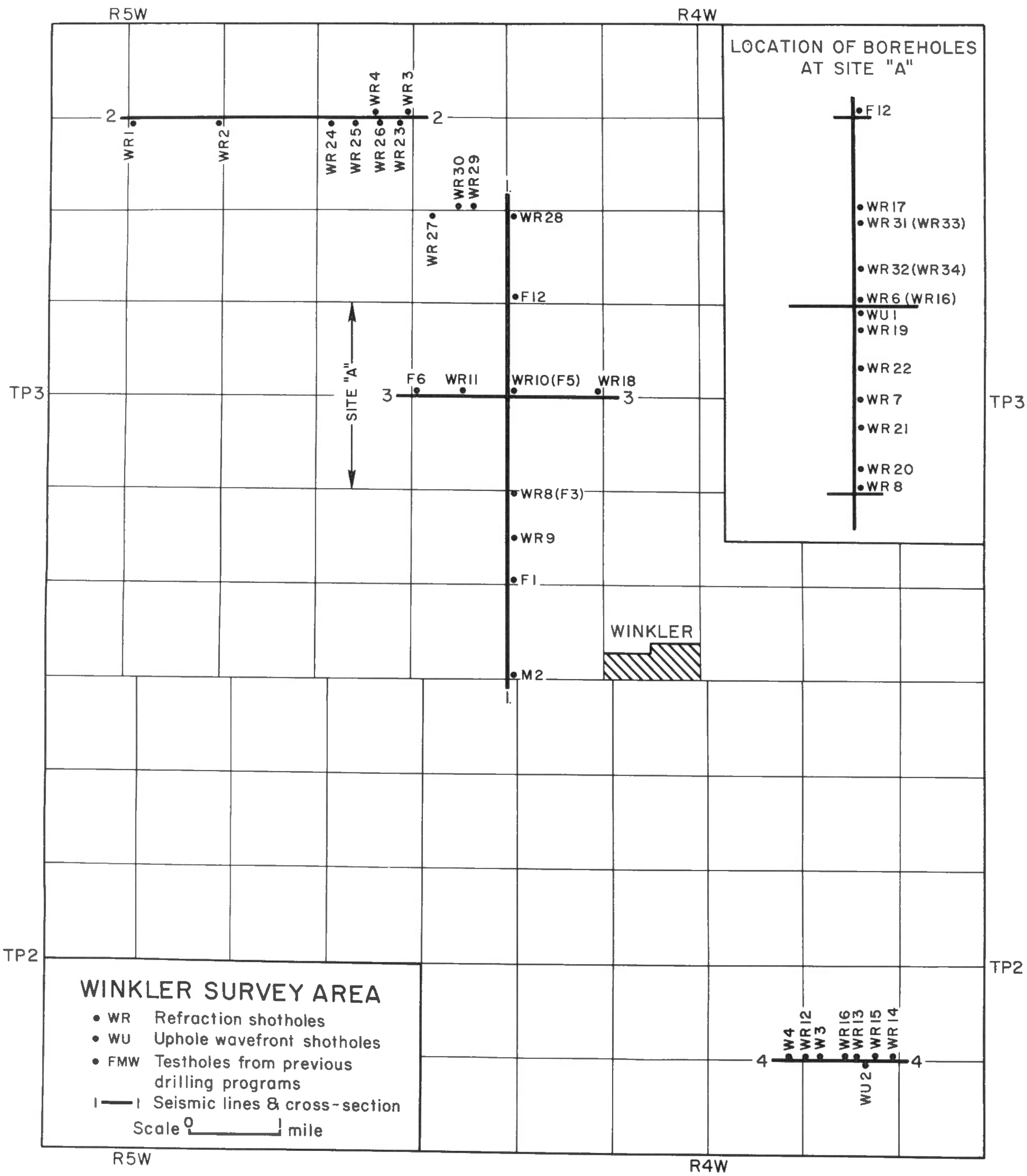

Figure 1. Location of seismic survey and boreholes, Winkler area, Manitoba.

A SEISMIC STUDY OF SURFICIAL DEPOSITS IN THE WINKLER AREA, MANITOBA

Abstract

The surficial deposits of the Winkler area, southern Manitoba, were investigated by a series of seismic experiments. Clay, gravel, sand, silt and till units overlie a bedrock of limestone, sandstone and shale. Within the survey area is northwest trending, glaciofluvial, sand and gravel deposit that was located by electric resistivity measurements and which is a major source of groundwater.

The seismic model established by uphole wavefront investigations showed that a thin, high velocity, till unit was the only consistent source of first arrival headwaves in the overburden. A till unit beneath the sand and gravel deposit gave rise to secondary arrivals. Two other refractors were identified in refraction profiles and were associated with a shale unit and a limestone unit. The dips on these refractors suggest a bedrock depression underlying the sand and gravel deposit.

A study of three-component particle motion at the site of the uphole wavefront investigations showed the absence of a direct compressional wave at shot detector distances of less than 150 feet. The directly travelling energy is instead carried in the form of a coupled surface wave with a down-away, up-toward particle motion.

Résumé

Les auteurs ont exécuté une série d'expériences sismiques pour étudier les dépôt meubles de la région de Winkler, au sud du Manitoba. Des unités d'argile, de gravier, de sable, de silt et de till recouvrent un suibstraturn de calcaire, de grès et de schiste argileux. Grâce à des mesures de résistivité, les chercheurs ont découvert dans cette région un dépôt sablo-graveleux fluvio-glaciaire orienté vers le nord, qui constitue la principale source d'eau souterraine.

Le modèle sismique, établi au moyen d'études du front d'ondes à son arrivée au haut du trou de tir, a révélé que la seule source consistante d'ondes de tête de la première arrivée dans couverture le terrain de était constituée de till de faible épaisseur et qu'elle était d'une grande vélocité. Une unité de till située sous le dépôt sablo-graveleux a provoqué des arrivées secondaires. Les profils de réfraction ont mis en évidence deux autres éléments de réfraction, à savoir une unité de schiste argileux et une autre de calcaire. Les pendages de ces éléments de réfraction laisse supposer qu'il existe une dépression du subtraturn rocheux au-dessous du dépôt sablo-graveleux.

L'étude du mouvement tridimensionnel des particules sur le site des études eu front d'ondes a démontré l'absence d'une onde de compression directe à des distances du détecteur de tir inférieures à 150 pieds. L'énergie qui se déplace directement est transmise plutôt sous forme d'une onde de surface où les particules ont un mouvement combiné d'éloignement vers le bas et de rapprochement vers le haut.

INTRODUCTION

A seismic project was undertaken by the Geological Survey of Canada to investigate the problems involved in applying seismic techniques to the mapping of the surficial deposits of the Canadian prairies. Two areas in Saskatchewan and one in Manitoba were selected for investigation on the basis of available geological control. A paper by Burke (1968) discussed the data from the Stenen, Saskatchewan area while this paper reports the results obtained from a seismic investigation in the Winkler, Manitoba area.

The area studied for this investigation lies in Townships 2, 3 and 4 of Ranges 4 and 5, west of the prime meridian in southern Manitoba (Fig. 1). The surface topography has the characteristic flatness of the Glacial Lake Agassiz region, with local relief nowhere exceeding 20 feet. The many grid roads along which the survey was conducted and the lack of topographical relief make it an excellent area in which to conduct seismic surveys. The mean surface elevation of the survey area is 875 feet above sea level.

The surficial deposits of the Winkler area have been the subject of previous geological, geophysical and drilling investigations of the Geological Survey of Canada (Charron, 1960, 1962; and Wyder, 1964).

These investigations revealed the presence of a linear sand and gravel deposit, the lacustrine silt and

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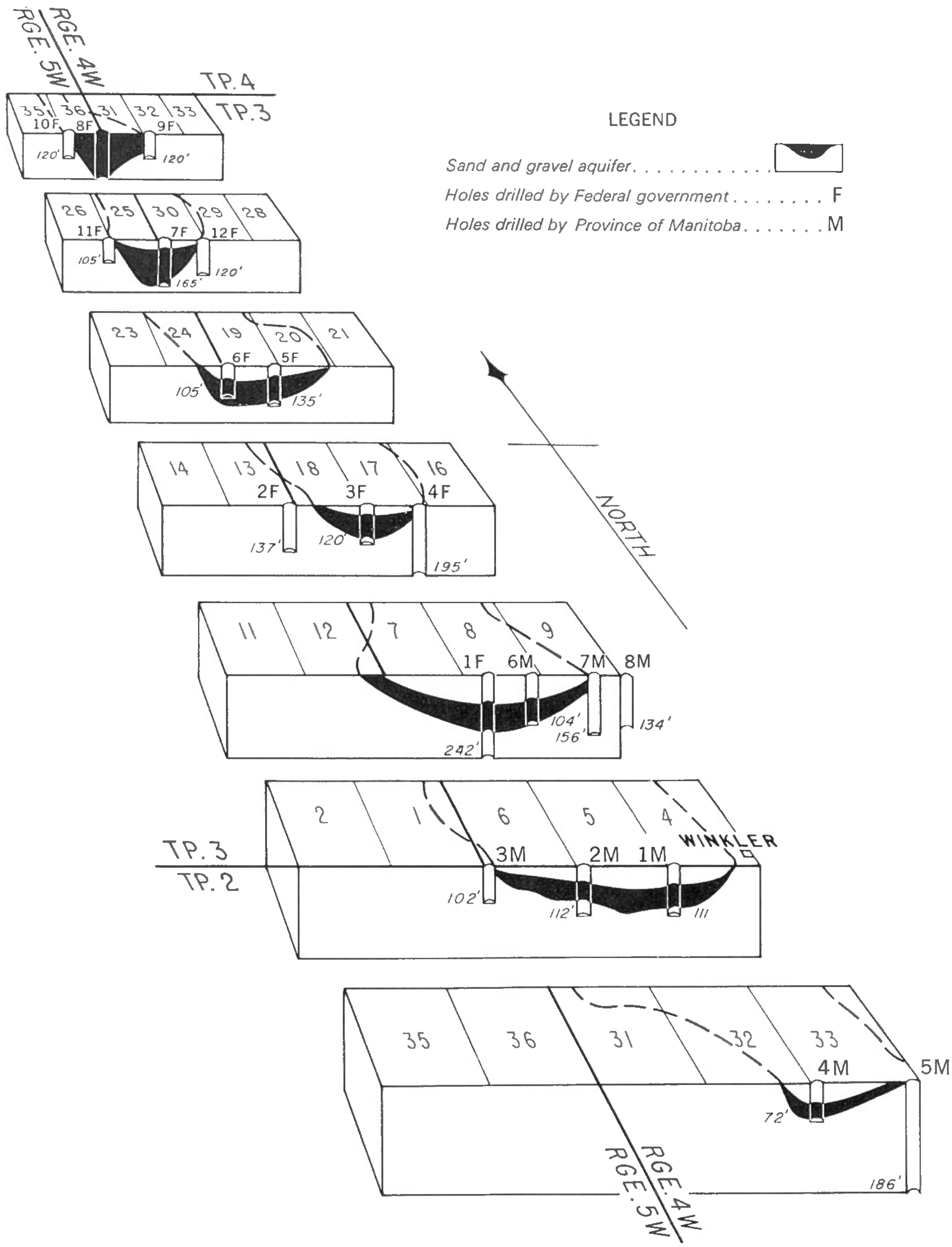


Figure 2. Block diagram of Winkler aquifer, after Charron 1962.

clay deposits of Glacial Lake Agassiz that extends 15 miles in a northwest direction, with the town of Winkler near its centre. Considerable knowledge of the extent and location of the deposit had been obtained previously from electric resistivity surveys and drilling and it was considered that this was an ideal area in which to evaluate the effectiveness of the seismic method as a technique for mapping surficial deposits.

Acknowledgments

The authors gratefully acknowledge the assistance of G. B. Finlayson, J. French and A. Ross who acted as student assistants on the field crew. In addition, some of the data were compiled and interpreted by G. B. Finlayson (1968) as part of an unpublished M. Sc. thesis at the University of Saskatchewan. Financial assistance was also provided to one of the authors (KBSB) by the National Research Council of Canada.

GEOLOGICAL SETTING

Charron (1960) has summarized the bedrock geology of the survey area in two cross-sections, based on four deep holes. One hole at Rosenfeld (sec. 8, tp. 3, R1WP) intersected granitic rock of the Precambrian basement at a depth of 1037 feet below the surface. Overlying the Precambrian rocks are limestones, sandstones and shales of Ordovician to Devonian age; the Devonian rocks, in turn, are unconformably overlain predominantly by shales, interbedded with sandstone and limestone, of Jurassic and Cretaceous age. This general sequence is present throughout the area, the sedimentary rocks having a gentle westward dip of between 5 to 16 feet to the mile.

The bedrock geology and topography map of Klassen *et al.* (1970) shows that the immediate area of the seismic survey is underlain by the Ashville and Favel formations of Cretaceous age. These formations are predominantly shale, with minor amounts of bentonite, limestone, sand and silt. The bedrock surface slopes downward towards a buried river valley of the ancestral Red River that lies to the northeast of the survey area. There is also evidence for a tributary of this buried river valley cutting across the northwestern corner of the survey area and trending in a northeasterly direction.

Bedrock is covered by Pleistocene glacial deposits. Immediately overlying bedrock is a till deposited principally as ground moraine and which varies from a soft clayey deposit to a dry pebbly hardpan. In some places, glaciofluvial deposits of sand and gravel occur, probably formed as ice contact features. The sand and gravel deposit of major interest to the seismic survey is such a feature. Its material is poorly sorted, varying in size from sand grains to boulders approximately 3 feet in diameter. Figure 2 is a block diagram (after Charron, 1962) of the deposit.

Lacustrine deposits of silt and clay overlie the till. The clay is greyish blue, very compact and sticky when wet, and varies in thickness from a few feet to over a hundred feet. The clay is overlain by a surficial deposit of silt that is usually less than 20 feet thick. Both the clay and silt are relatively soft and provide easy conditions for the drilling of shot holes.

An electrical resistivity survey, supplemented by a drilling program, had delineated the boundaries of the sand and gravel deposit (Wyder, 1964). An INPUT survey from the air had also produced similar results indicating that the deposit was marked by a contrast in electrical resistivity properties (Collett, 1966). The map of the deposit produced by the resistivity survey was the basis for planning the seismic profiles to be shot.

SEISMIC INSTRUMENTATION

A Southwestern Industrial Electronics, twelve channel, P. T. 100, seismic system was used to record all data. McManis (1961) and Hefer (1961) have given a detailed description of the amplifier and filter sections of this seismograph. The P. T. 100 system was coupled to a PMR-20 FM magnetic tape transport. Broad band recording (3-300Hz) was thus possible using only enough attenuation to control noise and avoid overmodulation of the tape transport. Playback of the tape through various filter settings and levels of gain was made to a VRO photographic recording oscillograph with conventional 'wiggly trace' display.

Vertical component geophones of three different natural frequencies (4. 5 Hz, 28 Hz and 85 Hz) were tested on an initial profile, from which the 4. 5 Hz geophones were selected for subsequent recording. Geospace, MP-6, pressure geophones were used in boreholes, while all three-component recordings were made from Geospace, HSJ, 4. 5 Hz, omnidirectional geophones.

The normal procedure was to record all information on magnetic tape in the field; later during playback in the laboratory, various instrument settings were adjusted to obtain clear records of the portion of the waveform of interest. Thus, first arrival times were obtained by playing back the tape with as little attenuation as possible and no filtering, whereas later events were enhanced by choice of gain and filter settings and use of a program gain control unit.

FIELD PROCEDURE

The original purpose of the project was to evaluate the seismic refraction method as a means of mapping surficial deposits in the Winkler area. From initial uphole shooting tests, it became apparent that suitable refractors are lacking in the upper section. This was confirmed by a study of three-component particle motion along 1000 feet of profile near the second uphole test. In subsequent investigations of the area, all refraction profiles were extended sufficiently to map shallow bedrock horizons. A brief outline of the field and recording procedure for each method of investigation follows.

Uphole Shooting

Uphole shooting was carried out in two boreholes, WU1 and WU2, by detonating small charges of explosives in the borehole generally every 10 feet, but sometimes every 5 feet. Each shot was recorded from a complete spread of 12 geophones, rather than from a single uphole geophone so that wavefront diagrams could be constructed using the method of Meissner (1961). Test WU1, a borehole at the northwestern corner of Sec. 17, Tp. 3, R4 WP, employed a 300-foot in-line spread of geophones, with 25 feet between each geophone. A split spread of geophones, 500 feet on each side of the borehole, with a geophone spacing of 50 feet, was used for the second test, WU2. The location of this test is approximately 1300 feet north of borehole WU1. In both uphole tests, Geospace, HS1, 4.5 Hz, geophones were used with recording parameters set to endure optimum first arrivals of energy.

Three-Component Recording

Uphole test WU2 was chosen also as the site for a more intensive study of the mode of wave propagation in the surficial deposits. At this site, three-component geophones recorded components of particle velocity at various distances along the surface from the borehole. Each spread consisted of three, Geospace, HS-J, omni-directional, 4.5 Hz geophones buried at 50-foot intervals. Spread distances were 50-200 feet, 250-400 feet, 450-600 feet, 650-800 feet and 850-1000 feet. Two shots were detonated at each of these spread distances, at depths ranging between 20 and 35 feet in the clay layer and between 45 and 60 feet in depth in the sand and till layers.

Correlation Refraction Profiles

Fifteen correlation refraction profiles were recorded, each profile containing a number of in-line spreads (usually twelve) and each spread composed of eleven channels with one 4.5 Hz geophone per trace. The first spread of a profile was 100 feet in length, with a geophone interval of 10 feet, while all succeeding spreads were 250 feet in length, with geophone intervals of 25 feet.

RESULTS

Uphole Wavefront Diagrams

A most important parameter to the seismologist is the velocity of propagation of seismic waves in a particular medium. In addition, it is imperative that wave types be correctly identified if meaningful estimates of depth and thickness of layers are to be made. The construction of uphole wavefront diagrams is of considerable assistance in establishing seismic velocities and identifying wave types.

Uphole shooting was conducted in two boreholes, as described previously, and the results of these tests are plotted in the form of wavefront diagrams in Figures 3 and 4. In the construction of these wavefront diagrams, an assumption is made that the travel time from the point of detonation to the surface is the same as from the top of the borehole to a point below the geophone position at a depth equivalent to the shot depth. This assumption is valid if all velocity changes take place either vertically or horizontally. However, local inhomogeneities in lithology and dipping high velocity layers will introduce deviations which are noticeable in the diagrams (Burke, 1973).

The first uphole test, Figure 3, indicates a rapid increase in velocity with depth near to the surface. This is seen in the wavefront diagram at horizontal distances up to 50 feet from the shot point and depths between the surface and 10 feet, where the wave travelling directly through the clay layer is progressively overtaken by wavefronts from below. As there is no change in lithology in the upper 25 feet of borehole

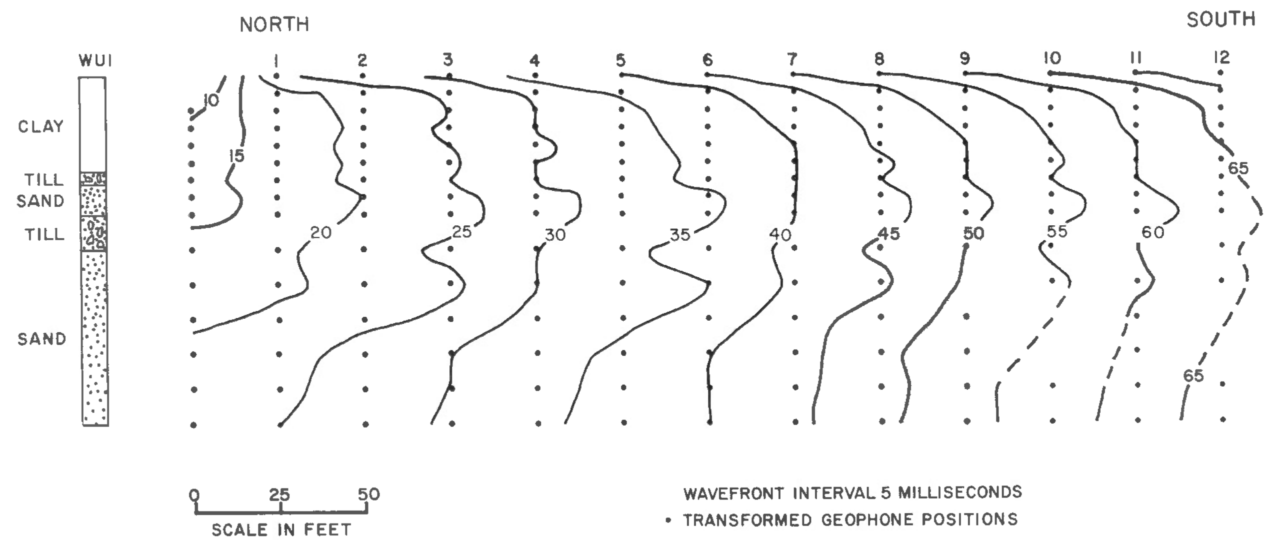


Figure 3. Uphole wavefront diagram, WU1, geophone spacing 25 feet.

WU1 variations in velocity probably result from an increasing overburden pressure and a rise in water content with depth.

Below 25 feet, wavefronts from WU1 are characteristic of refracted waves travelling in a medium of higher velocity than that of the upper layers. The bending back of wavefronts between depths of 10 and 25 feet are also characteristic of head waves generated by this higher velocity medium. The upper boundary of the latter correlates with the change in lithology from clay to till at a depth of 27 feet in borehole WU1. There is some evidence that the zone between 25 and 55 feet has a slightly higher velocity than the zone between 55 and 100 feet. The absence of till units below 55 feet may be responsible for an overall decrease in velocity with depth because the sand deposit lacks the consolidation of the till. However, irregularities in the wavefronts make interpretation of this section of the diagram uncertain.

A rapid increase in velocity near the surface is not apparent in the results of uphole test WU2 (Fig. 4), because there were no shots at depths of less than 10 feet. Instead, the diagram shows a refracted wave in the clay being overtaken by a head wave from below. To the south of the shot hole, a direct refracted wave is represented in the interval between 10 and 20 feet of depth out to the end of the spread. Lower down in the diagram, the wavefronts are again characteristic of a head wave overtaking a direct refracted wave. There is no apparent change in near-surface conditions that would explain the different behaviour on each side of the shothole and times of first arrivals of energy for the shot at 10 feet beyond 300 feet may therefore contain experimental errors. A zone of low velocity material beneath the vicinity of geophone S6 is indicated by the clustering of the wavefronts in the interval between geophones S5 and S6 and the spreading out of the wavefronts between S6 and S7.

Below depths of 50 feet, the wavefronts are characteristic of a refracted wave in a higher velocity medium. The upper boundary of this higher velocity medium correlates with the change in lithology within the borehole from clay to till. The bending back of the wavefronts for the shot at 100 feet suggests the presence of a deeper refractor but recordings from shots at greater depths would be required to substantiate this interpretation.

The bulge in the wavefronts in the till suggests that this unit may act as a thin, high velocity layer. The disappearance of the bulge toward both ends of the spread is explained by the thinness of the till unit and consequent attenuation of seismic energy in both directions away from the shot point. Alternatively, the bulge in the wavefront may be caused by a change in shot point lithology. It has been shown that a shot detonated in till has a higher proportion of high frequencies (Burke, 1968); therefore, first arrivals from such a shot should have a sharper onset than those from shots detonated in clay. The bulge in the wavefronts may therefore result from early timing of first arrivals, an explanation which is favoured because of the deviation of the bulge in the wavefronts away from the till unit at the northern end of the spread.

A typical range of velocities for each particular deposit may be obtained from wavefronts representing direct or refracted waves by drawing in rays normal to the wavefront and determining the distance covered by successive wavefronts along these rays in unit time. For a wavefront representing a head wave, it is possible to obtain the velocity in both the refractor and the

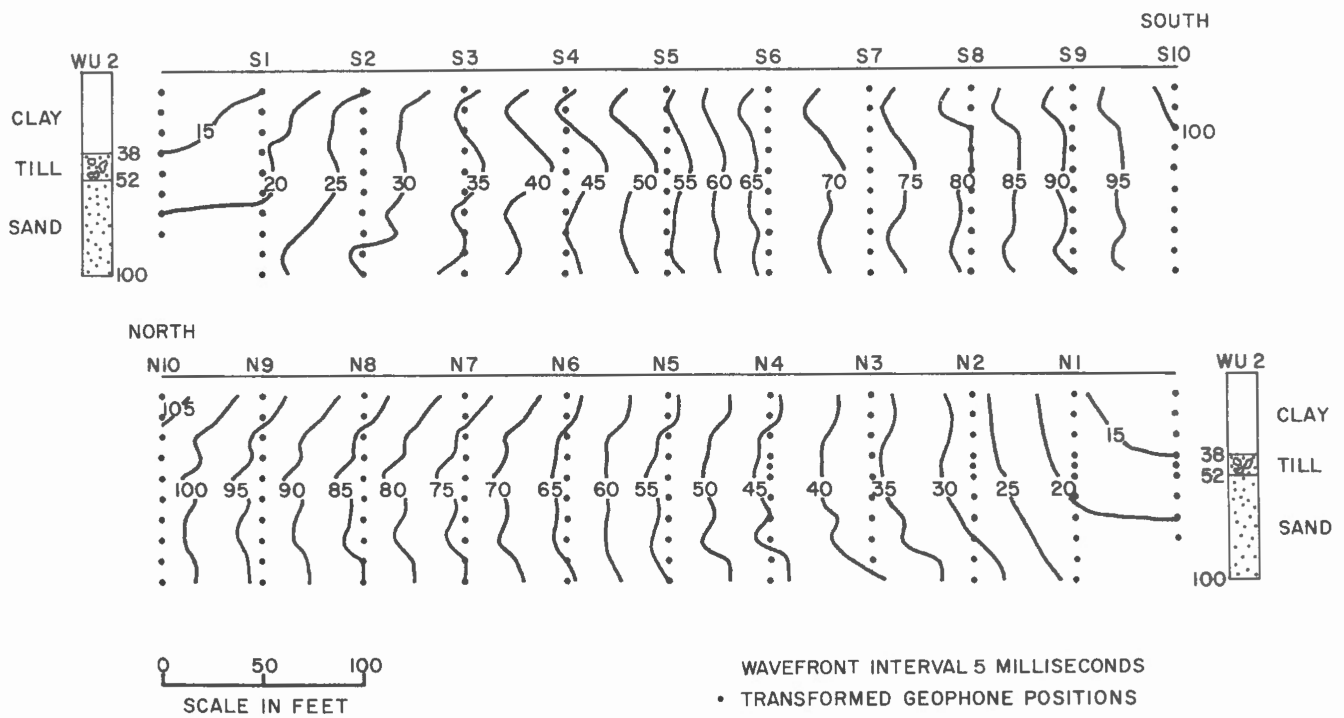


Figure 4. Uphole wavefront diagram, WU2, geophone spacing 50 feet.

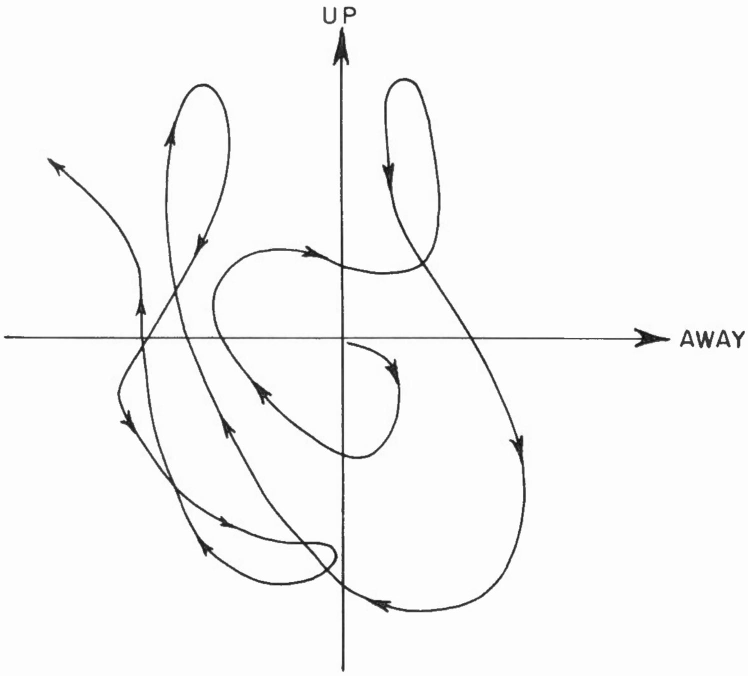
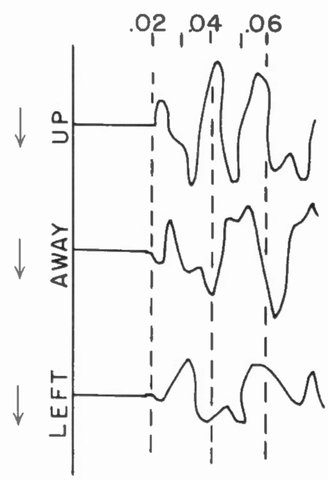


Figure 5

Hodograph of radial and vertical components of seismic energy for geophone 50 feet north of shotpoint WR-31.

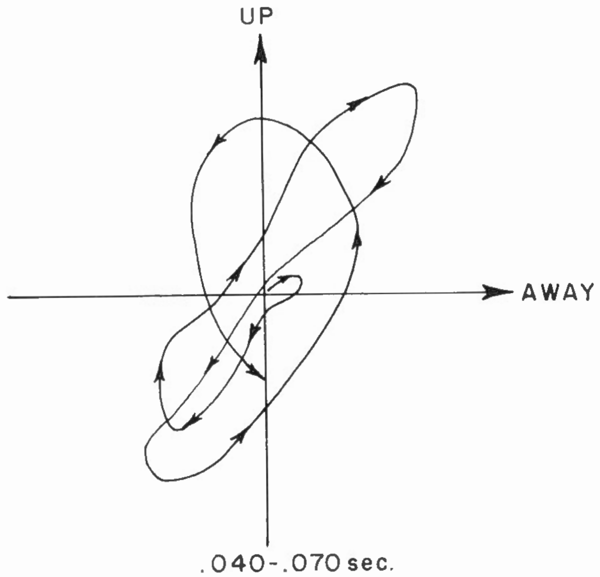


overlaying media. In the latter case, the same construction and measurements are used as for a direct or refracted wave. The refractor velocity can be obtained by drawing a line through the wavefronts parallel to the upper boundary of the refractor and measuring the distance travelled by a wavefront along this line in a unit time. Irregularities in the wavefront pattern often make the above methods unreliable and it is better to resort to a time-distance (T-X) diagram and determine values of velocity from a least squares fit of a straight line to the data. If a high velocity layer is present in the subsurface, most of the energy from layers below is channelled into this high velocity layer. It is then difficult to obtain meaningful values of velocity for the lower layers by any of the above methods. In this case, the most reliable value of velocity is obtained from the wavefronts near the shot hole.

The ranges of velocities obtained from the present data are:

Clay	700-4000 ft./s.	(213-1219 m/s.)
Till	5000-5500 ft./s.	(1524-1676 m/s.)
Sand	5000-5500 ft./s.	(1524-1676 m/s.)

Most of the variation in the velocity for the clay layer is accounted for by a rapid increase in velocity in the top ten feet below the surface.



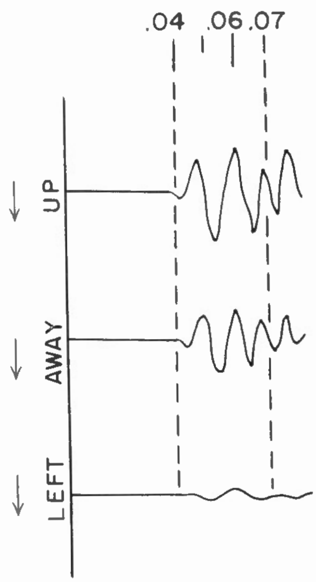
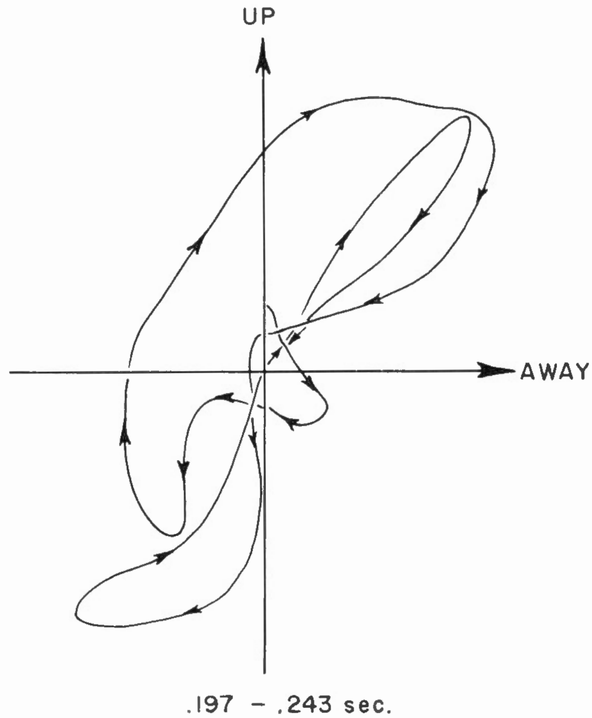


Figure 6. Hodograph of radial and vertical components of seismic energy for geophone 150 feet from shot point WR-31.

Three-Component Recording

An attempt was made to understand the mode of propagation of seismic waves, in surficial deposits of the area, by making three-component recordings of particle motion at the site of the second uphole test, WU2. Some of the hodographs of radial and vertical components for the first arrival of energy and the following 30 to 50 milliseconds of recording are shown in Figures 5, 6, and 7. All three components of motion are plotted below each hodograph in the form in which they were recorded. These traces were hand digitized at 1.5 millisecond intervals to produce the data used in construction of the hodographs.

The first hodograph, in Figure 5, is constructed from data recorded 50 feet north of shot hole WR-31. The initial motion of down-away-up-towards shows that the first arrival of energy at this station is not purely a compressional wave as might be expected from simple theory but that there is also a large component of transverse motion. Because the longitudinal component of



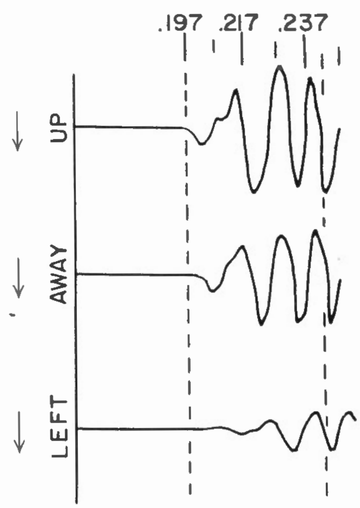


Figure 7. Hodograph of radial and vertical components of seismic energy for geophone 1000 feet from shot point WR-31.

motion is the strongest of the three components, this first arrival of energy has been identified as the coupled wave first described by Leet (1946). However, Howell and Budenstein (1955) showed that all components of coupled waves of this type are not in phase with one another so that there is probably interference from smaller components of other types of waves. The velocity of a coupled wave is less than that of a direct compressional wave (Leet, 1946), and therefore, it is concluded that a distinct and separate direct compressional wave does not exist for the conditions under which this recording was made.

A coupled wave mechanism dominates the motion over most of the hodograph, although the motion is modified to an elliptical retrograde motion between t = 37 milliseconds and t = 44 milliseconds, possibly signifying the arrival of a Rayleigh wave. The final part of the hodograph is also complicated by interference from other unidentified wavetypes.

The previously described hodograph is typical of particle motion at recording stations out to a distance of 100 feet. At larger distances, the first motion recorded in the radial — vertical plane becomes up-away-down-towards, signifying arrival of a compressional wave. A hodograph constructed from data recorded 150 feet north of WR-31, from a shot detonated at a depth of 55 feet, is shown in Figure 6. Up-away-down-towards motion dominates the hodograph for the first 20 milliseconds and identification of this motion as a compressional wave is confirmed by lack of movement on the transverse component. The large angle of emergence indicates the wave path has been influenced by passage through the upper few feet of low velocity material. An elliptical retrograde motion typical of a Rayleigh wave mechanism closely follows the initial pulse, although complicated by some movement on the transverse component. The type of motion plotted in Figure 6 persists out to the greatest recording distance, although motion typical of compressional waves tends to replace the elliptical retrograde motion for longer intervals of time as distance increases.

Figure 7 shows a hodograph plotted from data recorded at the maximum distance of 1000 feet from a shot detonated at a depth of 60 feet in borehole WR-31. The initial compressional wave is closely followed by another compressional wave, 13 milliseconds later. However, this secondary arrival has a significant transverse component, indicating a more complicated motion associated with its arrival.

The results of the three-component study confirm the model of wave propagation suggested by the wave-front diagrams. Between 100 and 1000 feet, the first arrival is a compressional wave with an apparent velocity of 5250 feet/second and an angle of emergence varying between 45 and 90 degrees. This first arrival is therefore identified as a head wave from the till layer. The variation of the angle of emergence is due to inhomogeneities in the near-surface layer, the large angles of emergence occurring where there is extremely low velocity material immediately underneath a geophone.

At distances greater than 750 feet, the first arrival is closely followed by another compressional wave which appears progressively to overtake the first arrival and has an apparent velocity of 7000 feet/second. This secondary arrival is identified as a head wave generated by a refractor in the bedrock.

Between the shot point and 100 feet, the first arrival is identified as a coupled wave and no direct compressional wave is recorded for this interval. Similar results were reported by Kroschunow (1955) from wave studies in loose media. He found that an independent compressional wave could not exist and propagate in a loose medium and that only compressional head waves from a high velocity refractor below the near-surface deposits were recorded. Kroschunow stated, however, "longitudinal waves inside the loose layer are always coupled with the Rayleigh wave mechanism which is generated and propagated inside the layer". From the present study, it is concluded that the energy is propagated in the form of the coupled waves, first identified by Leet (1946), rather than the Rayleigh wave mechanism described by Kroschunow. This conclusion is supported by the existence of large components of transverse motion which would not be present in a simple combination of compressional and Rayleigh waves.

Correlation refraction profiles

Table 1 sets out the velocity data and calculated depths to the various significant refractors in the survey area. The locations of the various profiles are shown in Figure 1. Depths were calculated using the critical distance method (Dobrin, 1960). The analysis of the frequencies of various arrivals yielded erratic results in that no consistent relationship could be found between a particular arrival and its frequency content and no attempt has been made to use this analysis in the identification of events.

In the following sections, seismic results and borehole information are used to construct geological cross-sections. For convenience the seismic profiles are grouped into four lines:

Line 1. Profiles WR-6. WR-7. WR-8. WR-9. WR-16. WR-17.
Line 2. Profiles WR-2. WR-3. WR-4.
Line 3. Profiles WR-10. WR-11. WR-18.
Line 4. Profiles WR-12. WR-13. WR-15.

Line 1 (Fig. 8)

This line extends five miles from shot hole WR-28 in the north to test hole M-2 in the south, cutting obliquely across the sand and gravel deposit. In the central part of the section, the sand and gravel is approximately 100 feet thick. To the north, the deposit thins rapidly and is not present in boreholes F12 and WR-28. There is also a decrease in thickness to the south, but 40 feet of sand is still present in the southernmost borehole M-2. A cover of lake clay which overlies the sand and gravel, varies in thickness from 30 feet at the centre to 80 feet at the northern extremity of the line. Underlying the sand and gravel is a consolidated till layer. In the only borehole to penetrate

Table 1

Velocity and depth data from seismic refraction profiles, Winkler area, Manitoba (from Finlayson, 1968)

		WR-2	WR-3	WR-4	WR-5	WR-6	WR-7	WR-8
Velocity Layer	1	5700	5300	5450	4700	5200	5300	5250
	2	——	6700	6500	6000	6100	6000	6600
(ft./sec.)	3	7900	8250	7400	7000	7150	8300	7600
	4	13 300	14 000	13 600	13 000	13 000	13 300	12 200
Depth to Layer	2	——	173'	151'	133'	146'	130'	142'
	3	212'	290'	231'	196'	233'	278'	322'
	4	342'	627'	566'	846'	559'	658'	542'

		WR-9	WR-10	WR-11	WR-12	WR-13	WR-15	WR-16
Velocity Layer	1	5350	5400	4900	5300	5300	4800	5250
	2	——	6800	6750	5430	5400	5400	5800
(ft./sec.)	3	7700	7700	7600	7830	8800	9500	7600
	4	12 500	12 500	12 700	13 300	13 100	12 400	13 100
Depth to Layer	2	—	110'	189'	52'	38'	95'	108'
	3	251'	164'	269'	219'	206'	227'	238'
	4	479'	660'	620'	582'	565'	626'	564'

		WR-17	WR-18
Velocity Layer	1	5300	5650
	2	6300	6100
(ft./sec.)	3	8300	7250
	4	12 800	12 300
Depth to Layer	2	144'	85'
	3	265'	187'
	4	584'	532'

bedrock (F-1), sandstone was logged between 185 and 230 feet and shale between 230 and 292 feet.

Four refracted events were identified on the seismic profiles. The absence of a direct compressional wave in the near-surface layer makes depth estimates based on the first refracted event unreliable and these depths were not included in the final analysis. However, a correction for the time delay in the upper layer was made in the depth estimates based on refracted events 'A', 'B' and 'C'. Refracted event 'A' appears as a secondary arrival on profiles WR-6, WR-7, WR-16 and WR-17, while events 'B' and 'C' were received as first arrivals. On profile WR-8, events 'A' and 'C' were observed as first arrivals, while event 'B' was a secondary arrival. Finally, on profile WR-9, event 'B' was again observed as a secondary arrival, while event 'C' was a first arrival and event 'A' was not identified.

The high velocity of the refractor associated with event 'C' suggests that it represents a limestone unit reported by Charron (1962) in a borehole at Winkler. An Ordovician limestone at a depth of 635 feet is present in this borehole, which is the same order of depth as the seismic interface. The depth of the refractor associated with event 'B' suggests that this probably represents the shale unit, identified as a Cretaceous shale in borehole F-1 by Charron. Event 'A' appears to be associated with an interface in the consolidated till layer but exact correlation is not possible with the available geological information. The change in the order of arrivals in profile WR-8 can be explained by a thickening of the consolidated till unit and a corresponding thinning of the shale unit. Similarly, the absence of event 'A' in profile WR-9 may be a result of a thinning of the till unit and disappearance of the refractor interface.

The dip of the bedrock refractors towards the centre of the section suggests the presence of a minor bedrock depression which may have controlled the deposition of the glacial deposits.

<u>Line 2</u> (Fig. 9)

This line is perpendicular to the axis of the sand and gravel deposit and extends from the centre of the deposit to its western edge. The thickness of the overlying clay layer decreases from 120 feet in the west to 10 feet at the centre. In the only borehole to reach bedrock (WR-1), a shale unit logged at a depth of 140 feet is overlain by a consolidated till unit 20 feet thick which is in turn overlain by 120 feet of clay.

Again, events 'B' and 'C' are prominent first arrivals on the seismic records, while event 'A' is only present as a secondary arrival on profiles WR-3 and WR-4. The consolidated till unit is therefore interpreted as

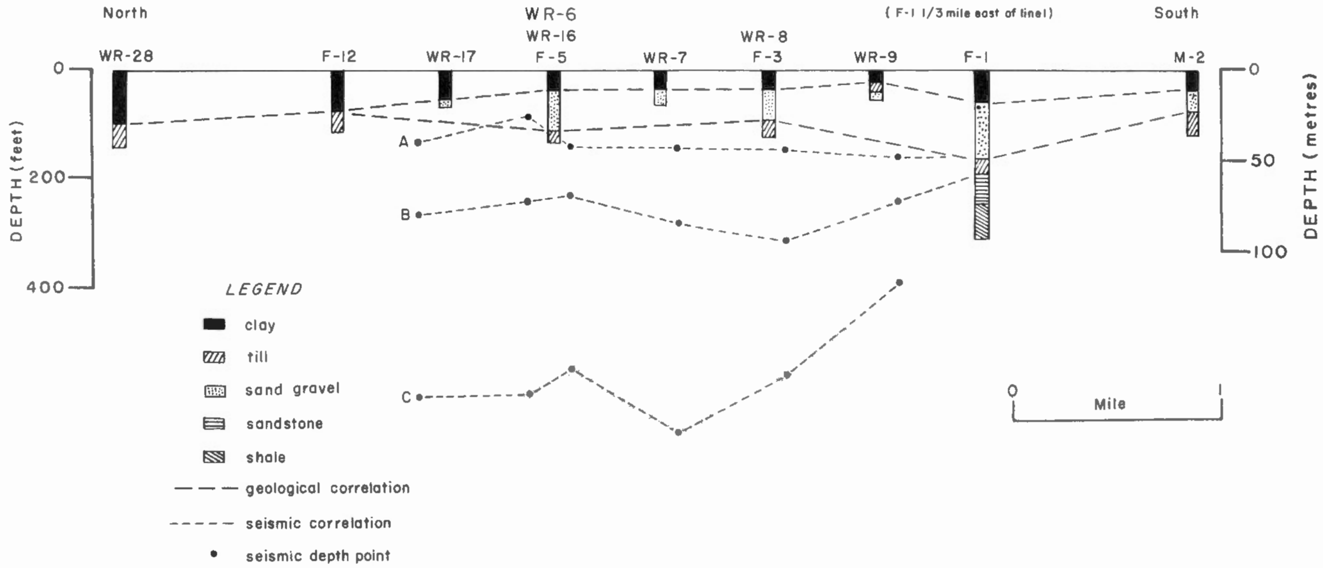


Figure 8. Cross-section, line 1, seismic data correlated with lithology.

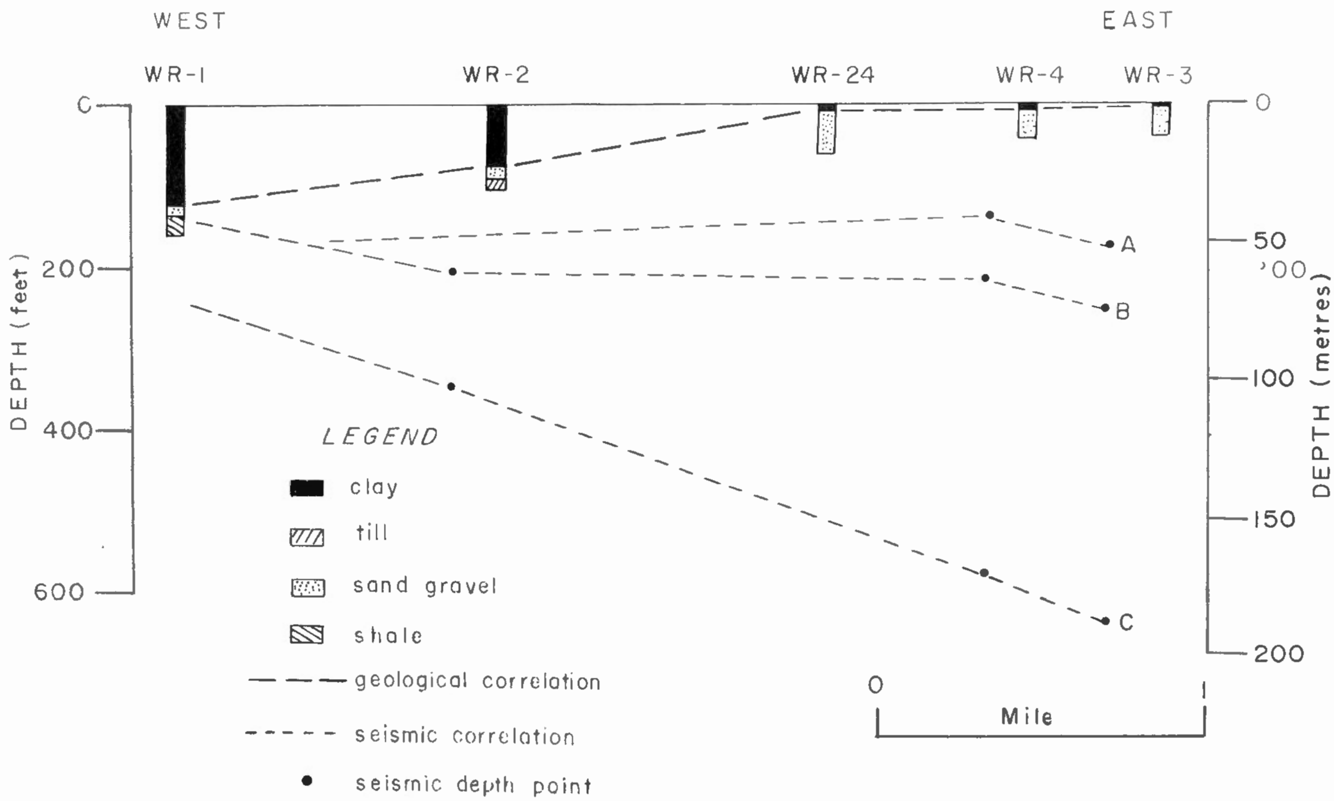


Figure 9. Cross-section, line 2, seismic data correlated with lithology.

thinning to the west. The dip of the bedrock refractors towards the east again suggests that a bedrock depression may underlie the sand and gravel deposit.

Line 3 (Fig. 10)

Line 3, also perpendicular to the axis of the sand and gravel deposit, extends across two thirds of the deposit to the eastern edge. In the east the sand and gravel deposit is absent (borehole WR-18), but is 84 feet thick in borehole F-5 one mile to the west. The thickening of the sand and gravel deposit is again associated with a thinning of the overlying clay, which is 100 feet thick in the east, decreasing to 10 feet at the centre of the deposit but increasing to a thickness of

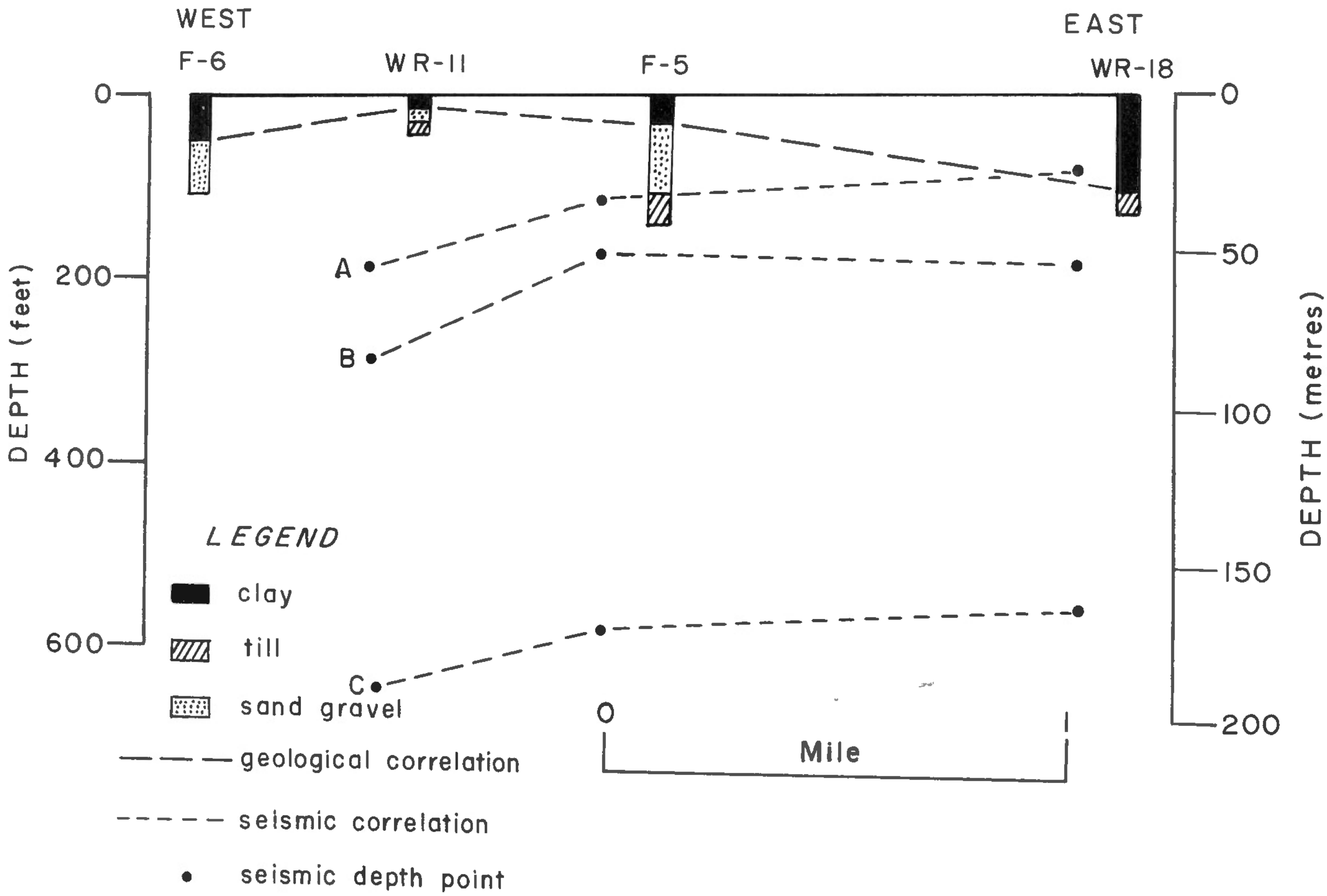


Figure 10. Cross-section, line 3, seismic data correlated with lithology.

45 feet at the western end of the seismic line. A consolidated till unit underlies the sand and gravel at the eastern end of the line.

The lower refractors exhibit a westward dip towards the centre of the sand and gravel deposit, again suggesting that there is a depression in the bedrock. Along this line, it appears that event 'A' correlates with the top of the consolidated till layer.

Line 4 (Fig. 11)

This line cuts across the southern end of the sand and gravel deposit. In the westernmost borehole WR-4, a shale bedrock unit was encountered at a depth of 210 feet, overlain by a till unit of 140 feet and an upper layer of silt and lake clay. Five hundred feet to the east, sand and gravel were encountered underlying the silt and clay in borehole WR-11, at a depth of 50 feet. The sand and gravel is present to a depth of 200 feet farther to the east, but was not penetrated at depths of 80 to 90 feet respectively in boreholes WR-14 and W15, at the eastern end of the line.

Refracted events 'B' and 'C' are again present as first arrivals on the seismic records and have been correlated with the bedrock shale and a lower limestone unit. However, a new secondary event 'E', also present on the records, appears to correlate with the top of the sand and gravel. The absence of event 'A' may be explained by the lack of a substantial till unit below the sand and gravel, the latter appearing to rest directly on the bedrock shale.

CONCLUSIONS

1. Three-component studies of particle motion show the absence of a direct compressional wave as first arrival at small shot-detector distances, i.e. less than 150 feet. Instead, directly travelling energy is carried in the form of a coupled wave with down-away-up-towards motion as described by Leet (1946).

2. The usefulness of the seismic method in mapping surficial deposits in the Winkler area is restricted by a high velocity channel in the form of the thin till layer overlying the sand and gravel deposit. Head waves generated by the upper boundary of the till dominate the first arrivals at shorter distances and velocity contrasts between other units are generally too small to give adequate secondary arrivals. One exception is the secondary arrival from refractor 'A' which is associated with the consolidated till unit beneath the sand and gravel deposit.

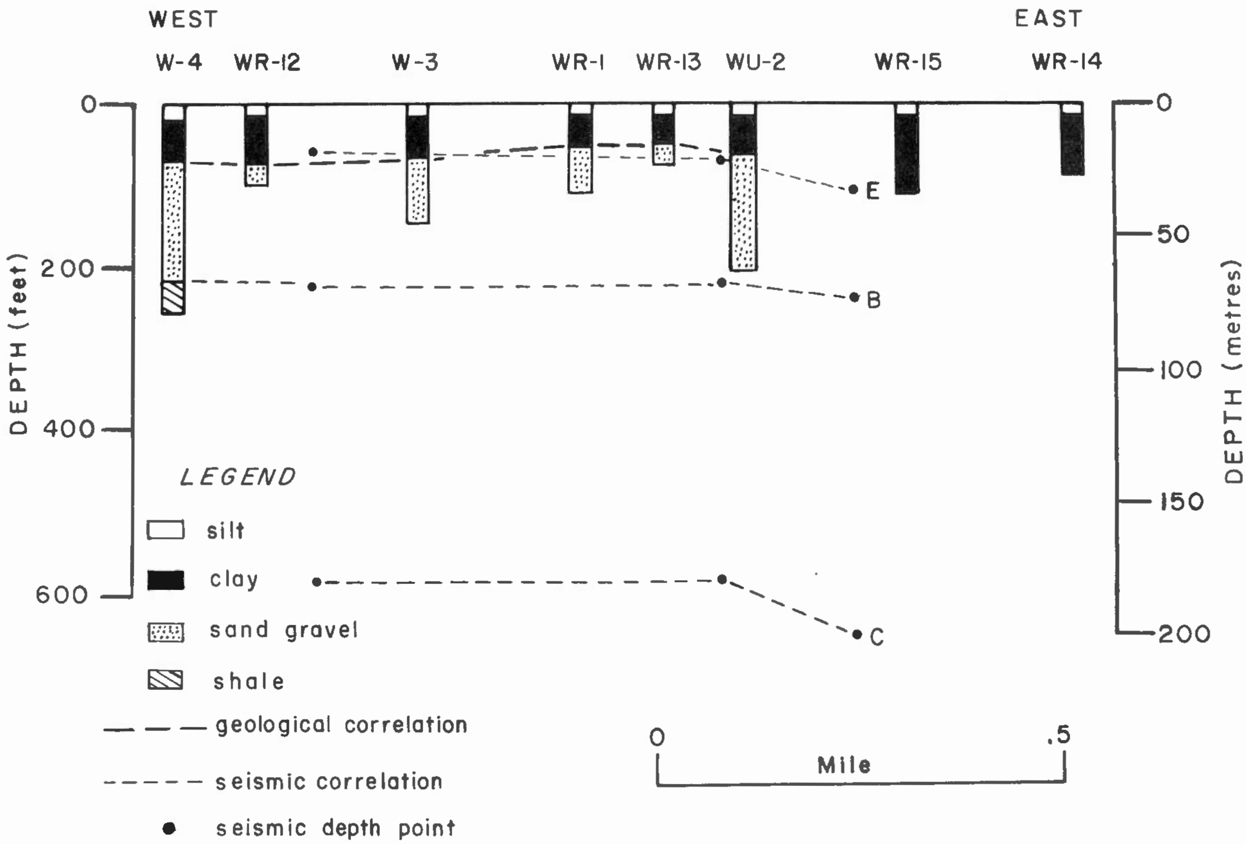


Figure 11. Cross-section, line 4, seismic data correlated with lithology.

3. Two refractors 'B' and 'C' were identified and correlated with lithological horizons in the bedrock. Refractor 'B' may be associated with the Cretaceous shale unit in the Winkler borehole and refractor 'C' has been related to the Ordovician limestone unit.

4. The dips on these bedrock refractors suggest a bedrock depression under the sand and gravel deposit.

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